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Auction Design for Edge Computation Offloading in SDN-based Ultra Dense Networks

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Abstract—Relying on offloading computation tasks to the network edge, ultra dense networks (UDNs) are capable of providing delay-aware service to nearby users. Meanwhile, software defined networking (SDN) is deemed as an effective technology to ease the management of infrastructure plane and control plane in UDNs, which is termed as SDN-based ultra dense networks. Specifically, the centralized SDN controller is capable of managing the whole network globally. With the increasing demands for various applications as well as the limitation of computation, storage and communication resource, how to allocate spectrum resource appropriately is imperative. In this paper, we mainly show solicitude for spectrum sharing and edge computation offloading problems in SDN-based ultra dense networks, constituted of various macro base stations (MBSs), small-cell base stations (SBSs) and user equipments (UEs). To address this issue, we propose a second-price auction scheme for ensuring the fair bidding for spectrum rent, which enables the MBS edge cloud and SBS edge cloud to occupy the channel in cooperative and competitive modes. Moreover, the MBS edge cloud is termed as the buyer, and the SBS edge clouds are the sellers who sell the offloading resource to the MBS edge cloud. To be specific, the spectrum sharing and computation offloading scheme is executed in the SDN controller, and the controller is responsible for distributing spectrum allocation instructions to the infrastructure plane. Finally, experimental results validate the effectiveness of our proposed scheme in SDN-based ultra dense networks.

Index Terms—Software defined networking, ultra dense networks, computation offloading, edge computing, spectrum sharing.

1 Introduction

With the rapid growth of wireless communication demand [1], [2], the transmission rate and network capacity of traditional networks are facing unprecedented challenges. In addition, novel increased business scenarios in the next generation networks (5G) [3], [4], e.g. vehicular networking, augmented virtual reality, and industrial Internet of things [5], [6], propose a higher requirement for the delay, energy efficiency, and other performance. In order to cope with the increasingly severe challenges above, ultra dense networks (UDNs) [7] empower 5G tremendous access capability, composed of extensive macro base stations (MBSs) and small-cell base stations (SBSs). Additionally, edge computing [8] technology promises the potential to provide available computation service ability for countless devices. It can effectively shorten the data transmission distance between the user equipments (UEs) and the data center as well as avoid the network congestion. With the assistance of edge computing, UDNs are capable of providing computation service for UEs, which is implemented by the MBS edge cloud and SBS edge cloud. Considering the severe channel interference of computation offloading in UDNs [9], therefore, cooperative and incentive spectrum management plays a significant influence in supporting of computation offloading between MBS edge cloud and SBS edge cloud.

To achieve rapid configuration as well as effective management in ultra dense networks, software defined networking (SDN) has been considered as an efficient network architecture to promise the potential to realize flexible network control and management. Recently, the concept of SDN has been applied into UDNs, which is termed as SDN-based ultra dense networks [10]. In this case, the primary computation and control functions are decoupled from the distributed SBS edge cloud and MBS edge cloud. Specifically, the control function is integrated at the centralized SDN controller [11]. The SDN controller [12] is capable of collecting information from UEs and edge clouds, as well as perceive network state from a global perspective. There is a technical challenge for MBS edge cloud working in the unlicensed spectrum that can degrade service quality without appropriate cooperate channel interference management. In LTE networks, two main mechanisms are focusing on this issue: carrier-sensing adaptive transmission (CSAT) scheme and listen-before-talk (LBT) scheme. However, CSAT can not deal with the response to on-off cycling, and LBT is difficult to assign proper backoff time and transmission length. Therefore, it is an emergency to explore an effective spectrum management mechanism for the cooperation between MBS edge cloud and SBS edge cloud. As a result, according to the decision instruction of the SDN controller,

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the channel is allocated to the MBS edge cloud or SBS edge cloud for providing computation offloading service for multiple users.

