Design of Contract-Based Trading Mechanism for a Small-Cell Caching System

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***Abstract*— Recently, content-aware-enabled distributed caching relying on local small-cell base stations (SBSs), namely, small-cell caching, has been intensively studied for reducing transmission latency as well as alleviating the traffic load over backhaul channels. In this paper, we consider a commercialized small-cell caching system consisting of a network service provider (NSP), several content providers (CPs), and multiple mobile users (MUs). The NSP, as a network facility monopolist in charge of the SBSs, leases its resources to the CPs for gaining profits. At the same time, the CPs are intended to rent the SBSs for providing better downloading services to the MUs. We focus on solving the profit maximization problem for the NSP within the framework of contract theory. To be specific, we first formulate the utility functions of the NSP and the CPs by modeling the MUs and SBSs as two independent Poisson point processes. Then, we develop the optimal contract problem for an information asymmetric scenario, where the NSP only knows the distribution of CPs' popularity among the MUs. Also, we derive the necessary and sufficient conditions of feasible contracts. Lastly, the optimal contract solutions are proposed with different CPs' popularity parameter γ. Numerical results are provided to show the optimal quality and the optimal price designed for each CP. In addition, we find that the proposed contract-based mechanism is superior to the benchmarks from the perspective of maximizing the NSP's profit.**

***Index Terms*— Wireless caching, small-cell networks, contract theory, stochastic geometry.**

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I. INTRODUCTION

WITH the dramatically growing demands on video entertainment and social connections, wireless multimedia communications have played an important role in future cellular networks. Unfortunately, the capacity of current networks has not been able to keep a similar pace with the tremendous growth of cellular traffic [1]–[3]. At the same time, it is pointed out that the next generation of mobile communication systems will have to meet the following requirements in 2020: high throughput, high access amount, high data rate, low power consumption and low latency [4], [5]. In order to fulfill these requirements, researchers begin conceiving 5G cellular networks [6], [7] and focusing on key techniques [8], such as millimeter wave technology [9], massive multiple-input multiple-output [10] and super density heterogeneous networks [11]. However, these techniques may need to intensively change the hardware equipments and network protocols, imposing high cost and complexity to current communication systems. It is urgent to find a solution more economically and conveniently.

A. Wireless Caching

Through the observations on network traffic, it can be found that there are numerous repetitive requests of popular contents, e.g., video clips, raised by mobile users (MU), leading to heavy traffic pressures on the backhaul channels [12]. The redundancy of transmissions can be effectively mitigated by storing popular contents into local caches of network nodes positioned at the edge of wireless networks, known as wireless caching [13]–[15].

Wireless caching generally consists of two stages: a data placement stage [16] and a data delivery stage [17]. In the first stage, files such as popular movies are pre-cached to the local storages during off-peak time. While in the second stage, MUs may acquire data directly from local facilities which are adjacent to them. As such, a caching mechanism can help offload data traffic from the macro-cell base stations (MBS) and bring contents closer to the MUs. The authors in [18] propose a femto-caching scheme in which data placement at the small-cell base stations (SBSs) is optimized in a centralized manner in order to reduce transmission delay. In [19], an optimal caching scheme is proposed to place the popular contents in device-to-device networks, where the cluster size is optimized to reduce the transmission delay. The authors in [20] present a many-to-many matching game algorithm for proactive caching in social networks to significantly reduce the transmission latency.

B. Commercial Issues and Contract Theory

While the current works on wireless caching mainly focus on the optimization of data placement in order to reduce the transmission delay, the authors of [21] and [22] consider a small-cell caching system from the commercial perspective. Particularly, authors in [21] research on a commercial video-caching system using the Stackelberg game by treating the SBSs as a specific type of resources within the scenario of one network service provider (NSP) and multiple content providers (CPs). Furthermore, the authors extend their researches to the scenario with one CP and multiple NSPs [22].

In the Stackelberg game, the utilities of both involved sides are assumed to be known to each other, which is the information symmetric environment [23]. However, when trading is modeled in an information asymmetry scenario, i.e., one side has certain private information, which can not be observed by the other side, in this case, contract theory is provided as an effective way to solve this kind of problem [24]. Most of the existing works on contract theory can be classified into two categories: one is adverse selection often referring to the problems of hidden information [25]–[31], and the other one is moral hazard related to the problems of hidden actions [32], [33].

Specifically, the work in [25] introduces contract theory into the quality discrimination spectrum trading in cognitive radio networks, where the buyer's types are the hidden information. In [26], the authors propose a contract-theoretic framework for the broker-based TV white space market. The difference between the database's and the white space devices's knowledge is regarded as information asymmetry. The authors in [27] address a hybrid access model employing either opportunistic or exclusive access of free frequency bands. By offering bandwidth-price contracts to the secondary users, the primary spectrum owner gains additional revenue. The authors of [28] research on the adverse selection problem where a primary license holder wishes to profit from its excess spectrum capacity via contract theory. Additionally, [34] designs the incentive contract between a mobile network operator (MNO) and multiple CPs in a fixed network. The proposed model exploits the strategic interdependence between the CPs, and the optimization problem is defined to maximize the utility of the CPs while the MNO is ensured to be budget balanced.

C. Our Contributions

The preceding discussions highlight that solving the problem of asymmetric information in resource trading process is the major advantage of contract theory. Similarly, in the small-cell caching system, there exists the asymmetric information scenario, where the NSP, as a network facility monopolist, intends to lease the SBSs to the CPs for maximizing its profits, while it does not know the specific type of each CP. Accordingly, we are inspired to solve the problem of asymmetric information within the framework of contract theory. Here, the SBSs owned by the NSP are divided into different *qualities*, i.e., various fractions of the SBSs. Moreover, the CPs can be classified into different *types* according to their popularity among the MUs. We model the trading in a monopoly market, where the monopolist NSP sets the contract entries with combinations of quality and price for its goods, and each buyer CP with a specific type chooses an appropriate entry to sign.

The proposed scheme, together with the derived solutions, can offer proper economic incentives to the NSP. The main contributions of this paper are summarized as follows:

1) A commercial caching system is constructed, where network nodes are modeled as Poisson point processes via stochastic geometry. The probability of MUs' successful downloading from SBSs is considered, based on which, the profits of the NSP and CPs are formulated.
2) Contract theory is proposed to address the resource-trading issues between the monopolist NSP and multiple CPs in our commercial small-cell caching system. The CPs are classified into different *types* according to their popularity. Correspondingly, the NSP divides its commodity, i.e., the SBSs in charge, into various fractions, defined by the term '*quality*' of commodity. The optimal contract is constructed in maximizing the utility of the NSP.
3) The necessary and sufficient conditions of a feasible contract are developed. Furthermore, these conditions are transferred and reduced for the purpose of facilitating the optimization process of the contract design. With regard to the CPs' popularity distribution parameter γ, the concavity and convexity of the utility functions are investigated, and the optimal contract entries are solved in the closed forms with different γ values.
4) Performance comparisons are conducted among the proposed, the uniform quality, and the Stackeberg game schemes. It can be found that in terms of maximizing the NSP's profits, the latter two schemes are inferior to the proposed one.

The rest of this paper is organized as follows: The system model is presented in Section II. The contract-based service model is elaborated in Section III. The optimal contract design and solutions are developed in Section IV. Other resource allocation and pricing strategies are discussed in Section V. Numerical results are presented in Section VI, and conclusions are drawn in Section VII.

II. System Model

We focus on a commercial small-cell caching system with one NSP, N CPs and multiple MUs. In this system, by viewing the SBSs as a kind of resources of the NSP, each CP rents a

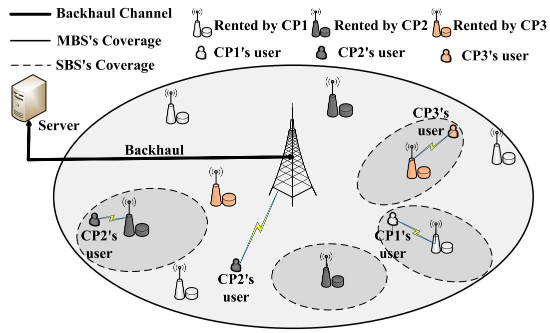

Fig. 1. An example model with one NSP and three CPs, where CP1 rents four SBSs, CP2 rents three SBSs, and CP3 rents two SBSs.

TABLE I
TABLE OF NOTATIONS

Notations	Meanings
$\mathcal{V}_\upsilon$	The υth CP
$\mathcal{L}$	The NSP
$\mathcal{F}_i$	The ith file
N	The number of CPs
F	The number of files
Q	The maximum file number stored in each SBS
γ	The CPs' popularity distribution parameter
β	The files' popularity distribution parameter
$\mathcal{E}_{\upsilon,i}$	The event that an MU of $\mathcal{V}_\upsilon$ requests a file $\mathcal{F}_i$ from the SBS
τ_υ	The fraction of the SBS assigned to $\mathcal{V}_\upsilon$
π_υ	The corresponding price of τ_υ
p_i	The popularity of $\mathcal{F}_i$
θ_υ	The popularity of $\mathcal{V}_\upsilon$
λ	The density of SBSs within a unit area $(/UA)$
ζ	The density of MUs within a unit area $(/UA)$
K	Average file downloading demands from each MU within a unit period $(/UP)$
s^{bh}	Average backhaul cost for a file transmission
s^{ld}	Average local downloading saving for a file transmission
κ	The scale parameter between s^{bh} and s^{ld}

certain fraction of these SBSs from the NSP for placing its popular contents. An MU affiliated with a CP may directly download data from its nearby SBSs that have been rented by this CP. Otherwise, the MU has to acquire data from the MBS. An example system is depicted in Fig. 1, where three CPs rent a number of SBSs owned by the NSP. A table of notations used throughout the paper is given in Table I.

A. Network Model

Let us consider a small cell network consisting of multiple SBSs owned by the monopolist NSP. We denote the set of N CPs by $\boldsymbol{\mathcal{V}} = \{\mathcal{V}_1, \cdots, \mathcal{V}_\upsilon, \cdots, \mathcal{V}_N\}$ and the NSP by $\mathcal{L}$. We assume that SBSs are equipped with an uniform transmission power of P and the same caching size of Q files. Also, the spatial distributions of the SBS and the MUs are modeled as two independent homogeneous Poisson point processes (PPP) Φ and Ψ, with densities λ and ζ, respectively. SBSs transmit on the orthogonal channels to the MBS, and hence we do not consider interferences induced by the MBSs.

We consider a typical MU located at the origin and an SBS located at x. The path-loss attenuation between an SBS and the typical MU is denoted by $||x||^{-\alpha}$, where α is the path-loss exponent. The channel between an SBS and the typical MU is denoted by h_x, where we have $h_x\sim$ exp(1). The noise is modeled as the additive white Gaussian noise (AWGN) with mean zero and variance σ^2.

A saturate network is considered in this model, where all SBSs are powered on and keep transmitting to their subscribers. Hence, the signal-to-interference-and-noise-ratio (SINR) at the typical MU from an SBS, whose location is x, can be expressed as

$$\rho(x) = \frac{Ph_x||x||^{-\alpha}}{\sum_{x'\in\Phi\backslash x} Ph_{x'}||x'||^{-\alpha} + \sigma^2}.$$

Note that if $\rho(x)$ is no less than a predefined threshold δ, this typical MU can be covered by the SBS located at x.

