Incentive Mechanism Design for Two-Layer Wireless Edge Caching Networks Using Contract Theory

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Abstract—Wireless caching technologies have been proposed to relieve the transmission pressures, especially, the transmission redundancy on back-haul channels. In this paper, we consider a two-layer caching network, consisting of traditional macro-cell base station (MBS) aided back-haul channels and small-cell base stations (SBSs) aided local links. The network service provider (NSP), who is in charge of the two layers, leases its resources of the secondary layer, i.e., coverage of the SBSs, to content providers (CPs) for making extra profits and releasing pressures on the back-haul channels. At the same time, CPs will evaluate whether they are provided with proper incentives to pre-cache their files in the SBSs. Considering different quality of services (QoS) provided by the two layers as well as the economical impact of the traditional layer on the secondary layer, the NSP designs the optimal incentive mechanisms within the framework of contract theory for maximizing its own profits. Firstly, we formulate the utility of the NSP and CPs. Then, the minimum transmission requirement, reserve price and limited resources are considered as constraints in designing the optimal contract. Also, some important properties of these constraints are analyzed to facilitate the optimal contract determination process. At last, an optimal contract determination scheme is proposed, based on which the optimal coverage set is determined firstly, and then the corresponding optimal prices are derived with the aid of equal cost line. Numerical results are provided to demonstrate the effectiveness of the proposed optimal contract in increasing the NSP's profits and incentivizing CPs to transmit on the secondary layer.

Index Terms—Contract theory, Incentive mechanism design, Wireless edge caching, Two-layer networks.

1 Introduction

Recently, we have witnessed a dramatic growth on entertainment requirements and social connections in cellular networks. It is reported that wireless multimedia transmissions have made the main contributions to this increment [1]. However, the capacity of the existing networks cannot keep a similar pace with the growing trends in wireless data traffic [2]. As a consequence, 5G wireless technologies such as millimeter wave technology [3], massive multiple-input multiple-output [4] and super density heterogeneous networks [5] have been introduced. However, most attempts still rely on changing the hardware equipments or network protocols, leading to high costs and complexity to current communication systems.

As an alternative, wireless caching technology, which is more convenient and economical, has been proposed to have popular contents cached into the local storages of the network nodes positioned at the edge of wireless networks, with the aim to mitigate the redundant transmissions on back-haul channels [6–10]. Specifically, wireless caching consists of two stages: the data placement stage [11] and the data delivery stage [12]. In the data placement stage, popular files are pre-cached in the local devices during off-peak time. While in the data delivery stage, mobile users (MUs) may request files directly from the local devices. In this scenario, wireless caching mechanism can help shift data traffic from macro-cell base stations (MBS) to local nodes, and provide popular files closer to the MUs. There are a number of works addressing data placement and delivery issues. The purposes of these literatures are mainly about reducing the transmission latency [13–15], improving the hit ratio of the cached files [16–18], or enhancing energy efficiency of the evolved networks [19–23].

On one hand, in wireless edge caching scenario, the local facilities will spend extra power and storage capacity to help content providers (CPs) cache files. On the other hand, the CPs would evaluate whether they are provided with proper incentives to pre-cache their files in local facilities. Otherwise, they may still response MUs' requests through back-haul channels. Therefore, besides the issues addressed in [13–23], mechanisms from the economic perspective, that the network service provider (NSP) offers CPs with incentives to store their popular files into the local facilities, should also be well addressed. However, there exists an asymmetric information environment, where the NSP, as a network facility operator, intends to lease its resource, i.e., the small-cell base stations (SBSs), to the CPs for mitigating data traffic from backbone networks and maximizing its own profits, while it does not know the specific property of each CP. Contract theory has been proposed as an effective approach to solve the resource

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allocation problem in an asymmetric information environment [24–30].

In this work, we are inspired to solve the problem of asymmetry information within the framework of contract theory. Works most related to the scenario proposed in this paper include [31, 32]. In specific, [31] designs the optimal contract between a mobile network operator (MNO) and multiple CPs in a fixed network architecture. Authors analyze the interdependent strategy between different CPs. The optimization problem is elaborated to maximize the utility of CPs, while ensuring the balanced budget of the MNO. Authors in [32] discuss the resource trading problem in a small-cell network, where the NSP designs the optimal contract on its SBS resources with the aim to maximize its own profits. However, in [32], authors do not consider the different quality of service (QoS) provided over the traditional back-haul channels and the newly introduced caching-enabled SBSs, as well as the economical impact between the two layers in designing the incentive mechanism.

Different from the existing works in [31, 32], in this paper we consider a two-layer market, where each layer provides a different QoS to MUs, and correspondingly they ask for different prices. The traditional layer refers to the MBS aided transmissions, providing guaranteed QoS. However, it might induce great traffic pressures on the back-haul channels. While the secondary layer refers to the SBSs aided transmission, which has pre-cached popular files locally to alleviate the back-haul pressures. However, since the SBSs have limited coverage, so they provide uncertain QoS to MUs. In such a two-layer network, NSP's purposes in designing the optimal contracts are, on one hand, to mitigate more data traffic from the traditional layer to the secondary layer, and on the other hand, to maximize its own profits. Meanwhile, each CP needs to evaluate whether it can accept the uncertainty provided by the secondary layer and which contract to sign. Overall, there exists some kind of economical impact of the traditional layer on the secondary layer. We consider the traditional layer as a baseline where CPs can purchase guaranteed services. The purpose of this paper is to design the optimal contracts which consider the uncertainty of the services provided by the secondary layer. It is possible that a CP may reject the contracts offered by the NSP if it is risk-averse or the offers are not appealing.

The study of this paper will shed a light on the incentive mechanism design for the edge caching networks which provide different QoS to MUs. The main contributions of this paper are listed as follows:

1) A two-layer commercial caching network is considered, where the first layer refers to the MBS aided traditional back-haul channels providing deterministic services to MUs, while the secondary layer refers to the caching-enabled SBSs, providing uncertainty services to MUs.
2) Contract theory is proposed to address the resource allocation problem in the two-layer caching networks, where the economical impacts of the traditional layer on the secondary layer are considered. We model this problem as an adverse selection.
3) Some properties derived from the traditional layer, such as the minimum transmission requirements and the reserve price are taken into consideration as constraints in developing the optimal contract for the secondary layer.
4) Important properties of these constraints are introduced for the purpose of facilitating the contract determination process. An optimal contract determination algorithm is proposed. Based on the algorithm, the optimal "coverage" is determined firstly, and then the optimal 'price' is obtained subsequently.
5) Numerical results are provided to show the effectiveness of the proposed scheme in incentivizing CPs to shift their transmissions from the traditional back-haul channels to the secondary caching-enabled SBSs, reducing CPs' costs, and increasing the NSP's profits.

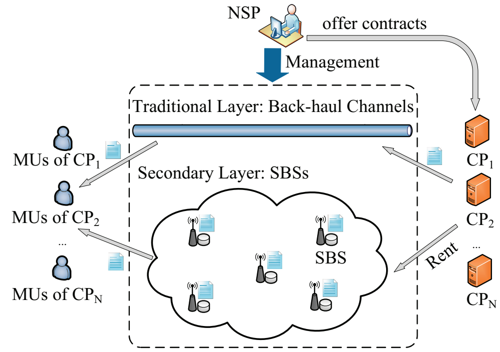

Fig. 1. An illustration of the proposed two-layer network.

The remainders of this paper are organized as follows: The system model is illustrated in Section 2. The contract-based service model is presented in Section 3. The optimal contract design and solutions are discussed in Section 4. Numerical results are elaborated in Section 5, and finally, conclusions are drawn in Section 6.

2 System Model

A commercial small-cell caching network with one NSP, N CPs and multiple MUs is investigated in this paper. In this network, each CP may purchase a certain coverage of the SBSs, which is regarded as a kind of resources, for placing its popular contents. An MU may directly download files from its nearby SBSs that have been rented by its affiliated CP. If its nearby SBSs did not cache the acquired files, this MU has to request files via the MBS. In this way, the activities of data transmissions in this network can be separated into two layers. Transmissions of the first layer are via the traditional back-haul channels, and transmissions of the secondary layer are via the SBSs. The system model is depicted in Fig. 1, where the NSP is in charge of the two layers. A table of notations used throughout this paper is given in Table 1.

2.1 Network Model

In this work, we consider a small cell network, which has one NSP, multiple SBSs and several MUs. We denote the N CPs by $\boldsymbol{\mathcal{V}} = \{\mathcal{V}_1, \cdots, \mathcal{V}_v, \cdots, \mathcal{V}_N\}$. SBSs are assumed to have a uniform transmission power P and the uniform caching capacity of Q files. The spatial distribution of the SBSs is modeled as an independent homogeneous Poisson point processes (PPP) Φ, with density λ. The distribution of the MUs is modeled as an independent homogeneous PPP Ψ, with density ζ. SBSs and MBS are assumed to transmit on orthogonal channels; therefore, interferences from the MBS are not considered in this paper.

We consider a saturate network in this model, where all SBSs are powered on and keep transmitting to their subscribers. Note that if the signal-to-interference-and-noise-ratio (SINR) at a typical MU from an SBS is not less than a predefined threshold δ, this typical MU can be covered by this SBS.