With the assistance of SDN controller, spectrum management and computation offloading for the MBS edge cloud and SBS edge cloud can be effectively dealt with. Besides, we focus on the issue on how to achieve an efficient negotiation between the MBS edge cloud and the SBS edge cloud with competition mode and cooperation mode in this network architecture. [13] employed SDN and mobile edge computing technology to manage end-users computing demands in 5G networks. A non-cooperative game model among the end-users is formulated and the Nash Equilibrium is verified. However, they did not consider the scenario of MBS edge cloud and multiple edge clouds. Game theory has been applied into spectrum sharing recently. [14] determined the prices of femtocell and macrocell services and model it as a Stackelberg game. [15] provided the analysis of cooperative spectrum sharing between primary user and secondary user by contract theory. However, both references do not focus on the models in computing offloading scenario. To avoid the malicious bidding in the market and guarantee fair and efficient spectrum resource sharing, a second auction theory [16], [17] is employed to provide an appropriate allocation scheme for spectrum management in this paper. Specifically, the MBS edge cloud is denoted as the auctioneer (the buyer), and the SBS edge clouds are set as the channel owners (the sellers). In this paper, we only consider communication resource in computation offloading. Moreover, we analyze the SBS edge clouds' equilibrium strategies under the MBS edge cloud's offloading rate. The mainly contribution of our paper can be summarized as follows.

- We establish an SDN-based ultra dense networks framework for managing spectrum appropriately. With the assistance of the SDN controller, the global information about channel quality on MBS edge cloud, SBS edge clouds, and UEs can be obtained. Thus this framework is conducive to improving the effectiveness of spectrum management scheme for computation offloading.
- We design a second-price auction aided spectrum sharing scheme for computation offloading in this novel framework. Relying on this designed scheme, the SBS edge clouds provide computation offloading service with the MBS edge cloud in two modes, i.e., cooperative mode and competitive mode. Therefore, the channels and spectrums can be utilized appropriately to support computation offloading.
- We analyze the proposed auction scheme and present the optimal bidding strategies in different possible cases. The expected utility of the MBS edge cloud and SBS edge clouds are discussed in the experiment section. Moreover, the different values of discounting factor parameters are set for comparison. Numerical results prove the effectiveness of our designed scheme.

The rest of this paper is organized as follows: the next section gives the related work of computation offloading problem and auction theory. The novel scenario is presented in Section 3. In Section 4, the system model of auction theory in computation offloading is described in detail. SBS edge clouds' equilibrium bidding strategies are analyzed in Section 5. In Section 6, the MBS edge cloud's expected utility is discussed. Experimental results are presented in Section 7. In Section 8, the conclusion is given.

2 Related Work

Computation offloading has attracted the researchers' great attention with the advantage that it can significantly shorten transmission delay and energy consumption of devices. Aiming at the power consumption and task delay of each mobile device, [18] proposed to minimize the offload delay at the constraints of considering power constraints, and find the optimal task scheduling strategy through one-dimensional search algorithm. Under the background of mobile edge computing (MEC), the problem of joint task offloading and resource allocation in the single-user system [19] and multi-unit multi-user system [20] is studied. [21] proposed a heuristic offloading decision algorithm to maximize single-server MEC system utility. Nevertheless, the above references neglect the congestion of computing resources on the MEC server. [22], [23], [24], [25] considered partial computation offloading problem with game theory [26], swarm algorithm [27], [28], *etc*. And they all perform well in their simulation scenario, respectively. [29], [30] were trying to solve the trade-off between computation energy consumption and execution delay of offloading problem. In the previous research above, computation offloading problem was modeled for reducing delay as well as energy consumption. However, how to apply these schemes into the ultra dense networks scenario appropriately were not involved in the studies above. In addition, they did not consider the influence of spectrum between MBS edge clouds and SBS edge clouds.

Auction theory is one widely known market-based mechanisms to redistribute resources, which has been applied to wireless networks. [31] proposed multiple scenarios of wireless networks by game theory. Specifically, Gaoning He et al employed game theory for OFDM systems with incomplete information and Hanna Bogucka proposed a novel radio resource management mechanism by game theory in OFDMA-based cognitive radio. [32] proposed a model of the combinatorial auction to redistribute heterogeneous channel, meanwhile exploited SMASHER to solve design challenges, which contains two strategy-proof auction mechanisms. [33] focused on the virtual resource allocation problem with diverse QoS requirements. Owing to hidden information of network operators for the auctioneer, this paper introduced a shadow price to maximize the total welfare for the system. To deal with the traffic offloading problem in heterogeneous wireless networks, [34] adopted a second-price auction method to allocate finite wireless networks resource to multiple users for maximizing social welfare. [35] designed a second-price reverse auction method to appropriately allocate the spectrum between LTE and Wi-Fi. Consequently, the framework is capable of achieving close-to-optimal social welfare. [36] focused on the spectrum management to support traffic offloading between satellite communication system. The proposed traffic offloading