B. Popularity and Preferences

Let us denote the file set by $\boldsymbol{\mathcal{F}} = \{\mathcal{F}_1, \mathcal{F}_2, \cdots, \mathcal{F}_F\}$ consisting of F files. The requested probabilities by the MUs, i.e., popularity distribution, of the files are denoted by $\mathbf{p} = \{p_1, \cdots, p_i, \cdots, p_F\}$, which has been shown to follow the Zipf distribution [35]–[37] as

$$p_j = \frac{1/j^\beta}{\sum_{f=1}^{F} 1/f^\beta}, \quad j = 1, \cdots, F, \tag{1}$$

where the positive value β represents the files' popularity. Note that each SBS can store at most Q files, and we assume $Q < F$. In this paper, we assume that all the CPs generate the same file set $\boldsymbol{\mathcal{F}}$. Note that different CPs may have different file sets in a practical system. However, this does not affect the design procedure for the optimal contract.

Usually, MUs have different preferences to the N CPs, combining with many factors including personal favor, quality of service and the charging standards, and so on. We again utilize the Zipf distribution to present MUs' preferences to $\boldsymbol{\mathcal{V}}$, denoted by $\boldsymbol{\Theta} = \{\theta_1, \cdots, \theta_\upsilon, \cdots, \theta_N\}$,

$$\theta_\upsilon = \frac{1/\upsilon^\gamma}{\sum_{j=1}^{N} 1/j^\gamma}, \quad \upsilon = 1, \cdots, N, \tag{2}$$

where γ is a positive value and determines the distribution of CPs' popularity among the MUs [35]. The parameter γ can be determined by questionnaires conducted by a consulting firm or through learning of the historical data flow by the NSP. Moreover, the distribution of MUs preferences can be any function other than Zipf, since it will not affect the design of the optimal contract.

C. Caching Procedures

In this subsection, we describe the content caching procedure in a small-cell caching system into details. There are three stages in our system. In the first stage, each CP rents a certain fraction of the SBSs from $\mathcal{L}$ for placing its files. We denote the fraction vector by $\boldsymbol{\Gamma} = \{\tau_1, \tau_2, \cdots, \tau_N\}$, in which τ_υ represents the fraction of the SBSs assigned to $\mathcal{V}_\upsilon$. In general, we have $\tau_\upsilon = 0$, if a CP $\mathcal{V}_\upsilon$ does not rent any fraction from $\mathcal{L}$. Obviously, fractions cannot be negative or infinity, and thus we have $\sum_{v=1}^{N} \tau_v = 1$ and $\tau_v \geq 0$. We assume that the SBSs rented by $\mathcal{V}_v$ are uniformly and randomly distributed and can be modeled as a thinned homogeneous PPP Φ_v of density $\tau_v \lambda$.

In the second stage, the data placement commences during off-peak time after each CP obtains the access to the SBSs. Due to the limited caching volume of each SBS, the Q most popular files will be placed for increasing the caching efficiency.

In the third stage, an MU of $\mathcal{V}_v$ requests a file $\mathcal{F}_i \in \boldsymbol{\mathcal{F}}$. It first searches the SBSs in Φ_v and connects to the nearest SBS that caches the requested file and covers it. If such an SBS exists, the subscriber will obtain this file directly from the caching of this SBS. This event is defined by $\mathcal{E}_{v,i}$. Otherwise, the MU will trigger the transmission via backhaul channels of the NSP for remotely dispatching the requested file, leading to an extra cost on $\mathcal{L}$.

Followed by the same derivation steps in [38], the probability $\Pr(\mathcal{E}_{v,i})$ of the event $\mathcal{E}_{v,i}$ can be derived as

$$\Pr(\mathcal{E}_{v,i}) = \frac{\tau_v}{\tau_v A(\delta,\alpha) + (1-\tau_v)C(\delta,\alpha) + \tau_v}, \quad i = 1, 2, \cdots, Q, \quad (3)$$

where $A(\delta,\alpha) = \frac{2\delta}{\alpha-2}{}_2F_1(1, 1-\frac{2}{\alpha}; 2-\frac{2}{\alpha}; -\delta)$ and $C(\delta,\alpha) = \frac{2}{\alpha}\delta^{\frac{2}{\alpha}} B(\frac{2}{\alpha}, 1-\frac{2}{\alpha})$. Furthermore, ${}_2F_1(.)$ in the function $A(\delta,\alpha)$ is the hypergeometric function and $B(.,.)$ is the beta function in $C(\delta,\alpha)$. From (3), we can see that the probability of $\Pr(\mathcal{E}_{v,i})$ is independent of the transmission power P and the intensity λ of the SBSs.

III. Contract-Based Service Model

We now focus our attention on modeling the contract-based trading on the SBSs in our small-cell caching system as shown in Fig. 1. Since the NSP $\mathcal{L}$ owns the network facilities and dominates the trading process, we consider a monopoly market, where $\mathcal{L}$ is the monopolist and designs different contract entries for the CPs in $\boldsymbol{\mathcal{V}}$ for incentivizing them to participate in the trading market. On the other hand, each CP is free to accept or decline any contract offered by $\mathcal{L}$ based on its own goodness. Contract theory is proposed to solve the profit maximization problem for a monopoly market, where there is only one monopolist controlling the resources. Considering the competitive sellers' scenario, other game theory schemes such as matching theory, auction theory or Stackelberg game theory might be applicable. Incorporating the caching and data transmission processes, we elaborate on the contract issues in our small-cell caching system in the following.

A. NSP Model

We assume that $\mathcal{L}$ sets the contract entries $\{\boldsymbol{\Gamma}, \boldsymbol{\Pi}\}$, where the set of prices is denoted by $\boldsymbol{\Pi} = \{\pi_1, \pi_2, \cdots, \pi_N\}$, and each quality τ_v in $\boldsymbol{\Gamma}$ corresponds to a price π_v. The SBSs are divided into different fractions with each fraction being regarded as a specific *quality*. The CPs are free to decide whether or which quality to purchase. The above discussions are the contract related construction and commitment taking place before caching procedures.

We assume that there are averagely K file downloading demands from each MU within a unit period ($/UP$), e.g., $/month$, and the average backhaul cost for a file transmission is s^{bh}. The profits of $\mathcal{L}$ in terms of per unit area times unit period ($/UAP$), e.g., $/month \cdot km^2$, come from leasing the SBSs plus the saved transmission costs over backhaul channels. If a CP rents the SBSs with quality τ_v, the first Q files $\mathcal{F}_i, i \leq Q$ will be cached in each local SBSs, since they are the most Q popular files among the users. This is the most efficient way to place files. Please be noted that each CP rents multiple SBSs and each CP caches the same set of files, i.e., the most Q popular files, to each SBSs it rents. Based on (3), the saved backhaul costs ($/UAP$) of $\mathcal{L}$ can be expressed by

$$S_v^{\mathrm{BH}} = \sum_{f=1}^{F} p_f \theta_v \zeta K s^{\mathrm{bh}} g(\tau_v), \quad \forall v, \quad (4)$$

where

$$g(\tau_v) = \begin{cases} \Pr(\mathcal{E}_{v,f}), & f \leq Q; \\ 0, & f > Q. \end{cases} \quad (5)$$

The CP_v's backhaul saving of a file $\mathcal{F}_f$ can be calculated as $p_f \theta_v \zeta K s^{\mathrm{bh}} g(\tau_v)$, in which $\theta_v \zeta$ represents the MUs' density affiliate to CP_v and $p_f K$ means the downloading demand for the file $\mathcal{F}_f$ from each MU. Thus, $\theta_v \zeta p_f K$ is the downloading demand of $\mathcal{F}_f$ of the MUs affiliated to CP_v. $g(\tau_v)$ represents the probability of the event that an MU can successfully download $\mathcal{F}_f$ from the local SBS. Therefore, $\theta_v \zeta p_f K g(\tau_v)$ is the number of successful downloading of the file $\mathcal{F}_f$ requested by the MUs affiliated to CP_v from the local SBSs instead of the backhaul channels. Thus, $\theta_v \zeta p_f K g(\tau_v) s^{\mathrm{bh}}$ is saved backhaul cost of the NSP from the successful local downloading of the file $\mathcal{F}_f$ requested by the MUs affiliated with CP_v. Then the utility of $\mathcal{L}$ can be formulated as

$$U_{\mathrm{NSP}}(\boldsymbol{\Theta}, \boldsymbol{\Gamma}, \boldsymbol{\Pi}) = \sum_{v=1}^{N} (\pi_v + S_v^{\mathrm{BH}}). \quad (6)$$

Note that there is no cost presenting in (6). Usually, costs of $\mathcal{L}$ come from two aspects: the power cost for transmitting cached files requested, and the storage consumption for caching. These costs can be considered to be included in the original price firstly, and then be nulled by subtracting them. Hence, in this paper we focus on the remaining part of the price π_v, and we represent the net profit of $\mathcal{L}$ as in (6).

B. CP Model

If $\mathcal{V}_v$ signs a contract of $\{\tau_v, \pi_v\}$, its MUs who locally trigger the event $\mathcal{E}_{v,i}, \forall i \leq Q$, will save a long-distance transmission for $\mathcal{V}_v$, referred to as local downloading savings (LDS). The LDS for a file transmission is denoted by s^{ld}. Based on (3), we can calculate the overall savings S_v^{LD} ($/UAP$) of $\mathcal{V}_v$ as

$$S_v^{\mathrm{LD}} = \sum_{f=1}^{Q} p_f \theta_v \zeta K s^{\mathrm{ld}} g(\tau_v), \quad \forall v. \quad (7)$$

According to the popularity distribution of the CPs, we classify these CPs into N different types.

Definition 1 (CPs' Types): We use popularity defined in (2) to represent the types of the CPs in $\boldsymbol{\mathcal{V}}$, which are sorted in a descending order as $\theta_1 > \cdots > \theta_\upsilon > \cdots > \theta_N$.

A higher type implies a greater popularity, and hence more data traffic potentially incurred on the backhaul channels. Please note that it is the information asymmetric environment, where the exact values of the CP types are private information. The NSP does not know the specific type of each CP, and is only aware of the distribution information about the CP types, i.e., the Zipf parameter γ.

To simplify the notations, we define

$$M^{\mathrm{ld}} \triangleq \sum_{f=1}^{Q} p_f \zeta K s^{\mathrm{ld}}$$

and

$$M^{\mathrm{bh}} \triangleq \sum_{f=1}^{Q} p_f \zeta K s^{\mathrm{bh}}.$$

Thus, we have $S_\upsilon^{\mathrm{BH}} = M^{\mathrm{bh}}\theta_\upsilon g(\tau_\upsilon)$. For the clearance of discussion, we further define the valuation of the quality τ_υ by the corresponding LDS S_υ^{LD} in (7), i.e.,

$$V(\theta_\upsilon, \tau_\upsilon) \triangleq S_\upsilon^{\mathrm{LD}} = M^{\mathrm{ld}}\theta_\upsilon g(\tau_\upsilon), \quad \forall \upsilon, \tag{8}$$

which is increasing with the type θ_υ and is also a strictly increasing and concave function of τ_υ, i.e., $\partial V/\partial \tau_\upsilon > 0$ and $\partial^2 V/\partial \tau_\upsilon^2 < 0$. Simply speaking, $V(\theta_\upsilon, \tau_\upsilon)$ can be viewed as the benefits a type θ_υ received from employing the quality τ_υ. The utility of $\mathcal{V}_\upsilon$ can be formulated as

$$U_\upsilon(\theta_\upsilon, \tau_\upsilon, \pi_\upsilon) = V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon. \tag{9}$$

A rational CP will not accept a negative utility U_υ, and thus we have $V(\theta_\upsilon, \tau_\upsilon) \geq \pi_\upsilon$.