TABLE 1
Table of Notations

Notations	Meanings
$\mathcal{V}_v$	The vth CP
$\mathcal{F}_i$	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
$\mathcal{E}_{v,i}$	The event that an MU of $\mathcal{V}_v$ requests a file $\mathcal{F}_i$ from the SBS
τ_v	The proportion of the rented SBSs number by a CP $\mathcal{V}_v$ over the total SBSs number
C_v	The coverage assigned to $\mathcal{V}_v$
π_v	The corresponding price of C_v
p_i	The popularity of $\mathcal{F}_i$
θ_v	The popularity of $\mathcal{V}_v$
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 back-haul cost for a file transmission
T_v^t	Transmissions via the traditional back-haul channels of $\mathcal{V}_v$
T_v^s	Transmissions via the SBSs of $\mathcal{V}_v$
ε	The loss threshold, below which, the MUs will not be satisfied
$y_v^{\min}$	The minimum transmission requirement of $\mathcal{V}_v$
c_v	Costs of $\mathcal{V}_v$
$c_v^{\min}$	Reserve price of $\mathcal{V}_v$
L_v	The transmission loss of $\mathcal{V}_v$
$\mathbf{A}_v$	The acceptance region of $\mathcal{V}_v$
$\mathbf{B}_v$	The acceptance boundary of $\mathcal{V}_v$
$\mathbf{E}_v$	The equal cost lines of $\mathcal{V}_v$

2.2 Popularity of Files and CPs

The file set is denoted by $\boldsymbol{\mathcal{F}} = \{\mathcal{F}_1, \mathcal{F}_2, \cdots, \mathcal{F}_F\}$, consisting of F files. The popularity of these files is denoted by a vector $\mathbf{p} = \{p_1, \cdots, p_i, \cdots, p_F\}$, which can be modeled by the Zipf distribution [33] 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 characterizes the file's popularity. Note that each SBS can store at most Q files, and we assume $Q < F$. In practical scenario, different CPs have different file sets. However, in this paper, we assume different CPs share the same file set, which doesn't affect the proposed design procedure.

Usually, MUs have different preferences to N CPs, combining with many factors including personal favor, provided QoS, charging standards, and so on.

Definition 1. CPs' Popularity: *MUs' preferences towards CPs are regarded as CPs' popularity, which is denoted by the set* $\boldsymbol{\Theta} = \{\theta_1, \cdots, \theta_v, \cdots, \theta_N\}$*, where* θ_v *represents the popularity of* $\mathcal{V}_v$.

2.3 Caching Procedures

In this subsection, we introduce the contract signing and content caching procedures in a small-cell caching system in detail. There are four stages in our system.

In the first stage, the NSP designs the optimal contracts and posts the contracts on it website. CPs will choose the appropriate contract according to its specific type. CPs will send a message and sign the optimal contract with NSP. This interaction will produce few bits overhead which is proportional to CPs number.

In the second stage, the NSP will inform the SBSs which CP will be associated with it. This information is broadcasted, and the overhead is proportional to the SBSs number. In what follows, each CP gets a certain coverage of the SBSs from the NSP for placing its files. Note that the coverage is usually determined by the fraction of the SBS. We denote the coverage set designed for CPs by $\boldsymbol{C} = \{C_1, C_2, \cdots, C_N\}$, in which $C_v = g(\tau_v)$ represents a mapping from fraction τ_v to coverage C_v. We will provide the specific expression of $g(\tau_v)$ in (3) and (4). In general, we have $g(0) = 0$, if a CP $\mathcal{V}_v$ does not rent any fraction, i.e., $\tau_v = 0$, from the NSP. Obviously, fractions and coverage cannot be negative or infinity, and thus we have $\tau_v \geq 0$, $\sum_{v=1}^{N} \tau_v \leq 1$, and $C_v = g(\tau_v) \geq 0$.

In the second stage, each CP will place its contents into the rented SBSs during off-peak time. Due to the limited caching capacity of each SBS, CP will place the most Q popular files in order to increase the caching efficiency.

In the third stage, an MU of $\mathcal{V}_v$ requests a file $\mathcal{F}_i \in \boldsymbol{\mathcal{F}}$. It firstly searches the SBSs in Φ_v and connects to the adjacent SBS that caches the requested file. If no such an SBS exists, the MU will directly request file from the MBS, and this MU will trigger transmissions via back-haul channels for dispatching the requested file, leading to extra costs on the NSP. If such an SBS exists, the MU will obtain this file directly from it. This event is defined by $\mathcal{E}_{v,i}$. The successful probability of the event $\mathcal{E}_{v,i}$ is denoted by

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

where τ_v represents the fraction of the SBS. In other words, it denotes the proportion of the rented SBSs number by a CP $\mathcal{V}_v$ over the total SBSs number. α is the path-loss exponent. δ is a pre-defined power threshold, below which, the MU is not covered by the SBS. $A(\delta,\alpha) = \frac{2\delta}{\alpha-2}\,{}_2F_1(1, 1-\frac{2}{\alpha}; 2-\frac{2}{\alpha}; -\delta)$ where ${}_2F_1(.)$ is the hypergeometric function, and $C(\delta,\alpha) = \frac{2}{\alpha}\delta^{\frac{2}{\alpha}} B(\frac{2}{\alpha}, 1-\frac{2}{\alpha})$ where $B(.,.)$ is the beta function in $C(\delta,\alpha)$. The detailed derivation of (2) can be found in [34].

2.4 Two-layer Market and Its Characteristics

When caching mechanism is incorporated into local SBSs, data transmissions may be transferred from the back-haul channels to the local links. In this way, CPs may choose to transmit files through back-haul channels, or alteratively choose to pre-cache files into SBSs, providing local transmissions for their subscribers.

Thus, there exists a two-layer market, i.e., the traditional back-haul channel market and the new emerging SBSs market. The two layers are all managed by the NSP as shown in Fig. 1, we name the first layer of trading back-haul channels as the traditional layer market, and the second layer market of trading SBSs as the secondary layer market.

The traditional and the secondary layers have distinct strengths and drawbacks. The traditional one can provide deterministic services for MUs. However, there might induce congestion problems on the back-haul channels. While the secondary one offers unguaranteed services due to the caching capacity constraint and the coverage limitation of each SBS, however, it can relieve burdens on the back-haul channels and the remote servers, especially in peak hours. How to take advantages of these two layers pose great challenges to both the NSP and CPs. On the one hand, the NSP wants CPs to shift their data streams to the local facilities as many as possible, for reducing the pressures on back-haul channels. It also wants to make more profits by selling its resources. Therefore, it needs to evaluate the uncertainty of the offered services by the secondary layer and the corresponding prices, making the secondary layer remain competitive against the traditional layer which provides guaranteed services and a relatively high price. On the other hand, CPs are willing to have their contents cached into the local SBSs for providing better services to their subscribers, but they need to evaluate the service uncertainty and assess whether the uncertainty is worth the price.

In this way, there are three choices for each CP, the first choice is to rent a certain coverage of the SBSs without buying any back-haul transmissions, the second one is not to rent any SBSs, transmitting all the requested files through back-haul channels instead, and the third one is to purchase a combination with a certain coverage of SBSs and some back-haul transmissions.

3 CONTRACT-BASED SERVICE MODEL

In this section, we focus on modelling the contract-related issues in the proposed two-layer network, incorporating the caching and data transmission stages.

3.1 NSP's Model

We assume that the NSP sets the contract entries $\{\boldsymbol{C}, \boldsymbol{\Pi}\}$, where $\boldsymbol{C} = \{C_1, C_2, \cdots, C_N\}$ denotes the set of coverage. Given τ_v, each coverage $C_v \in \boldsymbol{C}$ is then determined by

$$C_v = g(\tau_v), \tag{3}$$

where

$$g(\tau_v) \triangleq \begin{cases} \Pr(\mathcal{E}_{v,i}), & i \le Q; \\ 0, & i > Q. \end{cases} \tag{4}$$

$\Pr(\mathcal{E}_{v,i})$ has been defined in Subsection 2.3, and it denotes the probability of the event $\mathcal{E}_{v,i}$. The relationships among (2), (3), and (4) are discussed in **Remark 1**.

Remark 1. *Observing (3), it can be seen that the coverage C_v is determined by a segment function $g(\tau_v)$, while $g(\tau_v)$ is divided by the value of index i. When $i \le Q$, $g(\tau_v)$ is determined by (2), while $i > Q$, $g(\tau_v) = 0$.*

Observing (4), it can be seen that $g(\tau_v)$ is dependent on index i. due to the reason that this paper focuses on designing contracts for the secondary layer which only caches files with index $i \le Q$, thus, we omit the index i in $g(\tau_v)$ in the following for brevity.

The unit price of each coverage is denoted by $\boldsymbol{\Pi} = \{\pi_1, \pi_2, \cdots, \pi_N\}$, and each coverage C_v in $\boldsymbol{C}$ corresponds to a unit price π_v. The coverage C_v here is regarded as a specific *'quality'*. CPs are free to decide whether or which quality to purchase. The above discussions are the contract construction and commitment stages which are commenced before the data placement stage.