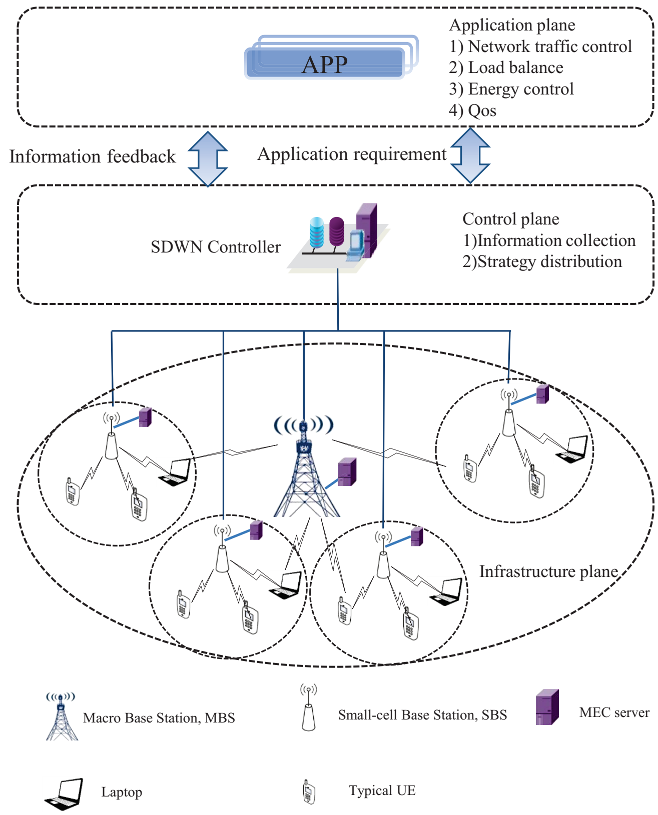

Fig. 1. Architecture of SDN-based Ultra dense networks

mechanism performed effectively in the simulation. Nevertheless, those aforementioned studies have not focused on the computation offloading scenario in SDN-based ultra dense networks. In this paper, we focus on the spectrum sharing and computation offloading in this novel scenario. Moreover, we adopt a second-price auction mechanism in a certain time to make the decision appropriately.

3 Architecture of SDN-based Ultra dense Networks

In traditional network architecture, control function and forwarding function are integrated at nearby network nodes. To overcome the high complexity of network management, researchers at Stanford University proposed the concept of SDN [37], [38], [39]. The idea of SDN separates control function from data forwarding layer, and the controller is capable of perceiving network topology, computing forward path, etc. Consequently, SDN greatly simplifies the infrastructure and enables network operators to manage and control the overall nodes more effectively. Recently, SDN technology is applied into wireless networks, which is termed as software-defined wireless networks (SDWN) [40]. SDWN consists of software defined cellular network [41], software defined mobile network [42], SDN-WiFi [43] and SDN-based ultra dense networks.

In general, SDWN architecture is divided into three planes: application plane, control plane, and infrastructure plane. Specifically, as shown in Fig. 1, in this paper we focus on introducing the application plane, control plane,

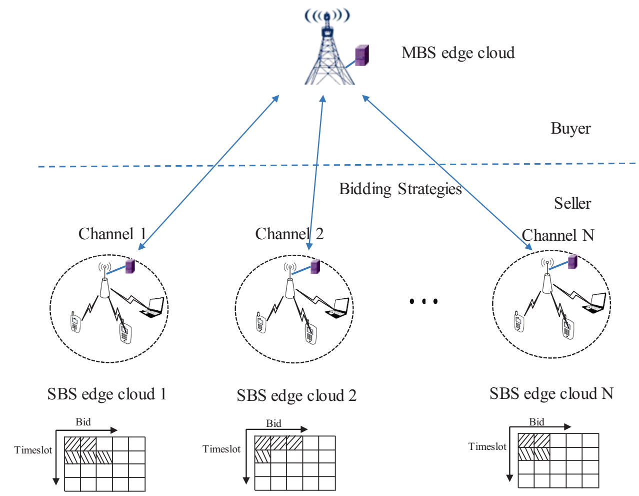

Fig. 2. Auction Model of Computation Offloading

infrastructure plane, and interfaces. Afterwards, we will introduce the architecture of SDN-based ultra dense networks as follows.