IV. Optimal Contract Design and Solution

In our contract-based caching system, the NSP $\mathcal{L}$ designs the contract and each CP in $\boldsymbol{\mathcal{V}}$ is free to choose an appropriate entry. The goal of $\mathcal{L}$ is to maximize U_{NSP} by offering the optimal contract entries $\{\tau_\upsilon^*, \pi_\upsilon^*\}, \upsilon = 1, 2, \cdots, N$.

A. Contract Formulation

A feasible contract, which is capable of attracting the CPs to buy certain fractions of SBSs for placing their contents, must comply with the feasibility constraint on the individual rationality (IR) and incentive compatibility (IC) [39] for all the N types.

Definition 2 (IR Constraint): Given that each CP is rational, it will not accept a contract when it receives a negative utility for its type. Therefore, the IR constraint can be expressed as

$$V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon \geq 0, \quad \forall \upsilon. \tag{10}$$

In other words, to stimulate $\mathcal{V}_\upsilon$ renting the SBSs, the rewards obtained must compensate its cost. In the case of $U_\upsilon < 0$, $\mathcal{V}_\upsilon$ will purchase nothing.

Definition 3 (IC Constraint): The incentive compatibility constraint means that $\mathcal{V}_\upsilon$ cannot gain more utility by accepting a contract entry which is not designed for its type. That is,

$$V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon \geq V(\theta_\upsilon, \tau_{\tilde{\upsilon}}) - \pi_{\tilde{\upsilon}}, \quad \forall \tilde{\upsilon} \in \{1, \cdots, N\},\ \tilde{\upsilon} \neq \upsilon, \tag{11}$$

where the contract $\{\tau_{\tilde{\upsilon}}, \pi_{\tilde{\upsilon}}\}$ is designed for type $\theta_{\tilde{\upsilon}}$. In other words, $\mathcal{V}_\upsilon$ with type θ_υ obtains the maximum utility if and only if choosing the contract $\{\tau_\upsilon, \pi_\upsilon\}$ designed for its type.

A feasible contract must guarantee the IC and IR constraints, and we focus on designing the optimal contract that maximizes the utility of $\mathcal{L}$ subject to these two basic constraints. In the following, we formulate the optimization of the contract problem as

$$\{\tau_\upsilon^*, \pi_\upsilon^*\} = \arg\max\ U_{\mathrm{NSP}}, \\ \text{s.t. IR(10)}, \quad \text{IC(11)}, \quad \sum_\mu \tau_\mu = 1,\ \tau_\mu \geq 0. \tag{12}$$

B. Constraints Reduction

The problem in (12) is not straightforward to solve, since there are N IR constraints and $N(N-1)$ IC constrains. We simplify these constraints followed by a standard method before solving the optimization problem [39]. Firstly, we simplify the IR constraints by **Lemma 1**.

Lemma 1 (To Simplify the IR Constraints): For the optimal solution, given that the IC constraints are satisfied, the IR constraint for the lowest type θ_N is binding, i.e.,

$$V(\theta_N, \tau_N) - \pi_N = 0. \tag{13}$$

Proof: Please refer to Appendix A. ■

The IR constrains can be reduced by **Lemma 1**, which indicates that the price π_N for the lowest type should be equal to the valuation of quality τ_N, i.e., the lowest type θ_N gains zero profit, while other CPs' profits are larger than that of the binding one.

Next, we will prove that the IC constraints can be simplified by the following Lemmas. We begin by introducing the necessary conditions for IC constrains.

Lemma 2: If the contract satisfies the IC constraints, the following condition holds true: given the quality $\tau_\upsilon > \tau_{\tilde{\upsilon}}$, if and only if the price satisfies $\pi_\upsilon > \pi_{\tilde{\upsilon}}$.

Proof: Please refer to Appendix B. ■

Lemma 2 presents an important property for a feasible contract, i.e., a higher quality corresponds to a higher price and vice versa.

Lemma 3: If the contract satisfies the IC constraints, the quality τ_υ of the SBSs monotonically increases with $\mathcal{V}_\upsilon$'s type θ_υ, i.e., if $\theta_\upsilon > \theta_{\tilde{\upsilon}}$, then we have $\tau_\upsilon > \tau_{\tilde{\upsilon}}$.

Proof: Please refer to Appendix C. ■

Lemma 3 implies that the quality τ_υ is monotonically increasing with the type θ_υ when the contract satisfies the IC constraints. This means that the quality assigned to a higher type must be larger than that to a lower one. Recall that the type θ_υ indicates the requesting proportion of the MUs, and the quality τ_υ is the fraction of the SBSs assigned to θ_υ. In a feasible contract, $\mathcal{V}_\upsilon$ with a higher type θ_υ will be allocated with a larger fraction τ_υ of the SBSs, and hence achieving a higher coverage and downloading probability.

From **Lemma 2** and **Lemma 3**, we find that the necessary conditions for IC constraints, given the types $\theta_1 > \theta_2 > \ldots > \theta_N$, are $\tau_1 > \tau_2 > \cdots > \tau_N$ and $\pi_1 > \pi_2 > \cdots > \pi_N$.

In addition, the corresponding sufficient conditions for IC constraints are shown in the following.

Definition 4 (Local Downward Incentive Constraint (LDIC)): the IC constraint between two types θ_υ and $\theta_{\upsilon-1}$ satisfies $V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon \geq V(\theta_\upsilon, \tau_{\upsilon-1}) - \pi_{\upsilon-1}$.

Definition 5 (Local Upward Incentive Constraint (LUIC)): the IC constraint between the types θ_υ and $\theta_{\upsilon+1}$ satisfies $V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon \geq V(\theta_\upsilon, \tau_{\upsilon+1}) - \pi_{\upsilon+1}$.

Lemma 4: If utility functions satisfy the LDIC and the LUIC simultaneously, the IC constraints will be satisfied.

Proof: Please refer to Appendix D. ∎

Lemma 4 attests that the LDIC and the LUIC are the sufficient conditions for the IC constraints. Thus, the IC constraints can be replaced by the LDIC and LUIC constraints. Furthermore, we employ **Lemma 5** to reduce the LDIC and LUIC constraints.

Lemma 5 (To Reduce the IC Constraints): For maximizing the NSP's profits, the IC constraints can be replaced by

$$V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon = V(\theta_\upsilon, \tau_{\upsilon+1}) - \pi_{\upsilon+1}. \tag{14}$$

Proof: Please refer to Appendix E. ∎

The proof of **Lemma 5** testifies that the LDIC can be derived from LUIC. Thus, we can reduce the IC constraints to LUIC and further to (14).

C. Solution to Optimal Contract

In this subsection, we will work on the solution to problem in (12) to obtain the optimal contract. By using the lemmas in the previous subsection, the optimization problem in (12) can be rewritten as

$$\begin{aligned}\{\tau_\upsilon^*, \pi_\upsilon^*\} &= \arg\max\ U_{\text{NSP}},\\ &\text{s.t. IR(13), IC(14)}, \quad \sum_\mu \tau_\mu = 1, \ \tau_\mu \geq 0. \end{aligned} \tag{15}$$

We iterate the IR and IC constraints in (15), and obtain

$$\begin{aligned}\{\tau_\upsilon^*\} &= \arg\max \sum_{\mu=1}^{N} \left(V(\theta_N, \tau_N) + \sum_{u=\mu}^{N} w_u + S_\upsilon^{\text{BH}} \right),\\ &\text{s.t.} \sum_\mu \tau_\mu = 1, \tau_\mu \geq 0, \end{aligned} \tag{16}$$

where

$$w_u = \begin{cases} 0, & u = N; \\ V(\theta_u, \tau_u) - V(\theta_u, \tau_{u+1}), & u = 1, \cdots, N-1. \end{cases} \tag{17}$$

Generally, the LDS s^{ld} obtained by $\mathcal{V}_\upsilon$ has a certain relationship with the s^{bh} induced by a file transmission over backhaul channels. For instance, the benefit of a CP from LDS may be partially supported by the NSP for saving its backhaul transmissions. Generally speaking, a higher value of the saved backhaul cost will contribute to a greater benefit from local downloading. Therefore, we assume there is a linear relationship between s^{bh} and s^{ld}, i.e., $s^{\text{bh}} = \kappa s^{\text{ld}}$, where $\kappa \geq 0$ represents the relationship between s^{bh} and s^{ld}. Substituting (17) and $s^{\text{bh}} = \kappa s^{\text{ld}}$ into (16), we rewrite the optimization problem in (15) as

$$\begin{aligned}\{\tau_\upsilon^*\} &= \arg\max \sum_{\mu=1}^{N} R_\mu,\\ &\text{s.t.} \sum_\mu \tau_\mu = 1, \tau_\mu \geq 0, \end{aligned} \tag{18}$$

where $R_1 \triangleq (1+\kappa) V(\theta_1, \tau_1)$,

$$R_\upsilon \triangleq (\upsilon+\kappa) V(\theta_\upsilon, \tau_\upsilon) - (\upsilon-1) V(\theta_{\upsilon-1}, \tau_\upsilon), \quad \forall \upsilon \geq 2. \tag{19}$$

We find that the optimal R_υ is only associated with quality τ_υ and independent of other qualities $\tau_{\tilde{\upsilon}}, \tilde{\upsilon} \neq \upsilon$. Obviously,

$$\frac{\partial R_1}{\partial \tau_1} = \frac{(1+\kappa) M^{\text{ld}} \theta_1 C(\delta, \alpha)}{(\tau_1 A(\delta, \alpha) + (1-\tau_1) C(\delta, \alpha) + \tau_1)^2} > 0$$

and

$$\frac{\partial^2 R_1}{\partial \tau_1^2} = \frac{-2(1+\kappa) M^{\text{ld}} \theta_1 C(\delta, \alpha) \left(A(\delta, \alpha) - C(\delta, \alpha) + 1\right)}{(\tau_1 A(\delta, \alpha) + (1-\tau_1) C(\delta, \alpha) + \tau_1)^3} < 0.$$

Thus, R_1 is an increasing and concave function of τ_1.

For $R_\upsilon, \upsilon \geq 2$, we have the first-order derivation with regard to τ_υ as

$$\frac{\partial R_\upsilon}{\partial \tau_\upsilon} = \frac{[(\upsilon+\kappa)\theta_\upsilon - (\upsilon-1)\theta_{\upsilon-1}] M^{\text{ld}} C(\delta, \alpha)}{(\tau_\upsilon A(\delta, \alpha) + (1-\tau_\upsilon) C(\delta, \alpha) + \tau_\upsilon)^2}, \quad \forall \upsilon \geq 2. \tag{20}$$

The second-order derivation of R_υ on τ_υ is calculated as (21) shown at the bottom of next page. Substituting $\theta_\upsilon = \frac{1/\upsilon^\gamma}{\sum_{i=1}^N 1/i^\gamma}$ and $\theta_{\upsilon-1} = \frac{1/(\upsilon-1)^\gamma}{\sum_{i=1}^N 1/i^\gamma}$ into (20) and (21), we get (22) and (23), are shown at the bottom of next page. Observing (22) and (23), we define the common part of the numerators of (22) and (23) as

$$f_\upsilon(\gamma) \triangleq (\upsilon+\kappa)\frac{1}{\upsilon^\gamma} - (\upsilon-1)\frac{1}{(\upsilon-1)^\gamma}, \quad \forall \upsilon \geq 2. \tag{24}$$

The property of R_υ with regard to τ_υ is determined by $f_\upsilon(\gamma)$. What is more, we substitute (8) and (2) into (19), and find that R_υ can be represented by $f_\upsilon(\gamma)$ as

$$R_\upsilon = \frac{f_\upsilon(\gamma)}{\sum_{j=1}^N 1/j^\gamma} M^{\text{ld}} g(\tau_\upsilon), \quad \forall \upsilon \geq 2.$$

Remark 1: $R_\upsilon, \forall \upsilon \geq 2$ has the same properties of positive and negative as $f_\upsilon(\gamma)$.