Then, the utility of the NSP can be formulated as

$$U_{\text{NSP}}(\boldsymbol{\Theta}, \boldsymbol{C}, \boldsymbol{\Pi}) = \sum_{v=1}^{N} \left(C_v \left(\pi_v - c\right)\right), \tag{5}$$

where c is the operation cost of the NSP on the unit coverage, considering the expenditures of the storage devices and power consumptions.

Remark 2. *The NSP would gain more profits if it sells more coverage C_v or charges a higher price π_v.*

3.2 CP's Model in the Three Cases

According to **Definition 1**, CPs' popularity represents MUs' preferences towards CPs. In other words, CPs' popularity θ_v denotes how many percentage of the MUs prefer a CP $\mathcal{V}_v$. So when the density of MUs ζ which is in the unit of unit area, i.e., $/UA$, and the average file downloading demand of each MU K within a unit period which is in the unit of unit period, i.e., $/UP$, are given, the total request amount of a CP θ_v in a unit period unit area, i.e., $/UPUA$, can be determined by $\theta_v \zeta K$.

Considering there are two layers in this system, the transmissions of these requests from $\mathcal{V}_v$ to its MUs can be classified in three cases concerning CP's purchasing choices.

3.2.1 Traditional-Layer-Only Case (the Benchmark)

In the following, we provide some important definitions and some comprehensive discussions on the traditional-layer-only case. Since this is a traditional way to transmit data in practical, this case can be considered as a benchmark in our proposed system. In the traditional layer, the successful transmissions T_v^t should satisfy the loss constraint, i.e.,

$$T_v^t \ge \theta_v \zeta K - \varepsilon, \quad \forall v, \tag{6}$$

where ε is a threshold, below which, the MUs will not satisfy the provided services of $\mathcal{V}_v$ and they are apt to switch to another CP in the next subscription period.

Definition 2. Minimum Transmission Requirement: *From this, we define the minimum transmission requirement $y_v^{\min}$ as*

$$y_v^{\min} \triangleq \theta_v \zeta K - \varepsilon, \quad \forall v. \tag{7}$$

The minimum transmission requirement $y_v^{\min}$ is regarded as the minimum successful responses of $\mathcal{V}_v$, below which, the subscribers will not be satisfied and probably change to another CP in the next subscription period. Assuming s^{bh} is the unit back-haul cost of a file transmission via the traditional layer. The minimum expenditure $c_v^{\min}$ of $\mathcal{V}_v$ is therefore determined by

$$c_v^{\min} = y_v^{\min} s^{\text{bh}} = \left(\theta_v \zeta K - \varepsilon\right) s^{\text{bh}}, \quad \forall v. \tag{8}$$

Definition 3. Reserve Price: $c_v^{\min}$ *defined in (8) is regarded as the reserve price.*

Reserve price $c_v^{\min}$ is the minimum expenditures that a CP $\mathcal{V}_v$ needs to pay in the traditional market.

Remark 3. *Note that the expenditures of other cases cannot exceed the reserve price $c_v^{\min}$. Otherwise there is no incentive for a CP to purchase from the secondary layer and to shift its transmissions to the secondary layer.*

3.2.2 Combined Two-layer Case

Alternatively, a CP $\mathcal{V}_v$ may buy a combination with T_v^t transmissions from the traditional layer and $\{C_v, \pi_v\}$ from the secondary layer, its cost c_v is

$$c_v(C_v, \pi_v) = T_v^t s^{\text{bh}} + C_v \pi_v, \quad \forall v. \tag{9}$$

If a subscriber of $\mathcal{V}_v$ requests a file $\mathcal{F}_i \in \boldsymbol{\mathcal{F}}, \forall i$, it firstly search the SBSs in Φ_v and connects to the nearest SBS that both caches the requested files and covers it. The number of successful transmissions T_v^s via the secondary layer depends on the coverage C_v and the storage size Q, i.e.,

$$T_v^s = \theta_v \zeta K C_v \sum_{j=1}^{Q} p_j, \quad \forall v. \tag{10}$$

Thus, the loss of transmission L_v of the combined two-layer case is

$$L_v(C_v, \pi_v) = \theta_v \zeta K - T_v^t - T_v^s, \quad \forall v, \tag{11}$$

where $\theta_v \zeta K$ is the total requests of a CP $\mathcal{V}_v$, T_v^t is the deterministic transmissions on the traditional layer, and T_v^s represents the successful transmissions on the secondary layer.

3.2.3 Secondary-Layer-Only Case

If a CP only signs a contract $\{C_v, \pi_v\}$, which indicates that the transmission over the back-haul channel is $T_v^t = 0$. In this case, all the transmissions will be transferred to the local SBSs instead of the back-haul channels. The cost c_v and the transmission loss L_v are determined by

$$c_v(C_v, \pi_v) = C_v \pi_v, \quad \forall v, \tag{12}$$

and

$$L_v(C_v, \pi_v) = \theta_v \zeta K - T_v^s, \quad \forall v, \tag{13}$$

respectively.

4 Optimal Contract Design and Solutions

In this system, the NSP designs the contracts, each CP in $\boldsymbol{\mathcal{V}}$ is free to reject or choose an appropriate entry. The goal of the NSP is to maximize its own profits U_{NSP} by offering the optimal contract entries $\{C_v^*, \pi_v^*\},\ v = 1, 2, \cdots, N$, and CPs need to evaluate whether to accept the offered contracts and decide which contract to sign.

4.1 Problem Formulation

A feasible contract, which is capable of attracting CPs to purchase certain coverage, in specific, certain fractions of the SBSs for placing their contents, must comply with the feasibility constraints on individual rationality (IR) and incentive compatibility (IC) for all the N CP *'types'* [35].

Definition 4. CPs' types: *CPs' popularity which has been defined in **Definition 1** is used to represent CPs' types. These types are sorted in a descending order as $\theta_1 > \cdots > \theta_v > \cdots > \theta_N$.*

Note that the information asymmetry is assumed in this network. The NSP is not aware of the specific type of each CP, and it only knows the distribution of CPs' types.

Definition 5. IR constraint: *Given that each CP is rational, it will not accept a contract which cannot satisfy the transmission loss constraint, nor exceed the reserve price. Therefore, the IR constraints can be written as*

$$L_v(C_v, \pi_v) \leq \varepsilon, \quad \forall v, \tag{14}$$

and

$$c_v(C_v, \pi_v) \leq c_v^{\min}, \quad \forall v, \tag{15}$$

where (14) represents the transmission loss constraint, and (15) denotes the constraint on the total cost, respectively.

It is natural to assume that in order to stimulate $\mathcal{V}_v$ to participate into contracting, i.e., purchasing from the secondary layer, the transmission loss should not exceed the threshold ε which is shown in (14) and the whole costs should be less than the reserve price, i.e., the expenditures if CPs choose to transmit via traditional layer. In the case of either $L_v(C_v, \pi_v) > \varepsilon$ nor $c_v(C_v, \pi_v) > c_v^{\min}$, $\mathcal{V}_v$ will purchase nothing.

Definition 6. IC constraint: *The IC constraint means that the buyer $\mathcal{V}_v$ will spend more money when it chooses a contract entry which is not designed for its type. That is,*

$$c_v(C_v, \pi_v) \leq c_v(C_{\tilde{v}}, \pi_{\tilde{v}}) \quad \forall \tilde{v} \neq v, \tag{16}$$

where the contract $\{C_{\tilde{v}}, \pi_{\tilde{v}}\}$ is designed for type $\theta_{\tilde{v}}$. In other words, $\mathcal{V}_v$ with type θ_v will spend the minimum money if and only if it chooses the contract $\{C_v, \pi_v\}$ designed for its type.

A feasible contract must guarantee the IR and IC constraints. Since the contracts are determined by the NSP, the objective function is to maximize the utility of the NSP. Thus, the optimization of the contract problem is formulated as

$$\begin{aligned} &\{\boldsymbol{C}^*, \boldsymbol{\Pi}^*\} = \arg\max\ U_{\text{NSP}}, \qquad (17)\\ \text{s.t.}\quad &\text{IR}(14),\ \text{IR}(15),\ \text{and IC}(16),\\ &\sum_{v=1}^{N} \tau_v \leq 1,\ \tau_v \geq 0,\ C_v \geq 0,\ \forall v. \end{aligned}$$

4.2 Constraints Analysis

Observing (17), we find that there are $2N$ IR constraints and $N(N-1)$ IC constraints. Before we set out to solve this optimization problem, some key concepts should be introduced to facilitate this process.

4.2.1 IR Constraints Analysis

Definition 7. Acceptance Region $\mathbf{A}_v$: *The acceptance region $\boldsymbol{A}_v$ denotes the set of all acceptable contracts for $\mathcal{V}_v$, i.e., $\boldsymbol{A}_v \triangleq \{\{C_v, \pi_v\}:\ c_v(C_v, \pi_v) \leq c_v^{\min}$ and $L_v(C_v, \pi_v) \leq \varepsilon\}$.*

According to **Remark 2**, the NSP wants CPs to purchase its resources as many as possible to gain more profits. However, due to the resource constraint in this network, the maximum resource that one CP may purchase is $C_v = g(1)$. Therefore, given $C_v = g(1)$ that one CP purchases, considering the relationship between the loss threshold ε and the transmission loss L_v, we have the following two scenarios.