Application Plane. Service providers are capable of developing various applications on the application plane, as well as realizing the different requirements of users, e.g., network traffic control, load balance, and energy control, etc.

Control Plane. The function of the control plane includes flow table control, strategy distribution, and the acquisition of network-wide information. After receiving the requirement from the application plane, the control plane transforms them into instructions that can be executed by the infrastructure plane, as well as sends them to the infrastructure plane through the flow table. Control plane connects to infrastructure plane by southbound interface [44], [45], and connects to application plane [46].

Infrastructure Plane. The infrastructure plane is composed of the MBS, SBS and UE. Moreover, MBS and SBS connect with mobile edge computing server, termed as the MBS edge cloud and the SBS edge cloud, respectively. By contrast, the SBS edge cloud is closer to UEs and can provide faster computation service via wireless link. UEs include smart devices (e.g. laptops and cell phones) connected to different application scenarios in the wireless networks. In addition, communication model in edge computing is from the resource allocation model in wireless access networks [47].

4 System Model

In this SDN-based ultra dense networks scenario, we consider one MBS edge cloud and a set $\mathcal{N} = \{1, 2, \cdots, N\}$ of SBS edge cloud, which provides computation offloading service for users. The n-th SBS edge cloud exclusively occupied channel n, ($n \in \mathcal{N}$). The MBS edge cloud is capable of providing a larger service area including different SBS edge clouds. In this case, it can work in channel n, which causes interference to the corresponding channel of the SBS edge cloud. Furthermore, we consider the auction between the MBS edge cloud and SBS edge cloud in timeslot $[t_1, t_2]$.

TABLE 1
Description of Notations

Notation	Definiation
$\mathcal{N} = \{1, 2, \cdots, N\}$	Set of the SBS edge clouds
N	Number of the SBS edge clouds
N	Number of channels for the SBS edge clouds
$r_n(t)$	Transmission rate for SBS edge cloud n at time t
$f(r)$	Probability distribution function of transmission rate r
$F(r)$	Cumulative distribution function of transmission rate r
σ^{MBS}	Discounting factor of the MBS edge cloud in competition mode
σ^{SBS}	Discounting factor of SBS edge cloud in competition mode
$r_{MBS}(t)$	Transmission rate of the MBS edge cloud
R	Maximum data offloading rate of the MBS edge cloud
D_j	Available offloading rate in channel j
$r_{compensation}(t)$	Guaranteed offloading rate
$b_n(t)$	Bidding strategy of SBS edge cloud n
J	Minimum bidding strategy
$U^{MBS}(b, R, t)$	The expected utility of the MBS edge cloud
$U_n^{MBS}(b, R, t)$	The expected utility of SBS edge cloud n

Each auction is conducted after the last timeslot relying on the offloading rate in the last timeslot.

4.1 SBS Edge Clouds' Transmission Rate

In this paper, we consider a full-offloading mechanism in SBS edge clouds. Moreover, SBS edge cloud n occupies channel n, and the number of channels is equal to the number of the SBS edge clouds. Specifically, $r_n(t)$ represents the value of the transmission rate at time t, which is the private information of SBS edge cloud n. In addition, for the following timeslot, the transmission rate dynamically changes with time. The other $N-1$ SBS edge clouds and MBS edge cloud only obtain the probability distribution of r_n. To be specific, r_n is assumed as a continuous random variable which generate in the range $[r_{min}, r_{max}]$, and r_{min} is the minimal value of r_n and r_{max} is the maximal value of r_n. Additionally, it obeys a probability distribution function $f(r)$ as well as a cumulative distribution function $F(r)$. In this case, all r_n is assumed to follow the same distribution.