What is more, from (22) and (23), the concavity and convexity of $R_\upsilon, \forall \upsilon \geq 2$, is associated with the value of $f_\upsilon(\gamma)$.

Theorem 1: There is an unique root $\hat{\gamma}(\upsilon)$ such that $f_\upsilon(\hat{\gamma}(\upsilon)) = 0$, given υ, which can be calculated as

$$\hat{\gamma}(\upsilon) = \frac{\ln(\upsilon+\kappa) - \ln(\upsilon-1)}{\ln \upsilon - \ln(\upsilon-1)}, \quad \upsilon \geq 2. \tag{25}$$

Additionally, we have $f_\upsilon(\gamma) > 0$ when $0 < \gamma < \hat{\gamma}(\upsilon)$, and $f_\upsilon(\gamma) < 0$, otherwise.

Proof: Please refer to Appendix F. ∎

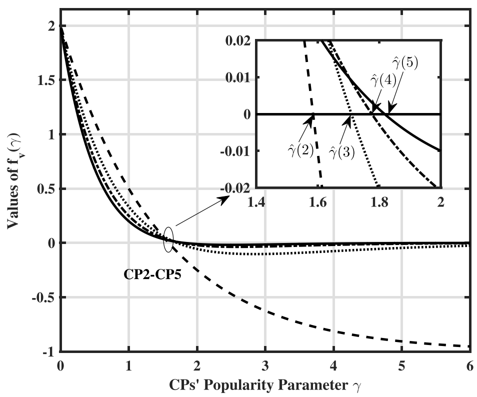

Fig. 2. Values of $f_\upsilon(\gamma)$ in (24), when $N = 5$, $\kappa = 1$, γ varies from 0.01 to 6.

*Remark 2: Therefore, according to **Theorem 1**, when $\gamma > \hat{\gamma}(\upsilon)$, we have $f_\upsilon(\gamma) < 0$, thus R_υ is monotonically decreasing and convex to τ_υ. When $0 < \gamma < \hat{\gamma}(\upsilon)$, we have $f_\upsilon(\gamma) > 0$ and thus R_υ is monotonically increasing and concave to τ_υ.*

Corollary 1: The value of $\hat{\gamma}(\upsilon), \forall \upsilon \geq 2$, increases with the growth of υ.

Proof: Please refer to Appendix G. ■

From **Corollary 1** we can see that a larger index υ leads to a larger value of $\hat{\gamma}(\upsilon), \forall \upsilon \geq 2$. Fig. 2 plots the curves of $f_\upsilon(\gamma)$ versus γ in the case of $\kappa = 1$. The aforementioned **Theorem 2** and **Corollary 1** can be verified by this figure. In specific, from Fig. 2, we have $\hat{\gamma}(2) = 1.585$, $\hat{\gamma}(3) = 1.710$, $\hat{\gamma}(4) = 1.776$, and $\hat{\gamma}(5) = 1.817$. Thus, as predicted by **Corollary 1**, $\hat{\gamma}(\upsilon)$ grows monotonously with the value of υ. Additionally from this figure, given υ, there is only one cross point between $f_\upsilon(\gamma)$ and the x-axis, thereby validating **Remark 2**.

Furthermore, we define

$$\hat{\gamma}_{min} \triangleq \min\{\hat{\gamma}(\upsilon), \upsilon = 1, \cdots, N\} = \hat{\gamma}(2)$$

and

$$\hat{\gamma}_{max} \triangleq \max\{\hat{\gamma}(\upsilon), \upsilon = 1, \cdots, N\} = \hat{\gamma}(N).$$

We have three cases according to the value of Zipf parameter γ, i.e., $\gamma \geq \hat{\gamma}_{max}$, $0 \leq \gamma \leq \hat{\gamma}_{min}$, and $\hat{\gamma}_{min} < \gamma < \hat{\gamma}_{max}$. In the following, we will conduct the optimization on the problem in (18) for these three cases.

*1) **Case 1** $\gamma \geq \hat{\gamma}_{max}$:* In this case, according to **Remark 2**, R_υ is a decreasing and convex function of $\tau_\upsilon, \forall \upsilon \geq 2$. Therefore, the optimal solution of $\arg\max R_\upsilon, \forall \upsilon \geq 2$, is $\tau_\upsilon = 0$. Also, R_1 is always an increasing function of τ_1. We consider the constraint $\sum_{\mu=1}^{N} \tau_\mu = 1, \tau_\mu \geq 0$, as well as the monotonicity of τ_υ in **Lemma 3**, i.e., $\tau_1 > \tau_2 > \cdots > \tau_N$, the rational solution in this case is to set $\tau_1 = 1$ and $\tau_\upsilon = 0, \forall \upsilon \geq 2$. Thus, it is optimal to assign the type θ_1 with the entire fraction of SBSs as long as $\gamma \geq \hat{\gamma}_{max}$. The optimal fraction τ_υ^* for ***Case 1*** can be expressed by

$$\tau_\upsilon^* = \begin{cases} 0, & \upsilon > 1, \\ 1, & \upsilon = 1. \end{cases} \tag{26}$$

Substituting (26) into (13) in **Lemma 1** and (14) in **Lemma 5**, we have

$$\pi_\upsilon^* = \begin{cases} 0, & \upsilon > 1, \\ V(\theta_1, \tau_1^*), & \upsilon = 1. \end{cases} \tag{27}$$

The utility of $\mathcal{L}$ can be thereby calculated as $U_{\text{NSP}}^* = (1+\kappa)V(\theta_1, \tau_1^*)$.

*2) **Case 2** $0 < \gamma \leq \hat{\gamma}_{min}$:* In this case, according to **Remark 2**, R_υ is an increasing and concave function of $\tau_\upsilon, \upsilon = 1, \cdots, N$. We resort to the optimization method of Lagrangian multipliers [40] and obtain

$$\tilde{\tau}_1^* = \max\left\{\frac{\sqrt{\frac{(1+\kappa)\theta_1 M^{\text{ld}} C(\delta,\alpha)}{\xi}} - C(\delta,\alpha)}{A(\delta,\alpha) - C(\delta,\alpha) + 1}, 0\right\} \tag{28}$$

and

$$\tilde{\tau}_\upsilon^* = \max\left\{\frac{\sqrt{\frac{((\upsilon+\kappa)\theta_\upsilon - (\upsilon-1)\theta_{\upsilon-1}) M^{\text{ld}} C(\delta,\alpha)}{\xi}} - C(\delta,\alpha)}{A(\delta,\alpha) - C(\delta,\alpha) + 1}, 0\right\}, \quad \forall \upsilon \geq 2, \tag{29}$$

where the value of ξ is given in the equation, at the top of the next page, and N^* satisfies the constraint that $\tau_\upsilon \geq 0$. Meanwhile, we need to check whether $\tilde{\tau}_\upsilon^*$ given above, $\forall \upsilon$, satisfies the monotonicity constraint in **Lemma 3**. If the constraint is satisfied, i.e., there is $\tilde{\tau}_1^* \geq \tilde{\tau}_2^* \geq \cdots \geq \tilde{\tau}_N^*$, the expressions of $\tilde{\tau}_\upsilon^*$ in (28) and (29) are the optimal solutions.

In the case that the constraint is not satisfied for certain range of υ, e.g., $[\underline{\upsilon}, \bar{\upsilon}]$ with $\tilde{\tau}_{\underline{\upsilon}}^* < \cdots < \tilde{\tau}_{\bar{\upsilon}}^*$, bunching-and-ironing method [39] will be adopted for adjusting the values of $\tilde{\tau}_\upsilon^*$, $\forall \upsilon \in [\underline{\upsilon}, \bar{\upsilon}]$ to ensure $\tilde{\tau}_{\underline{\upsilon}}^* = \cdots = \tilde{\tau}_{\bar{\upsilon}}^*$. In this case,

$$\frac{\partial^2 R_\upsilon}{\partial \tau_\upsilon^2} = \frac{-2[(\upsilon+\kappa)\theta_\upsilon - (\upsilon-1)\theta_{\upsilon-1}] M^{\text{ld}} C(\delta,\alpha)(A(\delta,\alpha) - C(\delta,\alpha) + 1)}{(\tau_\upsilon A(\delta,\alpha) + (1-\tau_\upsilon)C(\delta,\alpha) + \tau_\upsilon)^3}, \quad \forall \upsilon \geq 2. \tag{21}$$

$$\frac{\partial R_\upsilon}{\partial \tau_\upsilon} = \frac{\left[(\upsilon+\kappa)\frac{1}{\upsilon^\gamma} - (\upsilon-1)\frac{1}{(\upsilon-1)^\gamma}\right] M^{\text{ld}} C(\delta,\alpha)}{\left(\sum_{i=1}^{N} 1/i^\gamma\right)(\tau_\upsilon A(\delta,\alpha) + (1-\tau_\upsilon)C(\delta,\alpha) + \tau_\upsilon)^2}, \quad \forall \upsilon \geq 2, \tag{22}$$

$$\frac{\partial^2 R_\upsilon}{\partial \tau_\upsilon^2} = \frac{-2\left[(\upsilon+\kappa)\frac{1}{\upsilon^\gamma} - (\upsilon-1)\frac{1}{(\upsilon-1)^\gamma}\right] M^{\text{ld}} C(\delta,\alpha)(A(\delta,\alpha) - C(\delta,\alpha) + 1)}{\left(\sum_{i=1}^{N} 1/i^\gamma\right)(\tau_\upsilon A(\delta,\alpha) + (1-\tau_\upsilon)C(\delta,\alpha) + \tau_\upsilon)^3}, \quad \forall \upsilon \geq 2. \tag{23}$$

$$\xi = \left(\frac{\sqrt{(1+\kappa)\theta_1 M^{\text{ld}} C(\delta,\alpha)} + \sum_{i=2}^{N^*} \sqrt{((i+\kappa)\theta_i - (i-1)\theta_{i-1})\, M^{\text{ld}} C(\delta,\alpha)}}{A(\delta,\alpha) - (N^*-1)C(\delta,\alpha) + 1} \right)^2,$$

the optimization problem is reformulated as

$$\{\tau_\upsilon^*\} = \arg\max \sum_{\mu=1}^{N} R_\mu,$$
$$\text{s.t.} \sum_{\mu=1}^{N} \tau_\mu = 1, \quad \tau_\mu \geq 0,\ \tau_{\dot{\upsilon}} = \tau_{\underline{\upsilon}} = \tau_{\bar{\upsilon}},\ \forall \dot{\upsilon} \in [\underline{\upsilon}, \bar{\upsilon}]. \tag{30}$$

Obviously, Lagrangian multipliers can be again applied to the above problem to obtain the optimal solution, with the monotonicity constraint in **Lemma 3** being satisfied.