Definition 8. Scenario 1: *The situation, when*

$$\theta_v \zeta K - \theta_v \zeta K g(1) \sum_{j=1}^{Q} p_j \leq \varepsilon, \tag{18}$$

is defined as scenario 1.

In **Scenario 1**, if CP_v purchases the maximum coverage $g(1)$, the transmission loss constraint will be satisfied.

Definition 9. Scenario 2: *the situation, when*

$$\theta_v \zeta K - \theta_v \zeta K g(1) \sum_{j=1}^{Q} p_j \geq \varepsilon, \tag{19}$$

is defined as scenario 2.

In **Scenario 2**, even the maximum coverage $g(1)$ is purchased, the transmission loss constraint cannot be met. In this scenario, CPs have to trigger transmissions via the traditional layer.

In the following Lemmas, some intensive insights of the acceptance region $\mathbf{A}_v$ in two scenarios are presented.

Lemma 1. *In **Scenario 1**: the acceptance region $\mathbf{A}_v$ of a CP $\mathcal{V}_v$ is characterized by*

$$\pi_v \leq \begin{cases} \theta_v \zeta K s^{bh} \sum_{j=1}^{Q} p_j, & C_v < \frac{y_v^{\min}}{\theta_v \zeta K \sum_{j=1}^{Q} p_j}; \\ \frac{c_v^{\min}}{C_v}, & C_v \geq \frac{y_v^{\min}}{\theta_v \zeta K \sum_{j=1}^{Q} p_j}. \end{cases} \quad (20)$$

*In **Scenario 2**: the acceptance region $\mathbf{A}_v$ of a CP $\mathcal{V}_v$ is characterized by*

$$\pi_v \leq \begin{cases} \theta_v \zeta K s^{bh} \sum_{j=1}^{Q} p_j, & C_v \leq \frac{\varepsilon}{\theta_v \zeta K \left(1-\sum_{j=1}^{Q} p_j\right)}; \\ \frac{\varepsilon s^{bh} \sum_{j=1}^{Q} p_j}{C_v \left(1-\sum_{j=1}^{Q} p_j\right)}, & C_v > \frac{\varepsilon}{\theta_v \zeta K \left(1-\sum_{j=1}^{Q} p_j\right)}. \end{cases} \quad (21)$$

Proof: Please refer to Appendix A. ■

In **Scenario 1**, when $\mathcal{V}_v$'s purchasing amount from the secondary layer is sufficient large, i.e., $C_v \in \left[\frac{y_v^{\min}}{\theta_v \zeta K \sum_{j=1}^{Q} p_j}, g(1)\right]$, the minimum transmission requirements can be met without any purchase from the traditional layer. Thus, $\mathcal{V}_v$ may spend up to the whole reserve price $c_v^{\min}$ on the secondary layer. This corresponds to the second line in (20). However, when C_v is not sufficient large that $C_v \in \left[0, \frac{y_v^{\min}}{\theta_v \zeta K \sum_{j=1}^{Q} p_j}\right)$, the minimum transmission requirements cannot be met on the secondary layer, $\mathcal{V}_v$ needs to buy additional transmissions from the traditional layer. Thus the reserve price $c_v^{\min}$ will be separated into two markets. This is the case shown in the first line of (20).

In **Scenario 2**, even CP buys the whole coverage, i.e., $C_v = g(1)$, it is not sufficient large to guarantee the minimum transmission requirements. Contrast to **Scenario 1**, in **Scenario 2**, it is better to purchase less coverage from the secondary layer to guarantee not buying extra transmissions from the traditional layer. When $C_v \in \left[0, \frac{\varepsilon}{\theta_v \zeta K \left(1-\sum_{j=1}^{Q} p_j\right)}\right]$, the transmission loss of the secondary layer is

$$L_v(C_v, \pi_v) = \theta_v \zeta K C_v (1 - \sum_{j=1}^{Q} p_j) \in [0, \varepsilon]. \quad (22)$$

From (22), we find that C_v within the region $\left[0, \frac{\varepsilon}{\theta_v \zeta K \left(1-\sum_{j=1}^{Q} p_j\right)}\right]$ satisfies the loss constraint, and therefore will not trigger extra transmissions on the traditional layer. This corresponds to the first line of (21). When $C_v \in \left(\frac{\varepsilon}{\theta_v \zeta K \left(1-\sum_{j=1}^{Q} p_j\right)}, g(1)\right]$, the transmission loss is larger than ε, and thus $\mathcal{V}_v$ has to purchase additional transmissions from the traditional layer. This corresponds to the second line of (21).

Observing the expressions of acceptance region $\mathbf{A}_v$ in **Lemma 1**, we find that $\mathbf{A}_v$ is up bounded by a piecewise line. The first part is a straight line with a constant value regardless of C_v, and the second part is a function inversely proportional to C_v. In order to facilitate the optimal contract determination process, we give some definitions below.

Definition 10. Intersection Point $(C_v^{\circ}, \pi_v^{\circ})$:
*The intersection points $(C_v^{\circ}, \pi_v^{\circ})$ in **Scenario 1** of (20) and **Scenario 2** of (21) are*

$$C_v^{\circ} = \frac{y_v^{\min}}{\theta_v \zeta K \sum_{j=1}^{Q} p_j} \quad , \quad (23)$$

$$\pi_v^{\circ} = \frac{c_v^{\min}}{C_v^{\circ}} = \theta_v \zeta K s^{bh} \sum_{j=1}^{Q} p_j, \quad (24)$$

and

$$C_v^{\circ} = \frac{\varepsilon}{\theta_v \zeta K \left(1 - \sum_{j=1}^{Q} p_j\right)} \quad , \quad (25)$$

$$\pi_v^{\circ} = \frac{\varepsilon s^{bh} \sum_{j=1}^{Q} p_j}{C_v^{\circ}(1 - \sum_{j=1}^{Q} p_j)} = \theta_v \zeta K s^{bh} \sum_{j=1}^{Q} p_j, \quad (26)$$

respectively.

Remark 4. *It is easy to find that the intersection points $(C_v^{\circ}, \pi_v^{\circ})$ in **Scenario 1** satisfy the following relationship, i.e.,*

$$C_1^{\circ} > C_2^{\circ} > \cdots > C_N^{\circ}, \quad \pi_1^{\circ} > \pi_2^{\circ} > \cdots > \pi_N^{\circ}. \quad (27)$$

as well as

$$C_1^{\circ}\pi_1^{\circ} > C_2^{\circ}\pi_2^{\circ} > \cdots > C_N^{\circ}\pi_N^{\circ} = y_v^{min} s^{bh} = c_v^{min}. \quad (28)$$

Proof: Please refer to Appendix B. ■

Remark 5. *Observing (25), it is easy to find that, in **Scenario 2**, the intersection points $(C_v^{\circ}, \pi_v^{\circ})$ satisfy the following relationships:*

$$C_1^{\circ} < C_2^{\circ} < \cdots < C_N^{\circ}, \quad \pi_1^{\circ} > \pi_2^{\circ} > \cdots > \pi_N^{\circ}, \quad (29)$$

as well as

$$C_1^{\circ}\pi_1^{\circ} = C_2^{\circ}\pi_2^{\circ} = \cdots = C_N^{\circ}\pi_N^{\circ} = \frac{\varepsilon s^{bh} \sum_{j=1}^{Q} p_j}{\left(1 - \sum_{j=1}^{Q} p_j\right)}. \quad (30)$$

Proof: The proof follows the same steps in Appendix B. For brevity, we omit this proof here. ■

Definition 11. Acceptance Boundary $\mathbf{B}_v$:
The acceptance boundary $\mathbf{B}_v \triangleq \{\{C_v, \pi_v^b\} : \forall \{C_v, \pi_v\} \in \mathbf{A}_v$, when C_v is given, we have $\pi_v^b = \max\{\pi_v\}\}$.

The acceptance boundary $\mathbf{B}_v$ can be easily understood by looking at the curves in Fig. 2, below which is the acceptance region $\mathbf{A}_v$. In the following, we present an essential property of the acceptance boundary in **Lemma 2**.

Lemma 2. *On the acceptance boundary $\mathbf{B}_v$ of a CP $\mathcal{V}_v$, when $C_v \leq C_v^{\circ}$, we have $\pi_v^b = \pi_v^{\circ}$, and when $C_v > C_v^{\circ}$, we have $\pi_v^b < \pi_v^{\circ}$ as well as $C_v^{\circ}\pi_v^{\circ} = C_v \pi_v^b$.*

Proof: Please refer to Appendix C. ■

Based on the expressions of acceptance region in **Lemma 1** and the property of the acceptance boundary in **Lemma 2**, we arrive at **Theorem 1** and **Proposition 1**.

Theorem 1. *The utility of the NSP is an increasing function of C_v and π_v until the intersection point $\{C_v^{\circ}, \pi_v^{\circ}\}$ for a particular CP .*

Proof: Please refer to Appendix D. ■

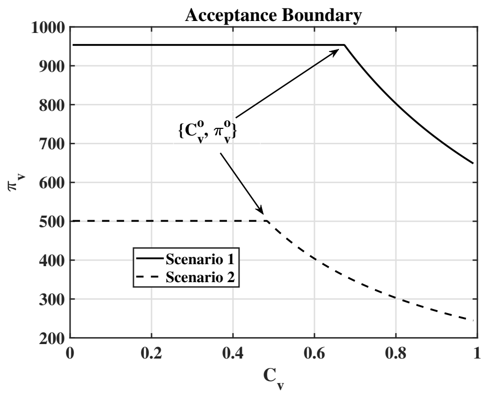

Fig. 2. An illustration of the Acceptance Boundaries of the two scenarios in **Lemma 1**.