4.2 MBS Edge Cloud's Cooperative and Competitive Modes

In this system, the MBS edge cloud should provide its computation service by occupying one of the channel N. Each SBS edge cloud has only one channel for its computation offloading service, but it can not always be working which causes the consumption of channel. Besides, this scheme helps MBS edge cloud and SBS edge cloud cooperate with the channel, and makes the transmission channel be utilized in an appropriate way. Furthermore, the competitive mode motivates the SBS to cooperate because each edge cloud will earn more profit in this mode. Specifically, the computation offloading service is operated in the following modes:

Competition Mode. In this mode, the MBS edge cloud will choose a random channel with an equal probability. As a result, the MBS edge cloud will provide service in the channel at the case of SBS edge cloud n. Meanwhile, this will cause interference between the MBS edge cloud and SBS edge cloud n. We assume the original edge cloud in this channel will suffer more serious interference, which decreases the service quality of this edge cloud. In this case the transmission rate decreases by a certain discount. Because the discounting factors are not easy to be acquired in the real world, we denote $\sigma^{MBS} \in (0, 1)$ as the discounting factor of the MBS edge cloud and $\sigma^{SBS} \in (0, 1)$ as the discounting factor of the SBS edge cloud, respectively. In this mode, the computational complexity is *O(N)*, and N is the maximal number of SBS edge clouds.

Cooperation Mode. In this mode, the MBS edge cloud will achieve the agreement with SBS edge cloud n, the transmission channel n will be occupied by the MBS edge cloud and SBS edge cloud n. Specifically, there is no interference in channel n and the transmission rate of the MBS edge cloud is set as r_{MBS}. As a compensation, the MBS edge cloud will serve the UEs of the SBS edge cloud in a timeslot with the guaranteed offloading rate $r_{compensation}(t) \in [0, r_{MBS}]$. In addition, the other $N-1$ SBS edge clouds are not interfered by this channel occupied by the MBS edge cloud. In this mode, the computational complexity is *O(1)*, the MBS edge cloud will choose the SBS edge cloud with agreement. In the case of two modes, edge clouds prefer to choose cooperation mode when the channel is available. Nevertheless, when the channel is occupied, the competition mode is a reasonable way to assist edge computing.

4.3 Second-Price Auction Design

In the real world, different SBS edge clouds belong to different operators, and it is difficult to coordinate with each other. From the system model, the SDN controller has the ability to control the spectrum allocated to different SBS edge clouds. This can make it possible to complete the spectrum sharing in this architecture. The rules of the second price auction are basically the same as the traditional bidding. The only difference is that the price paid by the winner is no longer his bid, but the second highest bid, so it is also termed as the 'sub-highest price bidding method'. [48] gave a comprehensive research of second-price forward auction, which characterized bidding strategies for general payoff functions. [49] researched auction bidding strategies in the WTO system. Nevertheless, both references only consider two bidders and not apply to the scenario with multiple bidders.

As shown in Fig. 2, a second-price auction mechanism is designed, which the MBS edge cloud is the buyer and the SBS edge clouds are denoted as the sellers. Each SBS edge cloud owns only one channel and tries to sell it. In addition, the bidding price is changing with different timeslots, and we assume that in a timeslot the bidding price doesn't change. When the SBS edge clouds are interested in the auction, they send their intentional bids to the controller. Afterwards, the controller determines the lowest price of the SBS edge cloud with the auction rule, and deliver this information to the MBS edge cloud and the SBS edge clouds. With the assistance of the controller, two kinds of edge clouds need not communicate with each other directly. Moreover, we consider this auction in a timeslot and it can be termed as a differential game problem. In this case, we assume that the MBS edge cloud cannot occupy more than one channel simultaneously, therefore the MBS edge cloud is only interested in the winning seller of the SBS edge cloud. The MBS edge cloud will provide the offloading rate $r_{compensation}(t) \in [0, r_{MBS}]$ as the compensation.

The auction operation includes two stages: In the first stage of the auction, the MBS edge cloud announces its maximum data offloading rate R, which serves the winning the SBS edge cloud's users. In addition, in the second stage of the auction, after obtaining the data offloading rate R, SBS edge cloud n submits a bid $b_n(t) \in [0, R] \cup \emptyset$. Meanwhile, $b_n(t) \in [0, R]$ represents the data offloading rate that SBS edge cloud n requests the MBS edge cloud to serve SBS edge cloud n's users at time t. In addition, $b_n(t) = \emptyset$ indicates that at time t SBS edge cloud n does not provide sell service.