After obtaining the optimal quality τ_υ^*, the optimal price can thus be recursively derived by **Lemma 1** and **Lemma 5** as

$$\pi_\upsilon^* = V(\theta_N, \tau_N^*) + \sum_{i=\upsilon}^{N} w_i^*, \tag{31}$$

where

$$w_\upsilon^* = \begin{cases} 0, & \upsilon = N, \\ V(\theta_\upsilon, \tau_\upsilon^*) - V(\theta_\upsilon, \tau_{\upsilon+1}^*), & \upsilon = 1, \cdots, N-1. \end{cases} \tag{32}$$

Consequently, the utility of $\mathcal{L}$ can be calculated as

$$U_{\text{NSP}}^* = (1+\kappa)V(\theta_1, \tau_1^*) + \sum_{\upsilon=2}^{N} \left((\upsilon+\kappa)V(\theta_\upsilon, \tau_\upsilon^*) - (\upsilon-1)V(\theta_{\upsilon-1}, \tau_\upsilon^*) \right).$$

*3) **Case 3** $\hat{\gamma}_{min} < \gamma < \hat{\gamma}_{max}$:* According to **Theorem 1** and **Corollary 1**, given γ, there exists $\upsilon_{th} \in \{3, \cdots, N\}$ such that $f_{\upsilon_1}(\gamma) < 0$, $\forall 2 \leq \upsilon_1 \leq \upsilon_{th} - 1$, and $f_{\upsilon_2}(\gamma) > 0$, $\forall \upsilon_{th} \leq \upsilon_2 \leq N$. According to **Remark 2**, in the case of $2 \leq \upsilon_1 \leq \upsilon_{th} - 1$, R_{υ_1} is decreasing and convex to τ_{υ_1} due to $f_{\upsilon_1}(\gamma) < 0$. Therefore, we need to set $\tau_{\upsilon_1}^* = 0$ for maximizing R_{υ_1}. At the same time, to comply with the monotonicity in **Lemma 3**, i.e., $\tau_{\upsilon_1}^* \geq \tau_{\upsilon_2}^*$, we have $\tau_{\upsilon_2}^* = 0$, $\forall \upsilon_{th} \leq \upsilon_2 \leq N$. Consequently, the rational and feasible solution in this case is $\tau_1 = 1, \tau_\upsilon = 0, \forall \upsilon \geq 2$.

V. Discussions on Other Schemes

A. Uniform Quality Scheme

In this subsection, we discuss on the uniform quality scheme, where the NSP deliberately imposes the same quality (fraction) $\tau_\upsilon = \frac{1}{N}$ on different CPs. Then by substituting $\tau_\upsilon^* = \tau_{\upsilon+1}^* = \frac{1}{N}$ into (31) and (32), the optimal price of the uniform quality scheme can be calculated as

$$\pi_\upsilon^* = V\left(\theta_N, \frac{1}{N}\right), \quad \forall \upsilon. \tag{33}$$

From the above optimal price, we can see it is uniform for all the types of CPs, i.e., it is equal to the valuation of quality $\frac{1}{N}$ by the lowest type θ_N. In this case, the NSP can simply provide one contract option to all the CPs instead of diverse options. Furthermore, the utility of the NSP can be calculated as

$$U_{\text{NSP}}^{\text{UQC}} = \sum_{\upsilon=1}^{N} \left(\pi_\upsilon^* + \kappa V\left(\theta_\upsilon, \frac{1}{N}\right) \right).$$

B. Stackelberg Game Scheme

In this subsection, we formulate the interaction between the NSP $\mathcal{L}$ and the CPs $\boldsymbol{\mathcal{V}}$ within the framework of a Stackelberg game, which has been well investigated in [38]. In the Stackelberg game scheme, $\mathcal{L}$ acts as a leader who moves firstly and $\boldsymbol{\mathcal{V}}$ are the followers who move subsequently. We assume that $\mathcal{L}$ offers a price vector $\boldsymbol{s} \triangleq \{s_1, \cdots, s_\upsilon, \cdots, s_N\}$, where s_υ is defined as the price of each SBS rented by $\mathcal{V}_\upsilon$. According to the price vector $\boldsymbol{s}$, each CP then determines the optimal fraction of the resources for maximizing its profit. The fraction vector is denoted by $\boldsymbol{\mu} \triangleq \{\mu_1, \cdots, \mu_\upsilon, \cdots, \mu_N\}$, where μ_υ is the fraction rented by $\mathcal{V}_\upsilon$.

The utility functions of $\mathcal{L}$ and $\boldsymbol{\mathcal{V}}$ can be expressed as

$$U_{\text{NSP}}^{\text{SGS}} = \sum_{\upsilon=1}^{N} \left(s_\upsilon \mu_\upsilon + M^{\text{bh}} \theta_\upsilon g(\mu_\upsilon) \right),$$

and

$$U_\upsilon^{\text{SGS}} = M^{\text{ld}} \theta_\upsilon g(\mu_\upsilon) - s_\upsilon \mu_\upsilon, \tag{34}$$

respectively, where $M^{\text{bh}} \theta_\upsilon g(\mu_\upsilon)$ is the saved backhaul cost, $M^{\text{ld}} \theta_\upsilon g(\mu_\upsilon)$ denotes the savings of $\mathcal{V}_\upsilon$ for employing the caching mechanism, and $s_\upsilon \mu_\upsilon$ is the fees for leasing/renting a fraction of μ_υ of the SBSs. Note that the profits of the NSP and each CP in the Stackelberg game scheme in (34) correspond to (6) and (9) in the contract-based scheme, respectively.

The Stackelberg game is formulated as follows,

1) Optimization formulation of the NSP:

$$\max_{\boldsymbol{s}^*} \ U_{\text{NSP}}^{\text{SGS}}(\boldsymbol{s}, \boldsymbol{\mu}), \quad \text{s.t.} \sum_{\upsilon=1}^{N} \mu_\upsilon = 1, \quad \mu_\upsilon > 0. \tag{35}$$

2) Optimization formulation of the CPs:

$$\max_{\boldsymbol{\mu}^*} \ U_\upsilon^{\text{SGS}}. \tag{36}$$

The goal of the Stackelberg game is to find the point $(\boldsymbol{s}^*, \boldsymbol{\mu}^*)$ forming a equilibrium, where both sides of the game will not gain more utilities if they deviate their strategies.

According to [38], we write the optimal solutions as follows,

$$s_\upsilon^* = \frac{C(\delta,\alpha) s^{\text{ld}} (\sum_{j=1}^{N} \sqrt[3]{\Gamma_j})^2 \sqrt[3]{\Gamma_\upsilon}}{(A(\delta,\alpha) + (N-1)C(\delta,\alpha) + 1)^2}, \tag{37}$$

and (38), as shown at the bottom of this page, where $\Gamma_{\upsilon} \triangleq \sum_{f=1}^{Q} p_f \zeta K \theta_{\upsilon}$. The utility of $\mathcal{L}$ can thus be calculated as

$$U_{\mathrm{NSP}}^{\mathrm{SGS}} = \sum_{\upsilon=1}^{N} \frac{\xi_{\upsilon}\left(-C(\delta,\alpha)s_{\upsilon} + \Gamma_{\upsilon} s^{\mathrm{ld}}\right)}{A(\delta,\alpha) - C(\delta,\alpha) + 1}, \tag{39}$$

where ξ_{υ} is an indicator, with $\xi_{\upsilon} = 1$ if $s_{\upsilon} < \frac{\Gamma_{\upsilon} s^{\mathrm{ld}}}{C(\delta,\alpha)}$, and $\xi_{\upsilon} = 0$ otherwise.

C. Discussions on the Stackelberg Game Scheme and the Contract Scheme

Generally, the Stackelberg game is based on information symmetric scenarios, where the CPs knows the price charged on the resources, and the NSP $\mathcal{L}$ is aware of the quantity of the resources to be purchased by each CP. Even though $\mathcal{L}$ is the leader in this game, its strategy is designed based on the actions the followers employ, thereby allowing the CPs to purchase the optimal quota of the resources for maximizing their own profits. In other words, the Stackelberg game offers both sides with autonomies to maximize their own profits.

By contrast, in the contract-based scheme, $\mathcal{L}$ acts as a monopolist in the market, and designs the contract entries for various CPs so as to achieve its maximum profit. The NSP $\mathcal{L}$ will not consider the profits of the CPs, though it needs to consider the IR and IC constraints when designing the contract, for the purpose of attracting each CP to accept the offered contract. However, compared with the Stackelberg game, these IR and IC constraints are quite weak in terms of maximizing CPs' profits. Thus, in the contract-based scheme, the monopolist NSP will gain a higher profit than in a scheme with the Stackelberg game, whilst the CPs will suffer from obtaining lower profits relative to those gained from the Stackelberg game.

D. Discussions on Auction Scheme

Auction is a branch of game theory [41]. It is also widely used in the asymmetric information environment where there are usually not enough commodities for all the potential buyers and the buyers' valuations of the commodities are unknown [42]. There are three roles in auction game: the bidder who is the buyer, the seller who wants to sell commodities and the auctioneer who conducts the auction processes, usually, the seller can be an auctioneer itself. The final prices are determined by the competition among the potential buyers after bidding. Comparing to the auction approach, contract scheme is more efficient, since the seller has determined and posted the final prices at the beginning of the game. The buyer needs to determine whether to join the game and which contract to sign. Reference [43] has proven that the two approaches are equivalent in extracting profit under ideal conditions.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Path loss parameter	$\alpha = 4$
Transmit power	P=10W
SINR threshold	$\delta = 0.02$
Density of SBS	$\lambda = 20/\mathrm{km}^2$
Density of MUs	$\zeta = 80/\mathrm{km}^2$
Files' popularity parameter	$\beta = 0.2$
File number	$F = 100$
Storage size	$Q = 40$
Number of CPs	$N = 5$
Coefficient κ	$\kappa = 1$
Local downloading savings	$s^{\mathrm{ld}} = 1$
File demands from each MU within an unit period	$K = 50/month$

E. Discussions on a Heterogeneous System

In a heterogeneous network, the macro-cell base station, small-cell base station and femto access point with different transmission powers coexist in the system. They can be divided into multiple layers according to their transmission powers. As a piece of possible future work, the fraction as well as the transmission power can be regarded as trading resources, based on which the NSP will design the optimal contract.

VI. NUMERICAL RESULTS

In this section, we conduct numerical analysis to evaluate the performance of our contract-based caching system. The main parameters are listed in Table II.

A. Discussions on R_{υ} and $\hat{\gamma}(\upsilon)$

First, we make an investigation of the convexity and concavity of R_{υ} in **Remark 2** by numerical results under different values of γ and υ. Note that from Fig. 2, we have $\hat{\gamma}_{min} = 1.585$ and $\hat{\gamma}_{max} = 1.817$. As we have derived, in the case of $\gamma \in [\hat{\gamma}_{max}, +\infty)$, R_{υ} is decreasing and convex to τ_{υ}, while in the case of $\gamma \in [0, \hat{\gamma}_{min}]$, R_{υ} is increasing and concave to τ_{υ}. When $\gamma \in (\hat{\gamma}_{min}, \hat{\gamma}_{max})$, the convexity or concavity of function R_{υ} depends on the values of υ.