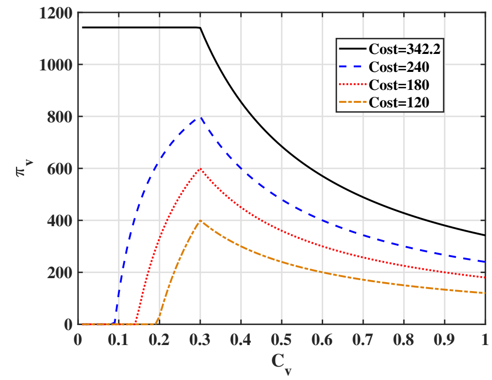

Fig. 3. An illustration of Equal Cost Lines.

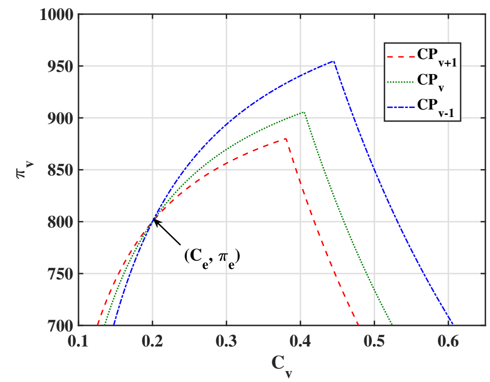

Fig. 4. An illustration of **Lemma 4**.

Proposition 1. *If C_v is given, the maximum utility of the NSP can be obtained on the acceptance boundary $\boldsymbol{B}_v, \forall v$.*

Proof: Please refer to Appendix E. ■

Theorem 1 highlights that, for one CP with type θ_v, the NSP can offer it with $\{C_v^\circ, \pi_v^\circ\}$ on the acceptance boundary $\mathbf{B}_v$ to maximize the NSP's utility.

However, there are usually more than one CPs existing in this network and the coverage C_v is limited, i.e., $\sum_{v=1}^{N} C_v \leq g(1)$, the conclusion drawn in **Theorem 1** is not sufficient when general case is considered in this network. Thus, we introduce the following concepts and lemmas to further design the optimal contracts intended for multiple CPs.

4.2.2 IC Constraints Analysis

Definition 12. Equal Cost Line: *The equal cost line $\boldsymbol{E}_v$, which is defined as the set of contracts within the acceptance region $\boldsymbol{A}_v$, poses equal cost to $\mathcal{V}_v$. It is defined as*

$$\boldsymbol{E}_v = \{\{C_v^E, \pi_v^E\}: \; c_v(C_v^E, \pi_v^E) = c_v(\tilde{C_v^E}, \tilde{\pi_v^E}), \quad \forall \{C_v^E, \pi_v^E\} \in \boldsymbol{E}_v \text{ and } \{\tilde{C_v^E}, \tilde{\pi_v^E}\} \in \boldsymbol{E}_v\}. \tag{31}$$

Note that there are multiple equal cost lines in the acceptance region $\mathbf{A}_v$, and each line with a different cost. In the following lemma, we will give a detailed description of the equal cost line.

Lemma 3. *For a CP with type θ_v, the intersection point is $\{C_v^\circ, \pi_v^\circ\}$. Given a contract $\{C_e, \pi_e\}$ within the acceptance region $\boldsymbol{A}_v$, the price π_v on the equal cost line crossing $\{C_e, \pi_e\}$ can be expressed as:*

Case A: if $C_e \leq C_v^\circ$

$$\pi_v(C_e, \pi_e, C_v) = \tag{32}$$
$$\begin{cases} \frac{C_e\pi_e - C_e\theta_v\zeta K s^{bh}\sum_{j=1}^{Q} p_j}{C_v} + \theta_v\zeta K s^{bh}\sum_{j=1}^{Q} p_j, & C_v \leq C_v^\circ; \\ \frac{\left(\theta_v\zeta K C_v^\circ\sum_{j=1}^{Q} p_j - \theta_v\zeta K C_e\sum_{j=1}^{Q} p_j\right)s^{bh} + C_e\pi_e}{C_v}, & C_v > C_v^\circ. \end{cases}$$

Case B: if $C_e > C_v^\circ$

$$\pi_v(C_e, \pi_e, C_v) = \tag{33}$$
$$\begin{cases} \frac{C_e\pi_e - C_v^\circ s^{bh}\theta_v\zeta K\sum_{j=1}^{Q} p_j}{C_v} + \theta_v\zeta s^{bh} K\sum_{j=1}^{Q} p_j, & C_v \leq C_v^\circ; \\ \frac{C_e\pi_e}{C_v}, & C_v > C_v^\circ. \end{cases}$$

Proof: Please refer to Appendix F. ■

Fig. 3 illustrates a set of equal cost lines. Note that given C_v, the contract with a lower price is more preferable than the contract with a higher price from the perspective of CPs.

Remark 6. *Observing (32) and (33), it is easy to find that $\frac{\partial \pi_v(C_e, \pi_e, C_v)}{\partial \pi_e} > 0$. Thus $\pi_v(C_e, \pi_e, C_v)$ is an increasing function of π_e.*

That is to say, given C_e, if $\pi_e > \tilde{\pi}_e^{'}$, we have $\pi_v(C_e, \pi_e, C_v) > \pi_v(C_e, \tilde{\pi}_e^{'}, C_v)$. The equal cost line crossing $\{C_e, \pi_e\}$ will always on top of the one crossing $\{C_e, \tilde{\pi}_e^{'}\}$. It also can be understood by observing Fig. 3.

Lemma 4. *In Case A, i.e., $C_e \leq C_v^\circ$ shown in **Lemma 3**, the equal cost lines crossing the point $\{C_e, \pi_e\}$, have the following properties:*

when $C_v \geq C_e$,

$$\frac{\partial \pi_v(C_e, \pi_e, C_v)}{\partial \theta_v} \geq 0; \tag{34}$$

when $C_v < C_e$,

$$\frac{\partial \pi_v(C_e, \pi_e, C_v)}{\partial \theta_v} < 0. \tag{35}$$

Proof: Please refer to Appendix G. ■

Lemma 4 can be easily understood by observing Fig. 4. Since θ_v, according to **Definition 4**, decreases as the index v increases. Thus, in the $C_v < C_e$ region, the equal cost line of θ_{v-1} crossing the point (C_e, π_e) has a smaller π_{v-1}. On the contrary, when $C_v \geq C_e$, the equal cost line of θ_{v-1} crossing the point (C_e, π_e) has a larger π_{v-1}.

In the following, we propose a simple way by employing the properties of the equal cost line to construct the IC constraints for **Scenario 1**.

Theorem 2. *In **Scenario 1**, given $C_1 > \cdots > C_v > \cdots > C_N$, contract is determined by $\{C_v, \pi_v\} =$*

$\{C_v, \pi_v(C_{v+1}, \pi_{v+1}, C_v)\}$. *Followed by such procedures, the generated contracts will satisfy the IC constraints.*

Proof: Please refer to Appendix H. ■

Then, we have

$$c_v(C_v, \pi_v) = c_v(C_{v+1}, \pi_{v+1}). \tag{36}$$

That is to say the contracts $\{C_v, \pi_v\}$ and $\{C_{v+1}, \pi_{v+1}\}$ generated by **Theorem 2** pose equal costs for CP $\mathcal{V}_v$.

4.3 Solution to Get the Optimal Contract in Scenario 1

Theorem 2 provides a simple way to construct the IC constraints. By employing lemmas and theorems in the previous subsection, the optimization problem in (17) can be reduced as

$$\{\boldsymbol{C}^*, \boldsymbol{\Pi}^*\} = \arg\max\ U_{\text{NSP}}, \tag{37}$$
$$\text{s.t. IR: } \{C_v, \pi_v\} \in \mathbf{A}_v,\ \text{IC: } c_v(C_v, \pi_v) = c_v(C_{v+1}, \pi_{v+1}),$$
$$\sum_{v=1}^{N} \tau_v = 1,\ \tau_v \geq 0,\ 0 \leq C_v \leq C_v^o, \quad \forall v.$$

We employ the expression shown in the first line of (32) to generate the IC constraints. We iterate the IC constraints, and have

$$\{\boldsymbol{C}^*, \boldsymbol{\Pi}^*\} = \arg\max \sum_{v=1}^{N} R_v, \tag{38}$$
$$\text{s.t.} \quad \text{IR: } \{C_v, \pi_v\} \in \mathbf{A}_v$$
$$\sum_{v=1}^{N} \tau_v = 1, \tau_v \geq 0,\ 0 \leq C_v \leq C_v^\circ, \quad \forall v,$$

where

$$R_1 = C_1 \left(\theta_1 \zeta K \sum_{j=1}^{Q} p_j s^{\text{bh}} - c \right), \tag{39}$$

and

$$R_v = C_v \left(v\theta_v \zeta K \sum_{j=1}^{Q} p_j s^{\text{bh}} - (v-1)\theta_{v-1} \zeta K \sum_{j=1}^{Q} p_j s^{\text{bh}} - c \right), \quad \forall v > 1. \tag{40}$$

We find that the target function in (38) is only related to $C_v, \forall v$, regardless of $C_{\tilde{v}}, \forall \tilde{v} \neq v$. Thus if $\frac{\partial R_v}{\partial C_v} > 0$, we want to make C_v as large as possible until $C_v = C_v^\circ$ according to **Theorem 1**. When $\frac{\partial R_v}{C_v} \leq 0$, we set $C_v = 0$.