4.4 Auction Outcomes

In the following we will discuss the outcomes of auction for different values of b and R. Then the minimum bid $\mathcal{J}$ is defined as the following equation $\mathcal{J} = \{j \in \mathcal{N} : j = argmin_{n\in\mathcal{N}} \int_{t_1}^{t_2} b_n(t)\, dt\}$ and it has the following three possible outcomes:

(1) $|\mathcal{J}| = 1$. In this case, SBS edge cloud j is the winner and channel j is sold to the MBS edge cloud. The MBS edge cloud works in the cooperation mode. Then according to the principle of second-price auction theory, the transmission rate of the MBS edge cloud served SBS edge cloud j is $r_{compensation} = min\{R, \int_{t_1}^{t_2} b_1(t)\, dt, \cdots, \int_{t_1}^{t_2} b_{j-1}(t)\, dt, \int_{t_1}^{t_2} b_{j+1}(t)\, dt, \cdots, \int_{t_1}^{t_2} b_N(t)\, dt\}$. Specifically, allocated transmission rate $r_{compensation}$ is larger than the minimum SBS edge cloud's bid.

(2) $|\mathcal{J}| \geq 2$. In this case, the MBS edge cloud works in the cooperation mode and it will choose a channel for minimum bid $\mathcal{J}$ with possibility $\frac{D_j}{\Sigma_{i=1}^{|\mathcal{J}|} D_i}$, where D_j is the available offloading rate in channel j. In the real scenario, the offloading rate plays an important role in the chosen possibility. The MBS edge cloud prefers to choose a channel with a higher service quality. Therefore, we define the chosen possibility with different values according to their offloading rates. The more offloading rate can be provided, the higher the service quality will be, and the larger possibility the channel will be chosen. To be specific, the MBS edge cloud serves SBS edge cloud j's users with the data offloading rate $r_{compensation} = min_{n\in\mathcal{N}} \int_{t_1}^{t_2} b_n(t)\, dt$. Allocated transmission rate $r_{compensation}$ equals the minimum SBS edge cloud's bid.

(3) $|\mathcal{J}| = 0$. In this case, there is no SBS edge cloud is willing to sell the channel to the MBS edge cloud, the MBS edge cloud chooses the competition mode and it will occupy a random channel with probability $\frac{1}{K}$. Specifically, the chosen channel will be shared by both two providers.

Based on the above outcomes of three different cases, the $r_{compensation}$ can be given as

$$r_{compensation}(b, R, t) = \begin{cases} A, & if\ |\mathcal{J}| = 1, j = \min\limits_{n\in\mathcal{N}} \int_{t_1}^{t_2} b_n(t)dt, \\ \min\left\{R, \min\limits_{n\in\mathcal{N}} \int_{t_1}^{t_2} b_n(t)dt\right\}, & if\ |\mathcal{J}| \geq 2, \\ 0, & if\ |\mathcal{J}| = 0, \end{cases} \tag{1}$$

where A denotes $\min\{R, \min\limits_{n\in\mathcal{N}\setminus\{j\}} \int_{t_1}^{t_2} b_n(t)dt\}$. The utility of the MBS edge cloud obtained from offloading is defined as

$$U^{MBS}(b, R, t) = \begin{cases} R - r_{compensation}(b, R, t), & if|\mathcal{J}| \geq 1, \\ \sigma^{MBS} R, & if|\mathcal{J}| = 0, \end{cases} \tag{2}$$

where if $|\mathcal{J}| \geq 1$, the MBS edge cloud works in the cooperation mode and its utility is denoted as $R - r_{compensation}(b, R, t)$. In addition, if $|\mathcal{J}| = 0$, the MBS edge cloud works in the competition mode, and then the utility is influenced by the interference of channel and it can be denoted as $\sigma^{MBS} R$.

Then relying on the analysis above, the expected utility of SBS edge cloud n can be formulated as

$$U_n^{SBS}(b, R, t) = \begin{cases} \int_{t_1}^{t_2} r_n(t)dt, & if\ \int_{t_1}^{t_2} b_n(t)dt > \min\limits_{j\in\mathcal{N}} \int_{t_1}^{t_2} b_j(t)dt, \\ B, & if\ \int_{t_1}^{t_2} b_n(t)dt = \min\limits_{j\in\mathcal{N}} \int_{t_1}^{t_2} b_j(t)dt, \\ C, & if\ \min\limits_{j\in\mathcal{N}} \int_{t_1}^{t_2} b_j(t)dt = \emptyset, \end{cases} \tag{3}$$