Fig. 3 plots the curve of R_{υ} versus τ_{υ} with three values of γ. In particular, Fig. 3(a) considers the case of $\gamma = 1 \in [0, \hat{\gamma}_{min}]$. From this sub-figure, it is evident that the curves of all the R_{υ} from R_1 to R_5 are concave and increasing to τ_{υ}. Increasing the value of γ up to $1.68 \in (\hat{\gamma}_{min}, \hat{\gamma}_{max})$, we demonstrate the corresponding curves of R_{υ} versus τ_{υ} in Fig. 3(b). Observing this sub-figure, R_2 becomes convex to τ_2. However, the remaining curves of R_{υ} still keep concave. Also, Fig. 3(c) illustrates the corresponding curves of R_{υ} versus τ_{υ} at $\gamma = 2 \in [\hat{\gamma}_{max}, +\infty)$. From this sub-figure, only R_1 keeps concave, while other curves from R_2 to R_5 change to

$$\mu_{\upsilon}^{*} = \left(\sqrt{\frac{\Gamma_{\upsilon} s^{\mathrm{ld}} C(\delta,\alpha)}{(A(\delta,\alpha) - C(\delta,\alpha) + 1)^2}}\sqrt{\frac{1}{s_{\upsilon}}} - \frac{C(\delta,\alpha)}{A(\delta,\alpha) - C(\delta,\alpha) + 1}\right)^{+}. \tag{38}$$

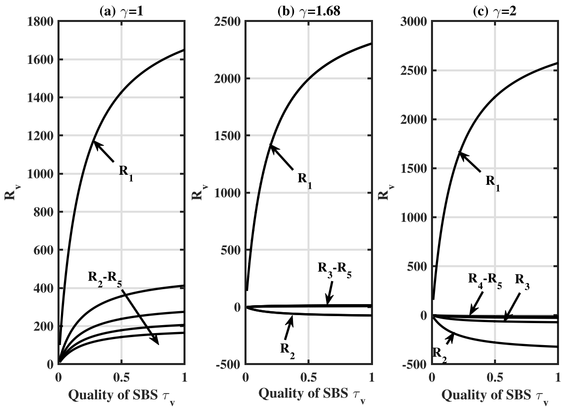

Fig. 3. Verification of convexity and concavity of function R_v over τ_v ($\gamma = 1$, 1.68 and 2).

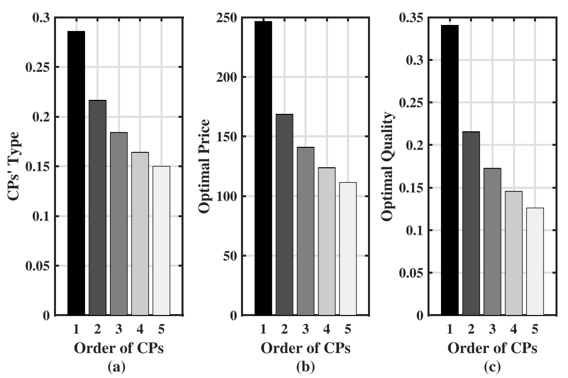

Fig. 4. Types, optimal prices and qualities of CPs utilizing the proposed scheme ($\gamma = 0.4$).

be convex. The above results are consistent with the theoretical analysis in Subsection IV-C.

B. Impact of γ on Optimal Price and Quality

We now investigate the impact of the popularity parameter γ on the optimal contract design. Fig. 4 demonstrates the bar chart of the CPs' type (i.e., the CPs' popularity, which is inversely proportional to order), the optimal price and quality versus the order of the CPs given $\gamma = 0.4$ under our proposed scheme. From Fig. 4(a), we can see that the type of CPs, which varies from 0.2856 to 0.15, decreases as their order increases. In Fig. 4(b), when the type of CP θ_v is large, the optimal price charged by $\mathcal{L}$ is correspondingly high. Moreover, the optimal price declines as the type of CP decreases. In Fig. 4(c), there are the same trends as those in Fig. 4(a) and Fig. 4(b) in terms of the optimal quality. Thus, a CP with a larger type tends to be provided with a higher quality of resources, please be aware that higher quality here means more fractions. These results are consistent with **Lemma 2** and **Lemma 3** in Section IV-B.

In Fig. 5(a), we change the value of CPs' popularity parameter γ to see how it affects the optimal price. In the small-value region of γ, for example $\gamma = 0.1$, the prices of all CPs are approximately identical. As the value of γ increases

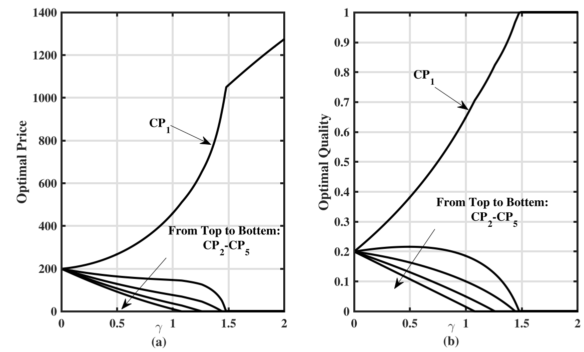

Fig. 5. (a) Optimal price design for each CP utilizing the proposed scheme. (b) Optimal quality design for each CP utilizing the proposed scheme.

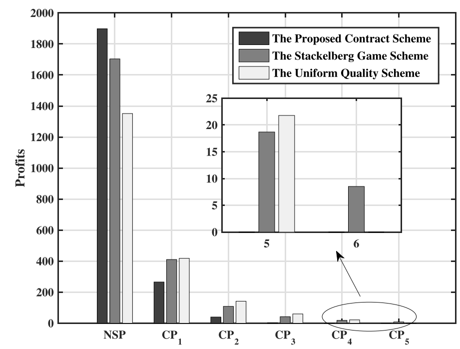

Fig. 6. Comparisons among the profits of the proposed, the uniform quality, and the Stackelberg game schemes, ($\gamma = 1.2$).

from 0.1 to 2, the distinction among the prices of all CPs becomes significant. Hence, the value of γ plays an important role in pricing.

Fig. 5(b) illustrates the curves of optimal quality versus γ. Observing this figure, we find the following results: For small values of γ, the approximate same quality is allocated to all CPs while the quality difference among all CPs becomes large with the increase in the value of γ. For instance, $\gamma = 1.2$ and $\gamma = 2$, the quality of CP1 is far larger than those of the remaining CPs. In other words, CP1 is dominant compared to other CPs.

C. Comparisons of NSP's and CPs' Profits Achieved by the Three Different Schemes

Fig. 6 plots the bar chart of the NSP's and CPs' profits among the proposed, the unform quality and the Stackelberg game schemes when γ is set to 1.2. From the figure, we can see that the NSP can gain more profits by using the proposed scheme relative to using the other two schemes. This is due to the fact that the proposed contract-based scheme is conducted by the monopolist, whose aim is to maximize its own profit. As we discussed in Subsection V-B, in the contract design process, the NSP squeezes more profits from CPs by using the proposed scheme relative to the Stackelberg game scheme. Also, we observe that when the uniform quality scheme is adopted, the profits achieved by NSP are less than

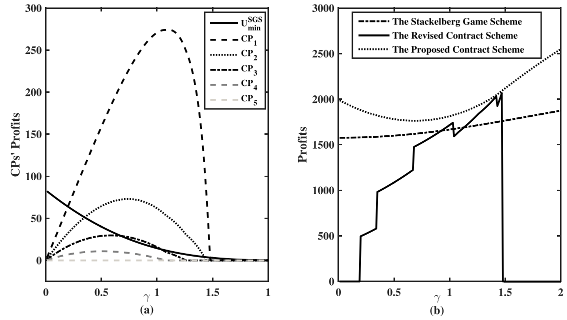

Fig. 7. (a) Profit of each CP when the revised contract scheme are employed, γ varies from 0.01 to 2. (b) Total profit of the NSP when the Stackelberg game scheme and the revised contract scheme are employed.

that achieved by the proposed scheme. This can be explained by the following facts. As per the discussion provided in Subsection V-A, the uniform quality scheme, which charges a uniform price on all CPs, is a special case of the proposed scheme. The uniform quality scheme also has to guarantee the IR constraint, especially for the lowest type of CPs. As such, the uniform price in (33) cannot be set too high. Otherwise, the uniform quality scheme cannot guarantee the IR constraint for the lowest type of CPs. This leads to the fact that the prices charged on other high types of CPs are relatively low, which results in that the profits achieved by the NSP in the uniform quality scheme is lower than that achieved in the proposed scheme.

In addition, we compare the profits gained by the CPs in the aforementioned three different schemes in Fig. 6. We first observe that the profits achieved by the CPs decrease as their indices increase. Focusing on one particular CP, we find that each CP gains the minimum profit in the proposed scheme. Furthermore, in this figure we find that the profits of CP5 are all zeros in the proposed and the uniform quality schemes, while they are positive in the Stackelberg game scheme. The lowest type of CP, i.e., the type of CP5, is designed to gain zero profit in the proposed scheme as shown in **Lemma 1**, while in the Stackelberg game model, the CP who gains zero profit will opt out for renting any resources from the NSP.

In order to make a comprehensive comparison between the Stackelberg game scheme and the contract scheme, we investigate a novel contract scheme with the revised IR constraint, which is henceforth referred to as "revised contract scheme". We denote by $U_{\upsilon,\min}^{\text{SGS}}$ the achieved utility of the CP with the lowest popularity in the Stackelberg scheme. Then, a CP in the revised contract scheme will accept the offered contract if this CP's utility is no less than $U_{\upsilon,\min}^{\text{SGS}}$ and reject the contract otherwise.

In Fig. 7(a) we vary the CPs' popularity parameter γ from 0.01 to 2 to clarify the relationship between the minimum profit $U_{\min}^{\text{SGS}}$ in the Stackelberg game scheme and CPs' profits in the revised contract scheme. It can be seen in Fig. 7(a) that, at first, the profits of CP_1 to CP_5 are all smaller than $U_{\min}^{\text{SGS}}$ until $\gamma \approx 0.2$. Then, the profit of CP_1 becomes larger than $U_{\min}^{\text{SGS}}$, and the profits of CP_2 and CP_3 become larger than $U_{\min}^{\text{SGS}}$ at $\gamma \approx 0.35$ and $\gamma \approx 0.68$, subsequently. However, when $\gamma \approx 1.04$, the profit of CP_3 drops below $U_{\min}^{\text{SGS}}$ at first, followed by CP_2 at $\gamma = 1.43$ and CP_1 at $\gamma = 1.48$. It can be inferred from Fig. 7(a) that CP_1 accepts the offered contract in the interval $\gamma \in [0.2, 1.48]$, CP_2 accepts the offered contract in the interval $\gamma \in [0.35, 1.43]$ and CP_3 accepts the offered contract in the interval $\gamma \in [0.68, 1.04]$.

In Fig. 7(b), we compare the NSP's total profit between the Stackelberg game scheme and the revised contract scheme when γ varies from 0.01 to 2. We also plot the NSP's profit utilizing the proposed contract scheme as a benchmark. The total profit of the NSP using the revised contract scheme is the summations of CP_1, CP_2 and CP_3, while CP_4 and CP_5 always reject the offered contracts. It can be seen that the overall profit gained by the NSP in the Stackelberg game scheme is not always larger than that in the revised contract scheme. When $\gamma = 1.48$ in the revised contract scheme, there is a sharp drop on the NSP's profit, due to the reason that the profit gained by CP_1 drops below $U_{\upsilon,\min}^{\text{SGS}}$ shown in Fig. 7(a). According to the criteria we set at the beginning of this section, CP_1 will definitely not accept the offered contract. Thus, the NSP's profit drops to zero.

The proceeding simulations highlight that even under such a strict IR constraint, the Stackelberg game scheme does not always outperform the revised contract scheme regarding NSP's revenue. Generally, contract scheme only focuses on maximizing the NSP's profit under the IR and IC constraints. On the other hand, in the Stackelberg game, both the NSP and the CPs are trying to maximize their own profits to achieve the Nash equilibrium. In this sense, the NSP in the contract scheme acts as a monopolist in the market and thus will gain more profits than that in the Stackelberg game.