Algorithm 1 helps us determine the optimal coverage set $\{C_1^*, \cdots, C_N^*\}$. We define $b_v \triangleq \theta_v \zeta K \sum_{j=1}^{Q} p_j s^{\text{bh}}$ in the algorithm for brevity. Observing (40), we have $\frac{\partial R_v}{\partial C_v} = v b_v - (v-1) b_{v-1} - c$.

In **Algorithm 1**, we first determine the optimal coverage C_1^* which will be assigned to CP_1, then we determine C_2^*, all the way until there is no resource left. Since limited resource scenario is considered in this model, we cannot simply assign C_v° to C_v^*, when $\frac{\partial R_v}{\partial C_v} > 0$. In particular, we need to check whether there is enough resources left, if there is not enough left, we will assign all the remaining resources to this CP whose index is supposed to be $M, M \leq N$ and then terminate this determination process. Otherwise, we assign C_v° to C_v^*.

Algorithm 1 Determine the Optimal C_v^* for **Scenario 1**

Input: C_v° and $\frac{\partial R_v}{\partial C_v}$.
Output: C_v^*.
Initialize: $\tau_{\text{temp}} = 1$.
For $v = 1 : N$ do:
if $\tau_{\text{temp}} \geq 0$ do
(1) if $\frac{\partial R_v}{\partial C_v} > 0$ and $g^{-1}(C_v^\circ) < \tau_{\text{temp}}$, then $C_v^* = C_v^\circ$, update $\tau_{\text{temp}} = \tau_{\text{temp}} - g^{-1}(C_v^\circ)$;
(2) if $\frac{\partial R_v}{\partial C_v} > 0$ and $g^{-1}(C_v^\circ) \geq \tau_{\text{temp}}$, then $C_v^* = g(\tau_{\text{temp}})$, update $\tau_{\text{temp}} = 0$;
(3) if $\frac{\partial R_v}{\partial C_v} \leq 0$, then $C_v^* = g(\tau_v) = 0$, update $\tau_{\text{temp}} = \tau_{\text{temp}}$.
End if
End For

After we get the optimal coverage set $\{C_1^*, \cdots, C_M^*\}$, the optimal price set $\{\pi_1^*, \cdots, \pi_M^*\}$ can be determined subsequently by procedure shown in **Theorem 2**, thus we have

$$\pi_v^* = \frac{C_{v+1}^* \pi_{v+1}^* - C_{v+1}^* b_v}{C_v^*} + b_v, \quad C_v^* \leq C_v^\circ. \tag{41}$$

After some manipulations, (41) can be written in terms of b_v, C_v^*, and π_M as

$$\pi_v^* = b_v + \frac{\sum_{j=v+1}^{M-1} (b_j - b_{j-1}) C_j^* + (\pi_M^* - b_{M-1}) C_M^*}{C_v^*}. \tag{42}$$

Since $\{C_1^*, \cdots, C_M^*\}$ has been determined and $b_v = \theta_v \zeta K \sum_{j=1}^{Q} p_j s^{\text{bh}}$ is a constant regardless of C_v and π_v. In order to maximize π_v^*, we need to set $\pi_M^* = \pi_M^\circ$ according to **Proposition 1**, since this is the maximum price acceptable to CP $\mathcal{V}_M$. When determining the optimal price, we begin from index M to 1. The optimal contract, followed by this procedure, may guarantee the feasibility of the designed contracts.

4.4 Discussions on Optimal Contract in Scenario 2

The above discussions give an explicit solution to **Scenario 1**, while for **Scenario 2**, it is impossible to get the explicit solution. Assuming we have two discrete sets $\boldsymbol{C}$ and $\boldsymbol{\Pi}$, with countable values $|\boldsymbol{C}|$ and $|\boldsymbol{\Pi}|$, respectively, the computation of exhaustive searching is on the order of $(|\boldsymbol{C}||\boldsymbol{\Pi}|)^N$. Usually, the elements in sets $\boldsymbol{C}$ and $\boldsymbol{\Pi}$ are infinite, making the computation complexity uncountable.

5 Numerical Results

In this section, we conduct numerical analysis to evaluate the performance of the contracts generated by **Algorithm 1** in the proposed two-layer caching system considering limited resource constraint. Since the contracts designed for **Scenario 2** is conducted in the manner of exhaustive searching, here we only investigate the performance in **Scenario 1**.

We assume that the popularity θ_v of CPs follows the Zipf distribution, i.e,

$$\theta_v = \frac{1/v^\gamma}{\sum_{j=1}^{N} 1/j^\gamma}, \quad v = 1, \cdots, N, \tag{43}$$

where γ is a positive value and determines the distribution of CPs' popularity [33]. The parameter γ can be obtained by learning

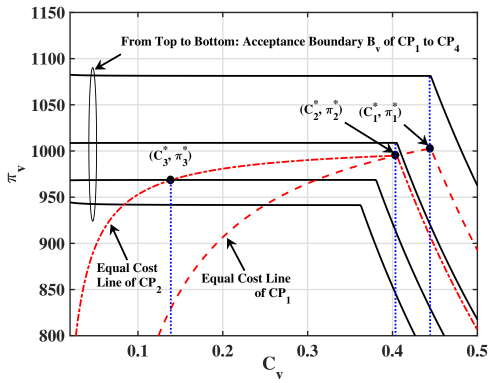

Fig. 5. An illustration of the optimal contract for each CP. Given $N = 4$ and $\gamma = 0.1$.

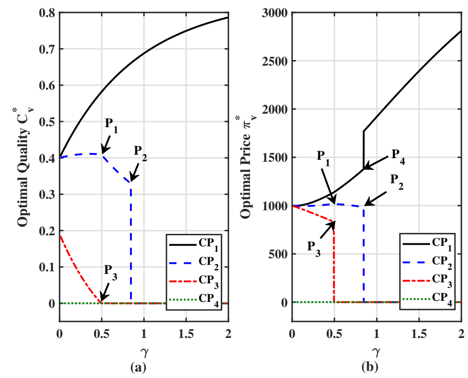

Fig. 6. Given $N = 4$. (a) Optimal quality designed for each CP versus γ. (b) Optimal price designed for each CP versus γ.

of the historical traffic by the NSP or through questionnaires conducted by a consulting firm. Note that the distribution of CPs' popularity can be any function other than Zipf.

5.1 Acceptance Boundary and the Optimal Contract

Given that there are $N = 4$ CPs in this network, and the popularity distribution parameter $\gamma = 0.1$, Fig. 5 plots the acceptance boundary $\mathbf{B}_v$ and illustrates the determination procedure of the optimal contract (C_v^*, π_v^*) for each CP. It is clear that the acceptance boundary of each CP is a piece-wise function of quality C_v. On the left side of the intersection point, the acceptance boundary is a straight line with a constant value, while on the right side of the intersection point, it is a curve inverse-proportional to C_v. It can be seen in Fig. 5 that CP who is the most popular, i.e., CP_1, has the highest acceptance boundary, while the least popular CP, i.e., CP_4, has the lowest boundary.

The optimal contracts designed for CPs are marked with black spots in Fig. 5. According to the contract determination algorithm, the optimal qualities C_v^* should be determined firstly. Here we assume $\gamma = 0.1$, CP_1, CP_2, CP_3, and CP_4 are all within the $\frac{\partial R_v}{\partial C_v} > 0$ region, they should be assigned with the optimal quality C_v°. However, it can be observed in Fig. 5 that only $\{C_1^*, C_2^*, C_3^*\}$ are involved, the NSP does not assign CP_4 with any resource due to the resource constraint. Also, we find that C_1^* and C_2^* are assigned with the optimal quality C_1° and C_2°, respectively. But C_3° is only assigned with the remaining resources. It is consistent with **Algorithm 1** that whether the NSP assigns resources to one CP depends on both the value of $\frac{\partial R_v}{\partial C_v}$ and the amount of resources left.

After determining the optimal quality $\{C_1^*, C_2^*, C_3^*\}$, the optimal price $\{\pi_1^*, \pi_2^*, \pi_3^*\}$ would be determined. It can be seen that π_3^* is assigned by π_3° to maximize the utility of the NSP. The equal cost line of CP_2 crossing (C_3^*, π_3^*) is plotted to assist in finding the optimal contract for CP_2, (C_2^*, π_2^*) can be found at the cross point of the equal cost line of CP_2 and the straight line of $C_v = C_2^*$. The optimal contract (C_1^*, π_1^*) is also determined by the same procedure.

5.2 Impact of γ on Optimal Quality and Price

In this subsection, we investigate the impact of the popularity parameter γ on the optimal contract. Same as subsection 5.1, we also assume $N = 4$.