where B represents $\frac{D_j}{\Sigma_{i=1}^{|\mathcal{J}|} D_i} r_{compensation}(b, R, t) + (1 - \frac{D_j}{\Sigma_{i=1}^{|\mathcal{J}|} D_i}) \int_{t_1}^{t_2} r_n(t)dt$ and C denotes $\frac{1}{N}\sigma^{SBS} \int_{t_1}^{t_2} r_n(t)dt + (1 - \frac{1}{N}) \int_{t_1}^{t_2} r_n(t)dt$. In the case of $b_n > min_{j\in\mathcal{N}} \int_{t_1}^{t_2} b_j(t)\, dt$, the MBS edge cloud occupies the other channel except channel n and SBS edge cloud n can provide its users with original transmission rate $\int_{t_1}^{t_2} r_n(t)\, dt$. In the case of $b_n = min_{j\in\mathcal{N}} \int_{t_1}^{t_2} b_j(t)\, dt$, the MBS edge cloud occupies channel n in the cooperation mode. Therefore, the SBS edge cloud's users can obtain the transmission rate $\frac{D_j}{\Sigma_{i=1}^{|\mathcal{J}|} D_i} r_{compensation}(b, R, t) + (1 - \frac{D_j}{\Sigma_{i=1}^{|\mathcal{J}|} D_i}) \int_{t_1}^{t_2} r_n(t)\, dt$. In the case of $b_n = min_{j\in\mathcal{N}} \int_{t_1}^{t_2} b_j(t)\, dt = \emptyset$, there is no SBS edge cloud is willing to sell its channel and the MBS edge cloud will chose a random channel in competition mode. As a result, the transmission rate of computation offloading service is $\frac{1}{N}\sigma^{SBS} \int_{t_1}^{t_2} r_n(t)\, dt + (1 - \frac{1}{N}) \int_{t_1}^{t_2} r_n(t)\, dt$.

5 SBSs' Equilibrium Bidding Strategies

5.1 Definition of the Symmetric Bayesian Nash Equilibrium

Assume the maximum data offloading rate R of the MBS edge cloud in Stage I is given, and the SBS edge clouds' equilibrium bidding strategies will be analyzed and discussed. In the following subsections, we analyze the SBS edge clouds' equilibrium bidding strategies by taking into account different intervals of R.

The definition of the symmetric bayesian nash equilibrium (SBNE) is first given in the following Definition 1.

Definition 1. *Given data offloading rate of the MBS edge cloud, a bidding strategy* $b^*(r_n(t), R, t)$, $r_n(t) \in [r_{min}, r_{max}], t \in [t_1, t_2]$ *constitutes the SBNE if* $s_n \in [0, R] \cup \emptyset$, $\forall r_n(t) \in [r_{min}, r_{max}]$ *at time t, it holds that:*

$$\begin{aligned}&E_{r_{-n}}\{\mathrm{U}_n^{SBS}(b*(r_1(t),R,t),\cdots,b*(r_{n-1}(t),R,t),\\&b*(r_n(t),R,t),b*(r_{n+1}(t),R,t),\cdots,b*(r_N(t),R,t)\\&|r_n(\mathrm{t}))\}\\&\geq E_{r_{-n}}\{\mathrm{U}_n^{SBS}(b*(r_1(t),R,t),\cdots,b*(r_{n-1}(t),R,t),\\&s_n,b*(r_{n+1}(t),R,t),\cdots,b*(r_N(t),R,t)|r_n(\mathrm{t}))\}.\end{aligned} \tag{4}$$

Inequality (4) shows the SBNE of the SBS edge clouds, and all the SBS edge clouds adopt the identical bidding strategy $b^*(r_n(t), R, t)$ owing to the symmetric equilibrium. The left side of (4) represents the expected utility of SBS edge cloud n. Moreover, all the other SBS edge clouds' types are unknown to SBS edge cloud n. This inequality implies that SBS edge cloud n is not capable of obtaining a better utility when changing its strategy from $b^*(r_n(t), R, t)$ to $\forall s_n \in [0, R] \cup \emptyset$.

In the following, we will analyze the symmetric bayesian nash equilibrium for bidding strategies when offloading rate R in different intervals. The intervals are constituted of $[0, \frac{N-1+\sigma^{SBS}}{N} r_{min}]$, $(\frac{N-1+\sigma^{SBS}}{N} r_{min}, r_{min})$, $[r_{min}, r_{max})$, $[r_{max}, +\infty)$. First, we will introduce the case in $R \in [r_{min}, r_{max})$, and a detailed proof will be described. Similar to this case, the proof in other cases will be presented in general.