D. Performance of Social Welfare Among Three Schemes

In what follows, we will evaluate the performance of the proposed scheme from the social welfare perspective. The social welfare is the sum of the utilities of NSP $\mathcal{L}$ and all CPs in $\boldsymbol{\mathcal{V}}$. The expression for social welfare is defined by

$$\begin{aligned} U_{\text{SW}} &= U_{\text{NSP}} + \sum_{\upsilon=1}^{N} U_\upsilon = \sum_{\upsilon=1}^{N} S_\upsilon^{\text{BH}} + \pi_\upsilon + S_\upsilon^{\text{LD}} - \pi_\upsilon \\ &= \sum_{\upsilon=1}^{N} S_\upsilon^{\text{BH}} + S_\upsilon^{\text{LD}}, \end{aligned} \quad (40)$$

which is actually the sum of the saved backhaul cost from $\mathcal{L}$ and the LDS gained from CPs. As per (40), we find that the price π_υ does not affect the social welfare. The price π_υ is the internal transfer between $\mathcal{L}$ and $\mathcal{V}_\upsilon$. It can be canceled out when the social welfare is considered. Based on (4), (7), and the simulation setup, i.e., $s^{\text{ld}} = 1$ and $\kappa = 1$ in Tab. II, we rewrite (40) as $U_{\text{SW}} = \sum_{\upsilon=1}^{N} 2M^{\text{ld}}\theta_\upsilon g(\tau_\upsilon)$.

Likewise, the social welfare expressions for the uniform quality and the Stackelberg game schemes are

$$U_{\text{SW}}^{\text{UQC}} = \sum_{\upsilon=1}^{N} 2V\left(\theta_\upsilon, \frac{1}{N}\right) = \sum_{\upsilon=1}^{N} 2M^{\text{ld}}\theta_\upsilon g\left(\frac{1}{N}\right) \quad (41)$$

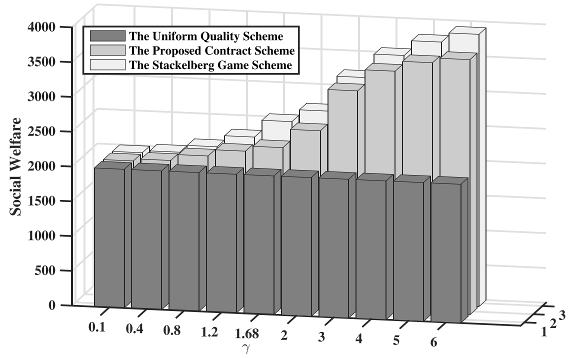

Fig. 8. Comparisons among the social welfare of the proposed, the uniform quality, and the Stackelberg game schemes.

and

$$U_{\rm SW}^{\rm SGS} = U_{\rm NSP}^{\rm SGS} + \sum_{\upsilon=1}^{N} U_{\upsilon}^{\rm SGS} = \sum_{\upsilon=1}^{N} 2M^{\rm ld}\theta_{\upsilon} g(\mu_{\upsilon}), \tag{42}$$

respectively. Comparing (41) with (42), we find that the difference between the uniform quality and the Stackelberg game schemes lies in the fractions $\frac{1}{N}$ and μ_υ assigned to the CPs.

In Fig. 8, we compare the social welfare among these three schemes. We vary the popularity parameter γ to examine its impact on social welfare. From Fig. 8, when γ is small, e.g., $\gamma = 0.1$, the social welfare of the three schemes is almost the same. It is due to the fact that when γ is relatively small, the popularity of different CPs are similar. In such a scenario, the optimal qualities determined by the three schemes are nearly equal. As we increase γ from 0.1 to a larger value, the social welfare of the proposed and the Stackelberg game schemes increases. In addition, we find that the social welfare for the uniform quality scheme in Fig. 8 is a constant, regardless of the values of γ. This is clear, since we can rewrite (41) as $\sum_{\upsilon=1}^{N} 2M^{\rm ld}\theta_\upsilon g\left(\frac{1}{N}\right) = 2M^{\rm ld} g\left(\frac{1}{N}\right)$. Furthermore, the Stackelberg game scheme achieves a larger social welfare relative to the proposed scheme. This is because the Stackelberg game scheme is to optimize the profits of both sides, while the proposed contract scheme is to maximize the monopolist $\mathcal{L}$'s profits.

VII. Conclusions

In this paper, we propose a contract-based trading scheme for a commercialized small-cell caching system consisting of one NSP, several CPs and multiple MUs. We model this system as a monopoly market, where the NSP owns the network facilities, and offers contract entries to different CPs in maximizing its own profits. First, we formulate the utility functions of the NSP and CPs by modeling the SBSs and the MUs as two independent PPP. Then the optimal contract problem is developed in an information asymmetric scenario, where the NSP only has the information about the distribution of CPs' popularity. Next, the feasibility of the proposed scheme is derived. Afterwards, the optimal contract solutions are provided when the CPs' popularity parameter γ takes different values. Simulation results verify the effectiveness of the proposed scheme by showing its superiority to the benchmarks in maximizing the NSP's profit.

Appendix A
Proof of Lemma 1

From **Definition 1** we know that user types θ_υ, $\forall \upsilon$, satisfy $\theta_1 > \cdots > \theta_\upsilon > \cdots > \theta_N$. Combining the IC constraints, we have $V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon \geq V(\theta_\upsilon, \tau_N) - \pi_N \overset{(a)}{\geq} V(\theta_N, \tau_N) - \pi_N$, $\forall \upsilon$, where (a) is satisfied by the fact that $V(\theta_\upsilon, \tau_\upsilon)$ is strictly increasing with θ_υ. Therefore, if we can guarantee $V(\theta_N, \tau_N) - \pi_N \geq 0$, all the CPs will satisfy the IR constraints. From the perspective of $\mathcal{L}$, in order to maximize its profit, $\mathcal{L}$ will raise the price π_N as much as possible. By setting $V(\theta_N, \tau_N) - \pi_N = 0$, $\mathcal{L}$ gets the maximal profit. This completes the proof. ■

Appendix B
Proof of Lemma 2

A. Sufficient

If the contract satisfies the IC constraints shown in (11), i.e., $V(\theta_{\tilde\upsilon}, \tau_{\tilde\upsilon}) - \pi_{\tilde\upsilon} \geq V(\theta_{\tilde\upsilon}, \tau_\upsilon) - \pi_\upsilon$, $\forall \upsilon \neq \tilde\upsilon$, which can be rewritten as $V(\theta_{\tilde\upsilon}, \tau_{\tilde\upsilon}) - V(\theta_{\tilde\upsilon}, \tau_\upsilon) \geq \pi_{\tilde\upsilon} - \pi_\upsilon$. Since $V(\theta_\upsilon, \tau_\upsilon)$ is an increasing function of τ_υ, we have $\tau_\upsilon > \tau_{\tilde\upsilon} \Longrightarrow V(\theta_{\tilde\upsilon}, \tau_{\tilde\upsilon}) - V(\theta_{\tilde\upsilon}, \tau_\upsilon) < 0 \Longrightarrow \pi_\upsilon > \pi_{\tilde\upsilon}$.

B. Necessary

If the contract satisfies the IC constraints, i.e., $V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon \geq V(\theta_\upsilon, \tau_{\tilde\upsilon}) - \pi_{\tilde\upsilon}$, $\forall \upsilon \neq \tilde\upsilon$, which can be rewritten as $V(\theta_\upsilon, \tau_\upsilon) - V(\theta_\upsilon, \tau_{\tilde\upsilon}) \geq \pi_\upsilon - \pi_{\tilde\upsilon}$. Since $V(\theta_\upsilon, \tau_\upsilon)$ is increasing with τ_υ, we have $\pi_\upsilon > \pi_{\tilde\upsilon} \Longrightarrow V(\theta_\upsilon, \tau_\upsilon) > V(\theta_\upsilon, \tau_{\tilde\upsilon}) \Longrightarrow \tau_\upsilon > \tau_{\tilde\upsilon}$. This completes the proof. ■

Appendix C
Proof of Lemma 3

Based on the IC constraints, we have $V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon \geq V(\theta_\upsilon, \tau_{\tilde\upsilon}) - \pi_{\tilde\upsilon}, \forall \upsilon \neq \tilde\upsilon$ and $V(\theta_{\tilde\upsilon}, \tau_{\tilde\upsilon}) - \pi_{\tilde\upsilon} \geq V(\theta_{\tilde\upsilon}, \tau_\upsilon) - \pi_\upsilon, \forall \upsilon \neq \tilde\upsilon$, which can be rewritten as

$$V(\theta_\upsilon, \tau_\upsilon) - V(\theta_\upsilon, \tau_{\tilde\upsilon}) \geq \pi_\upsilon - \pi_{\tilde\upsilon}, \tag{43}$$

and

$$V(\theta_{\tilde\upsilon}, \tau_\upsilon) - V(\theta_{\tilde\upsilon}, \tau_{\tilde\upsilon}) \leq \pi_\upsilon - \pi_{\tilde\upsilon}.$$

Combining the above equations, we have

$$V(\theta_\upsilon, \tau_\upsilon) - V(\theta_\upsilon, \tau_{\tilde\upsilon}) > V(\theta_{\tilde\upsilon}, \tau_\upsilon) - V(\theta_{\tilde\upsilon}, \tau_{\tilde\upsilon}). \tag{44}$$

Substituting (8) into (44), and after some manipulations, we have

$$(\theta_\upsilon - \theta_{\tilde\upsilon})\,(g(\tau_\upsilon) - g(\tau_{\tilde\upsilon})) \geq 0. \tag{45}$$

Thus, in the case of $\theta_\upsilon > \theta_{\tilde\upsilon}$, we have $g(\tau_\upsilon) > g(\tau_{\tilde\upsilon})$ from (45). Additionally, we have

$$\frac{\partial g(\tau_\upsilon)}{\partial \tau_\upsilon} = \frac{\tau_\upsilon}{(\tau_\upsilon A(\delta,\alpha) + (1-\tau_\upsilon)C(\delta,\alpha) + \tau_\upsilon)^2} > 0, \tag{46}$$

i.e., $g(\tau_\upsilon)$ grows with τ_υ. This indicates that $\theta_\upsilon > \theta_{\tilde\upsilon} \Longrightarrow \tau_\upsilon > \tau_{\tilde\upsilon}$. This completes the proof. ■

APPENDIX D
PROOF OF LEMMA 4

First, we show an essential property for CPs, which is the preliminary of **Lemma 4**.

Lemma 6: For any types with $\theta_n > \theta_{\tilde{n}}$, where $n, \tilde{n} \in \{1, \cdots, N\}$, $n \neq \tilde{n}$, and qualities with $\tau_\upsilon > \tau_{\tilde{\upsilon}}$, the following inequality holds, i.e., $V(\theta_n, \tau_\upsilon) - V(\theta_n, \tau_{\tilde{\upsilon}}) \geq V(\theta_{\tilde{n}}, \tau_\upsilon) - V(\theta_{\tilde{n}}, \tau_{\tilde{\upsilon}})$.