In Fig. 6 (a), we change CPs' popularity distribution parameter γ from 0.01 to 2 to show how it affects the optimal quality C_v^*. It can be seen that only 3 CPs are involved in the proposed contract scheme. This phenomenon is due to the limited-resource constraint. The curve of the optimal quality assigned for CP_1 is smoothly increasing as γ increases. Since we determine the optimal quality C_1^* at first according to **Algorithm 1**, therefore there are enough resources satisfying the requirements of CP_1. However, it can be seen that the optimal quality C_3^* assigned for CP_3 decreases as γ increases. At point 3, the optimal quality C_3^* approaches to zero. After that point, CP_3 is out of the secondary market due to the reason that there is not adequate resources for CP_3. On the curve of C_2^*, there are two inflection points, i.e., point 1 and point 2. It can be noticed that before point 1, C_2^* increases as γ increases. While after point 1, C_2^* decreases and drops to zero at point 2. The reason is that after point 1, as the increase of C_1^*, there is not adequate resources left for CP_2. It will be allocated with the remaining resources after the assignment of CP_1. However, there is a sharp drop of C_2^* at point 2, this is because at that point $\frac{\partial R_2}{\partial C_2} = 0$. Thus, at and after point 2, the NSP will not assign CP_2 with resources and CP_2 will leave the secondary market as well. It can be concluded that when γ increases, i.e., the distinctions of CPs' popularity become significant, the NSP tends to allocate more resources to CPs with higher popularity in maximizing its own profits.

In Fig. 6 (b), we plot the corresponding optimal price π_v^* of CP $\mathcal{V}_v$. As γ increases, the optimal price curve of CP_3 decreases and the NSP assigns π_3^* with π_3° to maximize its own profits until point 3. After this point, CP_3 exits the secondary layer, and hence the corresponding price drops to zero. The curve of CP_2 is divided into three segments by two points, i.e., point 1 and point 2. As we have discussed in Fig. 6 (a), we know that before point 1, three CPs are involved, C_2^* is assigned with C_2°, and therefore π_2^* is determined by the equal cost line crossing (C_3^*, π_3^*) in the way demonstrated in Fig. 5. Between point 1 and point 2, CP_2 is assigned with the remaining resources left after the assignment of CP_1. In this case, π_2^* will be assigned with π_2° to maximize NSP's profit. After point 2, CP_2 leaves the secondary market, and hence the price π_2^* drops to zero. The curve of π_1^* is divided into two segments by point 4. What happens at point 2 and point 4 are the same that CP_2 leaves the secondary market. Thus, after point 4, π_1^* is assigned with π_1° to maximize the NSP's profit.

5.3 CPs' Costs Comparison between the benchmark and the Proposed Two-layer network

In this subsection, we make comparisons between the benchmark and the proposed two-layer network regarding CPs' costs. Also,

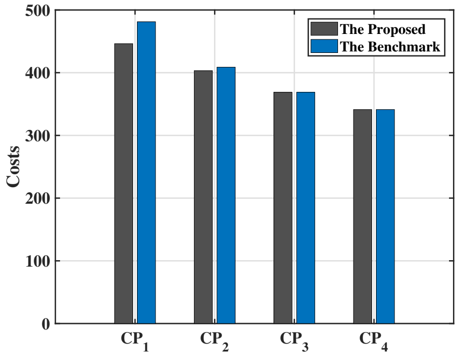

Fig. 7. Given $N = 4$. CPs' costs in the one-layer market and the proposed two-layer market.

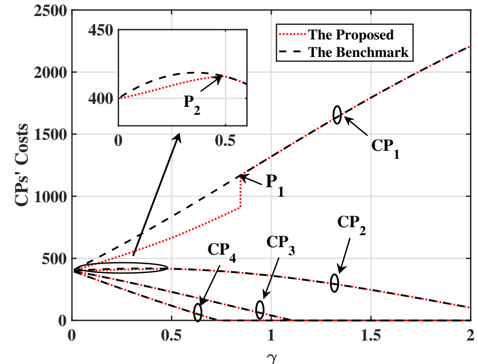

Fig. 8. Given $N = 4$. CPs' costs in the benchmark and the proposed two-layer networks.

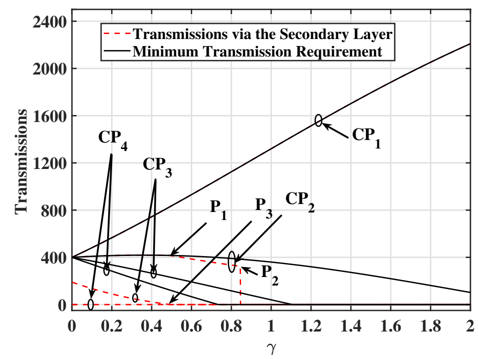

Fig. 9. Given $N = 4$, CPs' transmissions on the secondary layer and their minimum transmission requirements.

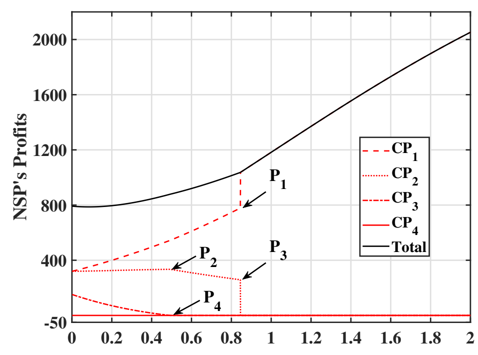

Fig. 10. NSP's profits on each CP and its total profits on the secondary layer.

the simulation setup is $N = 4$ and $\gamma = 0.1$.

Fig. 7 plots CPs' costs in the benchmark and the proposed two-layer network. It can be seen that costs of CP_1 and CP_2 in the proposed network are smaller than that in the benchmark. This is due to the reason that the optimal prices charged on CP_1 and CP_2 are below their acceptance boundary, respectively, which can be verified in Fig. 5. While the optimal price charged on CP_3 is on its acceptance boundary. The cost on the acceptance boundary equals to the reserve price, i.e., the cost of satisfying the minimum transmission requirement of the benchmark network. Thus Fig. 7 demonstrates that the costs of CP_3 are the same in both networks. Since CP_4 is not involved in the secondary layer. It certainly spends the same in both scenarios.

In Fig. 8, we vary CPs' popularity parameter γ from 0.01 to 2 to clarify the relationship between CP's costs in the proposed two-layer network and the benchmark. It can be seen in Fig. 8 that the costs of CP_3 and CP_4 are the same on both markets. As we have demonstrated in Fig. 5 that CP_3 is assigned with the contract on the acceptance boundary which equals to the reserve price. CP_4 does not participate into the secondary layer from the very beginning. It certainly costs the same on either network. Costs of CP_1 on the proposed two-layer network are smaller than that on the benchmark from the start point to point 1. As we have discussed in Fig. 6 (b), after point 1 (it is point 4 in Fig. 6 (b)), only CP_1 stays in the secondary layer, yet it will be assigned with the optimal price on the acceptance boundary. Therefore, after that point, they charge the same on CP_1 of the two networks. CP_2 costs less in the proposed network from the beginning until point 2. Point 2 in Fig. 8 corresponds to point 1 in Fig. 6 (b). This inflection point is induced by the fact that CP_3 exits the secondary market. CP_2 will be assigned with the contract on the acceptance boundary after point 2, and thus it costs the same in the two networks after point 2. It can be concluded that the proposed network can provide CPs with less or equal costs compared to the benchmark.

5.4 NSP's Gains

In Fig. 9, we vary CPs' popularity parameter γ from 0.01 to 2 to compare the transmissions on the secondary layer and the minimum transmission requirement defined in **Definition 2** of each CP. It can be seen in Fig. 9 that, by the proposed optimal contract, CP_1 shifts all its transmissions from the traditional layer to the secondary layer. When $\gamma \in [0, P_1]$, CP_2 transmits all the requirements on the secondary layer. While $\gamma \in [P_1, P_2]$, CP_2 transmits in a combined manner. However, after point P_2, CP_2 does not participate in the secondary layer any more, due to the reason that there is not enough resources left for CP_2 after that point. CP_3 transmits in a combined manner from the beginning until $\gamma = P_3$. After that point, CP_3 leaves the secondary layer, also due to the resource constraint. CP_4 is not involved in the secondary layer from the very beginning.

In Fig. 10, we vary CPs' popularity parameter γ from 0.01 to 2 to clarify the variation of the NSP's profits on each CP and its total profits on the secondary layer. It can be seen from Fig. 10 that 3 out of 4 CPs are involved in the secondary layer. The NSP gains positive profits on CP_1 to CP_3 until P_4. After that point, CP_3 is out of the secondary layer, because of the resource constraint. The resource constraint also affects the NSP's profits on CP_2, when $\gamma \in [P_2, P_3]$ where its profits decrease as γ increases. After P_1 or P_3, only CP_1 transmits on the secondary layer, and thus the NSP's total profits are equal to the profits on CP_1.

6 Conclusions

In this paper, we propose a contract-based trading scheme in the proposed two-layer caching network. The purpose of the NSP, who is in charge of the two layers, is to make extra profits and to alleviate pressures on back-haul channels, by offering contracts to different CPs. In specific, we formulate the utility function of the NSP and CPs based on the stochastic geometry. Considering the economical impact between two layers, the minimum transmission requirement, reserve price and limited resources are considered as constraints in designing the optimal contract. Also, information asymmetry environment is assumed in this network, where the NSP does not know the specific type of each CP. Then, some important properties of the constraints are analyzed to facilitate the contract determination process. Finally, an optimal contract determination algorithm is proposed, based on which the optimal coverage is determined firstly, and then the optimal prices are derived. Simulation results are provided to verify the effectiveness of the proposed incentive mechanism in the two-layer network on shifting CPs' transmissions from the traditional layer to the secondary layer. It can also help the NSP make extra profits by selling coverage to CPs.

Overall, this paper focuses on a theoretical analysis for a two-layer caching network, from the perspective of contract theory. The proposed scheme considers the economical impact of the traditional layer on the secondary layer. Considering such impact is more practical than our previous works which do not consider this point. In our future work, we will extend the proposed contract theory mechanism to more practical scenarios, such as considering the influence of users' behavior, multiple operators, and the lifetime of cached files.

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References

[1] Cisco. Cisco visual networking index: global mobile data traffic forecast update, 2016-2021 white paper. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.pdf

[2] E. Bastug, M. Bennis, and M. Debbah, "Living on the edge: The role of proactive caching in 5G wireless networks," *IEEE Communications Magazine*, vol. 52, no. 8, pp. 82–89, Aug. 2014.

[3] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.

[4] L. Lu, G. Y. Li, A. L. Swindlehurst, A. Ashikhmin, and R. Zhang, "An overview of massive MIMO: Benefits and challenges," *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 5, pp. 742–758, Oct. 2014.

[5] Z. Niu, Y. Wu, J. Gong, and Z. Yang, "Cell zooming for cost-efficient green cellular networks," *IEEE Communications Magazine*, vol. 48, no. 11, pp. 74–79, Nov. 2010.

[6] D. Liu, B. Chen, C. Yang, and A. F. Molisch, "Caching at the wireless edge: design aspects, challenges, and future directions," *IEEE Communications Magazine*, vol. 54, no. 9, pp. 22–28, Sept. 2016.

[7] G. Paschos, E. Bastug, I. Land, G. Caire, and M. Debbah, "Wireless caching: technical misconceptions and business barriers," *IEEE Communications Magazine*, vol. 54, no. 8, pp. 16–22, Aug. 2016.

[8] M. Dehghan, B. Jiang, A. Seetharam, T. He, T. Salonidis, J. Kurose, D. Towsley, and R. Sitaraman, "On the complexity of optimal request routing and content caching in heterogeneous cache networks," *IEEE/ACM Transactions on Networking*, vol. 25, no. 3, pp. 1635–1648, Jun. 2017.

[9] M. Tao, E. Chen, H. Zhou, and W. Yu, "Content-centric sparse multicast beamforming for cache-enabled cloud ran," *IEEE Transactions on Wireless Communications*, vol. 15, no. 9, pp. 6118–6131, Sept. 2016.

[10] K. Poularakis, G. Iosifidis, V. Sourlas, and L. Tassiulas, "Exploiting caching and multicast for 5g wireless networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 4, pp. 2995–3007, Apr. 2016.

[11] N. Golrezaei, K. Shanmugam, A. G. Dimakis, A. F. Molisch, and G. Caire, "Femtocaching: Wireless video content delivery through distributed caching helpers," in *IEEE International Conference on Computer Communications (INFOCOM), Orlando, FL*, Mar. 2012, pp. 1107–1115.

[12] H. Liu, Z. Chen, X. Tian, X. Wang, and M. Tao, "On content-centric wireless delivery networks," *IEEE Wireless Communications*, vol. 21, no. 6, pp. 118–125, Dec. 2014.

[13] K. Shanmugam, N. Golrezaei, A. Dimakis, A. Molisch, and G. Caire, "Femtocaching: Wireless content delivery through distributed caching helpers," *IEEE Transactions on Information Theory*, vol. 59, no. 12, pp. 8402–8413, Dec. 2013.

[14] N. Golrezaei, P. Mansourifard, A. F. Molisch, and A. G. Dimakis, "Base-station assisted device-to-device communications for high-throughput wireless video networks," *IEEE Transactions on Wireless Communications*, vol. 13, no. 7, pp. 3665–3676, Jul. 2014.

[15] K. Hamidouche, W. Saad, and M. Debbah, "Many-to-many matching games for proactive social-caching in wireless small cell networks," in *Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), Hammamet, Tunisia*, May 2014, pp. 569–574.

[16] J. Jiang, S. Zhang, B. Li, and B. Li, "Maximized cellular traffic offloading via device-to-device content sharing," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 1, pp. 82–91, Jan. 2016.

[17] M. Claeys, N. Bouten, D. D. Vleeschauwer, W. V. Leekwijck, S. Latr, and F. D. Turck, "Cooperative announcement-based caching for video-on-demand streaming," *IEEE Transactions on Network and Service Management*, vol. 13, no. 2, pp. 308–321, Jun. 2016.

[18] N. Kamiyama, Y. Nakano, and K. Shiomoto, "Cache replacement based on distance to origin servers," *IEEE Transactions on Network and Service Management*, vol. 13, no. 4, pp. 848–859, Dec. 2016.

[19] C. Fang, F. R. Yu, T. Huang, J. Liu, and Y. Liu, "A survey of energy-efficient caching in information-centric networking," *IEEE Communications Magazine*, vol. 52, no. 11, pp. 122–129, Nov. 2014.

[20] ——, "A survey of green information-centric networking: Research issues and challenges," *IEEE Communications Surveys Tutorials*, vol. 17, no. 3, pp. 1455–1472, third quarter 2015.

[21] X. Chen, L. Pu, L. Gao, W. Wu, and D. Wu, "Exploiting massive d2d collaboration for energy-efficient mobile edge computing," *IEEE Wireless Communications*, vol. 24, no. 4, pp. 64–71, Aug. 2017.

[22] J. Llorca, A. M. Tulino, M. Varvello, J. Esteban, and D. Perino, "Energy efficient dynamic content distribution," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 12, pp. 2826–2836, Dec. 2015.

[23] X. Chen, Q. Shi, L. Yang, and J. Xu, "Thriftyedge: Resource-efficient edge computing for intelligent iot applications," *IEEE Network*, vol. 32, no. 1, pp. 61–65, Jan. 2018.

[24] Y. Zhang and Z. Han, *Contract Theory for Wireless Networks*. Springer Press, 2017.

[25] Y. Zhang, L. Song, W. Saad, Z. Dawy, and Z. Han, "Contract-based incentive mechanisms for device-to-device communications in cellular networks," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 10, pp. 2144–2155, Oct. 2015.

[26] Y. Zhang, N. H. Tran, D. Niyato, and Z. Han, "Multi-dimensional payment plan in fog computing with moral hazard," in *IEEE International Conference on Communication Systems (ICCS), Shenzhen China*, Dec. 2016, pp. 1–6.

[27] Y. Zhang, M. Pan, L. Song, Z. Dawy, and Z. Han, "A survey of contract theory-based incentive mechanism design in wireless networks," *IEEE Wireless Communications*, vol. 24, no. 3, pp. 80–85, 2017.

[28] L. Gao, X. Wang, Y. Xu, and Q. Zhang, "Spectrum trading in cognitive radio networks: A contract-theoretic modeling approach," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 4, pp. 843–855, Apr. 2011.

[29] Y. Zhang, Y. Gu, M. Pan, Z. Dawy, L. Song, and Z. Han, "Financing contract with adverse selection and moral hazard for spectrum trading in cognitive radio networks," in *2015 IEEE China Summit and International Conference on Signal and Information Processing (ChinaSIP), Chengdu, China*, Jul. 2015, pp. 601–605.

[30] S. P. Sheng and M. Liu, "Profit incentive in trading nonexclusive access on a secondary spectrum market through contract design," *IEEE/ACM Transactions on Networking*, vol. 22, no. 4, pp. 1190–1203, Aug. 2014.

[31] K. Hamidouche, W. Saad, and M. Debbah, "Breaking the economic barrier of caching in cellular networks: Incentives and contracts," in *IEEE Global Communications Conference (GLOBECOM), Washington DC*, Dec. 2016.
[32] T. Liu, J. Li, F. Shu, M. Tao, W. Chen, and Z. Han, "Design of contract-based trading mechanism for a small-cell caching system," *IEEE Transactions on Wireless Communications*, vol. 16, no. 10, pp. 6602–6617, Oct. 2017.
[33] M. Cha, H. Kwak, P. Rodriguez, Y. Y. Ahn, and S. Moon, "I tube, you tube, everybody tubes: analyzing the world's largest user generated content video system," in *ACM SIGCOMM Conference on Internet Measurement, San Diego, CA*, Aug. 2007.
[34] J. Li, H. Chen, Y. Chen, Z. Lin, B. Vucetic, and L. Hanzo, "Pricing and resource allocation via game theory for a small-cell video caching system," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 8, pp. 2115–2129, Aug. 2016.
[35] P. Bolton and M. Dewatripont, *Contract Theory*. The MIT Press, 2005.

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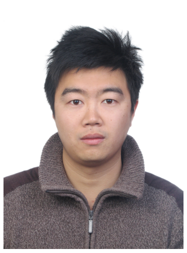

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