Proof: We have

$$\begin{aligned} &V(\theta_n, \tau_\upsilon) - V(\theta_n, \tau_{\tilde{\upsilon}}) - V(\theta_{\tilde{n}}, \tau_\upsilon) + V(\theta_{\tilde{n}}, \tau_{\tilde{\upsilon}}) \\ &= \int_{\tau_{\tilde{\upsilon}}}^{\tau_\upsilon} \partial V(\theta_n, y)/\partial\tau \mathrm{d}y - \int_{\tau_{\tilde{\upsilon}}}^{\tau_\upsilon} \partial V(\theta_{\tilde{n}}, y)/\partial\tau \mathrm{d}y \\ &= \int_{\theta_{\tilde{n}}}^{\theta_n} \int_{\tau_{\tilde{\upsilon}}}^{\tau_\upsilon} \partial^2 \, V(x, y)/\partial\theta\partial\tau \mathrm{d}y\mathrm{d}x. \end{aligned} \tag{47}$$

Furthermore, $V(\theta_\upsilon, \tau_\upsilon)$ satisfies the Spence-Mirrlees condition (SMC), i.e.,

$$\partial^2 V(\theta_\upsilon, \tau_\upsilon)/\partial\theta_\upsilon\partial\tau_\upsilon = \frac{M^{\mathrm{ld}}C(\delta, \alpha)}{(\tau_\upsilon A(\delta, \alpha) + (1 - \tau_\upsilon)C(\delta, \alpha) + \tau_\upsilon)^2} > 0. \tag{48}$$

Substituting (48) into (47), we obtain that $V(\theta_n, \tau_\upsilon) - V(\theta_n, \tau_{\tilde{\upsilon}}) > V(\theta_{\tilde{n}}, \tau_\upsilon) - V(\theta_{\tilde{n}}, \tau_{\tilde{\upsilon}})$. This completes the proof of Lemma 6.

Lemma 6 reveals an essential property for the CPs, i.e., for a given quality increment $\tau_{\tilde{\upsilon}} \to \tau_\upsilon$, the valuation increment for a higher type θ_n is larger than that for the type $\theta_{\tilde{n}}$.

Next, we use **Lemma 6** to prove **Lemma 4**. Considering three CPs, with their types satisfying the relationship $\theta_{\upsilon-1} > \theta_\upsilon > \theta_{\upsilon+1}$. If the LUIC is satisfied, there are

$$V(\theta_{\upsilon-1}, \tau_{\upsilon-1}) - \pi_{\upsilon-1} \geq V(\theta_{\upsilon-1}, \tau_\upsilon) - \pi_\upsilon,$$

and

$$V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon \geq V(\theta_\upsilon, \tau_{\upsilon+1}) - \pi_{\upsilon+1}. \tag{49}$$

According to **Lemma 6**, when $\theta_{\upsilon-1} > \theta_\upsilon$ and $\tau_\upsilon > \tau_{\upsilon+1}$, we have

$$V(\theta_{\upsilon-1}, \tau_\upsilon) - V(\theta_{\upsilon-1}, \tau_{\upsilon+1}) \geq V(\theta_\upsilon, \tau_\upsilon) - V(\theta_\upsilon, \tau_{\upsilon+1}). \tag{50}$$

Combining (49) and (50), we have

$$V(\theta_{\upsilon-1}, \tau_\upsilon) - \pi_\upsilon \geq V(\theta_{\upsilon-1}, \tau_{\upsilon+1}) - \pi_{\upsilon+1}. \tag{51}$$

Integrating (51) and (49), we have

$$V(\theta_{\upsilon-1}, \tau_{\upsilon-1}) - \pi_{\upsilon-1} \geq V(\theta_{\upsilon-1}, \tau_{\upsilon+1}) - \pi_{\upsilon+1}. \tag{52}$$

Observing (49) and (52), we can see that for the type $\theta_{\upsilon-1}$, the IUIC constraints are satisfied for both contracts $(\tau_\upsilon, \pi_\upsilon)$ and $(\tau_{\upsilon+1}, \pi_{\upsilon+1})$. We extend (52), and have

$$V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon \geq V(\theta_\upsilon, \tau_{\tilde{\upsilon}}) - \pi_{\tilde{\upsilon}}, \quad \forall \upsilon \leq \tilde{\upsilon}. \tag{53}$$

Thus, it can be concluded that $\forall \upsilon \leq \tilde{\upsilon}$, the IC constraints hold true.

Following the similar procedure, we can obtain, when the LDIC is satisfied, that

$$V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon \geq V(\theta_\upsilon, \tau_{\tilde{\upsilon}}) - \pi_{\tilde{\upsilon}} \quad \forall \upsilon \geq \tilde{\upsilon}. \tag{54}$$

In summary, when the utility function satisfies both the LUIC in (53) and the LDIC in (54), the IC constrains hold true. This completes the proof. ■

APPENDIX E
PROOF OF LEMMA 5

Assume that CPs' utilities satisfy LUIC. Then we have

$$V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon \geq V(\theta_\upsilon, \tau_{\upsilon+1}) - \pi_{\upsilon+1}, \quad \forall \upsilon. \tag{55}$$

In order to maximize NSP's profits, it will raise π_υ and $\pi_{\upsilon+1}$ as high as possible until

$$V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon = V(\theta_\upsilon, \tau_{\upsilon+1}) - \pi_{\upsilon+1}. \tag{56}$$

Since $\theta_\upsilon > \theta_{\upsilon+1}$ and $V(\theta_\upsilon, \tau_\upsilon)$ is an increasing function of θ_υ, we have

$$V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon \geq V(\theta_{\upsilon+1}, \tau_\upsilon) - \pi_\upsilon. \tag{57}$$

Furthermore, by integrating (56) and the IC constraint of $\theta_{\upsilon+1}$, i.e., $V(\theta_{\upsilon+1}, \tau_{\upsilon+1}) - \pi_{\upsilon+1} \geq V(\theta_\upsilon, \tau_{\upsilon+1}) - \pi_{\upsilon+1}$, we have

$$V(\theta_{\upsilon+1}, \tau_{\upsilon+1}) - \pi_{\upsilon+1} \geq V(\theta_\upsilon, \tau_\upsilon) - \pi_\upsilon. \tag{58}$$

Observing (57) and (58), we arrive at

$$V(\theta_{\upsilon+1}, \tau_{\upsilon+1}) - \pi_{\upsilon+1} \geq V(\theta_{\upsilon+1}, \tau_\upsilon) - \pi_\upsilon, \tag{59}$$

which satisfies the LDIC in **Definition 4**. That is, from LUIC in (55), we can derive LDIC in (59). Therefore, based on **Lemma 4** and the derivation in this Appendix, we can replace the IC constraints by (56) in maximizing NSP's profits. This completes the proof. ■

APPENDIX F
PROOF OF THEOREM 1

First, we prove the uniqueness of the root $\hat{\gamma}(\upsilon)$. Since $\hat{\gamma}(\upsilon)$ makes $f_\upsilon(\hat{\gamma}(\upsilon)) = 0$, we have $(\upsilon + \kappa)\frac{1}{\upsilon^{\hat{\gamma}(\upsilon)}} - (\upsilon - 1)\frac{1}{(\upsilon-1)^{\hat{\gamma}(\upsilon)}} = 0, \quad \forall \upsilon \geq 2$, which can be rewritten as

$$\frac{\upsilon + \kappa}{\upsilon - 1} = \frac{\upsilon^{\hat{\gamma}(\upsilon)}}{(\upsilon - 1)^{\hat{\gamma}(\upsilon)}}, \quad \forall \upsilon \geq 2. \tag{60}$$

Assuming there is another root $\dot{\gamma}(\upsilon)$ making $f_\upsilon(\dot{\gamma}(\upsilon)) = 0$, we have

$$\frac{\upsilon + \kappa}{\upsilon - 1} = \frac{\upsilon^{\dot{\gamma}(\upsilon)}}{(\upsilon - 1)^{\dot{\gamma}(\upsilon)}}, \quad \forall \upsilon \geq 2. \tag{61}$$

Combining (60) and (61), we have

$$\frac{\upsilon^{\hat{\gamma}(\upsilon)}}{(\upsilon - 1)^{\hat{\gamma}(\upsilon)}} = \frac{\upsilon^{\dot{\gamma}(\upsilon)}}{(\upsilon - 1)^{\dot{\gamma}(\upsilon)}}, \quad \forall \upsilon \geq 2.$$

It is easy to verify that $(\frac{\upsilon}{\upsilon-1})^x$ is an monotonically increasing function of x. Therefore, we have $\hat{\gamma}(\upsilon) = \dot{\gamma}(\upsilon)$, which proves the uniqueness of the root.

Next, in the case of $0 < \gamma < \hat{\gamma}(\upsilon), \forall \upsilon \geq 2$, we have $\gamma < \frac{\ln(\upsilon+\kappa) - \ln(\upsilon-1)}{\ln \upsilon - \ln(\upsilon-1)}, \quad \forall \upsilon \geq 2$. After some manipulations, we can obtain $(\upsilon - 1)\frac{1}{(\upsilon-1)^\gamma} < (\upsilon + \kappa)\frac{1}{\upsilon^\gamma}, \quad \forall \upsilon \geq 2$. Thus, we have $f_\upsilon(\gamma) > 0$ when $0 < \gamma < \hat{\gamma}(\upsilon)$. By following the similar method, we can prove $f_\upsilon(\gamma) < 0$ when $\gamma > \hat{\gamma}(\upsilon)$. This completes the proof. ■

APPENDIX G
PROOF OF COROLLARY 1

The first-order derivation of $\hat{\gamma}(\upsilon)$ over υ is

$$\frac{\partial \hat{\gamma}(\upsilon)}{\partial \upsilon} = \left(\frac{1}{\upsilon-1} - \frac{1}{\upsilon}\right)\ln(\upsilon+\kappa) + \left(\frac{1}{\upsilon+\kappa} - \frac{1}{\upsilon-1}\right)\ln\upsilon + \left(\frac{1}{\upsilon} - \frac{1}{\upsilon+\kappa}\right)\ln(\upsilon-1), \quad \forall \upsilon \geq 2, \quad (62)$$

where the first and the third parts on the right-hand side are positive, while the second part is shown to be negative. The summation of the first and the second parts has

$$\left(\frac{1}{\upsilon-1} - \frac{1}{\upsilon}\right)\ln(\upsilon+\kappa) + \left(\frac{1}{\upsilon+\kappa} - \frac{1}{\upsilon-1}\right)\ln\upsilon > \left(\frac{1}{\upsilon+\kappa} - \frac{1}{\upsilon}\right)\ln(\upsilon), \quad \forall \upsilon \geq 2. \quad (63)$$

Using (63) to replace the summation of the first and the second pats in (62), we have

$$\frac{\partial \hat{\gamma}(\upsilon)}{\partial \upsilon} > \left(\frac{1}{\upsilon+\kappa} - \frac{1}{\upsilon}\right)\ln(\upsilon) + \left(\frac{1}{\upsilon} - \frac{1}{\upsilon+\kappa}\right)\ln(\upsilon-1) > \left(\frac{1}{\upsilon+\kappa} - \frac{1}{\upsilon}\right)\ln(\upsilon-1) + \left(\frac{1}{\upsilon} - \frac{1}{\upsilon+\kappa}\right)\ln(\upsilon-1) = 0. \quad (64)$$

Thus, we have $\frac{\partial \hat{\gamma}(\upsilon)}{\partial \upsilon} > 0$. Therefore, $\hat{\gamma}(\upsilon), \forall \upsilon \geq 2$, is an increasing function of the index number υ. This completes the proof. ■

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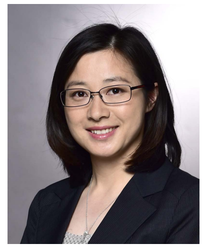

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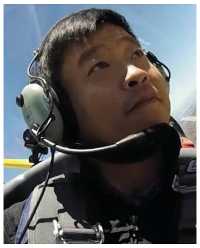

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