5.2 Equilibrium for $R \in [r_{min}, r_{max})$

First of all, we consider the most complex equilibrium analysis for the SBS edge clouds' equilibrium bidding strategies in the case of $R \in (r_{min}, r_{max}]$. To be specific, other cases are capable of being discussed in the same method. The following Lemma 1 is introduced to help analyze the SBS edge clouds' equilibrium bidding strategies.

Lemma 1. *There exists at least one solution* $r(t)$ *in the range* $(R, r_{max}]$ *meeting the following equation:*

$$\begin{aligned}&\Sigma_{n=1}^{N} C_{N-1}^{n}\left(\int_{t_1}^{t_2}\int_{R}^{r(t)} f\left(r\left(t\right)\right) d\left(r(t)\right) dt\right)^{n}\left(\int_{t_1}^{t_2}\int_{r(t)}^{\infty}\right.\\&\left.f(r(t))d(r(t))dt\right)^{N-1-n}\frac{\int_{t_1}^{t_2}[R-r(t)]dt}{n+1}+\left(\int_{t_1}^{t_2}\int_{r(t)}^{\infty}\right.\\&\left.f(r(t))d(r(t))dt\right)^{N-1}\left(R-\frac{N-1+\sigma^{SBS}}{N}r(t)\right)=0.\end{aligned} \tag{5}$$

Specifically, we denote $F(r(t))$ as the CDF of random variable $r_n(t)$ at time t. Furthermore, the solutions $r_n(t)$ in $(R, r_{max}]$ are denoted as $\tilde{r}_1(R,t), \tilde{r}_2(R,t), \cdots, \tilde{r}_K(R,t)$, where $K = \{1, 2, \cdots, K_{max}\}$ represents the number of solutions and K_{max} is the maximal number of solutions. To be specific, the proof of Lemma 1 is provided in the following.

Proof. In the following we will give the proof that there is at least one solution $r(t)$ satisfy (5). First, the function of left hand side of equation is defined as $\mathscr{X}(r(t))$, and then we can obtain that

$$\begin{aligned}&\mathscr{X}(r(t))\\&=\Sigma_{n=1}^{N} C_{N-1}^{n}\Big(\int_{t_1}^{t_2}[F(r(t))-F(R)]dt\Big)^{n}\Big(\int_{t_1}^{t_2}[1-F(r(t))]\\&dt\Big)^{N-1-n}\frac{\int_{t_1}^{t_2}[R-r(t)]dt}{n+1}+\Big(\int_{t_1}^{t_2}[1-F(r(t))]dt\Big)^{N-1}\Big(\int_{t_1}^{t_2}\\&\left[R-\frac{N-1+\sigma^{SBS}}{N}r(t)\right]dt\Big),\end{aligned} \tag{6}$$

where function $\mathscr{X}(r(t))$ is continuous for $r_n(t)$ in $(R, r_{max}]$. Then we can obtain that

$$\begin{aligned}&\mathscr{X}(R)\\&=\Big(\int_{t_1}^{t_2}[1-F(R)]dt\Big)^{N-1}\Big(\int_{t_1}^{t_2}\Big[R-\frac{N-1+\sigma^{SBS}}{N}R\Big]dt\Big)\\&=\Big(\int_{t_1}^{t_2}[1-F(R)]\,dt\Big)^{N-1}\Big(\int_{t_1}^{t_2}\Big[R-\frac{1-\sigma^{SBS}}{N}R\Big]\,dt\Big).\end{aligned} \tag{7}$$

And since $F(r_{max}) = 1$, we can obtain that

$$\begin{aligned}&\mathscr{X}(r_{max})\\&=\Sigma_{n=1}^{N} C_{N-1}^{n}\Big(\int_{t_1}^{t_2}[F(r_{max})-F(R)]dt\Big)^{n}\Big(\int_{t_1}^{t_2}[1-F(r_{max})]\\&dt\Big)^{N-1-n}\frac{\int_{t_1}^{t_2}[R-r_{max}]dt}{n+1}+\Big(\int_{t_1}^{t_2}[1-F(r_{max})]dt\Big)^{N-1}\\&\Big(\int_{t_1}^{t_2}\Big[R-\frac{N-1+\sigma^{SBS}}{N}r_{max}\Big]dt\Big)\\&=\Big(\int_{t_1}^{t_2}[1-F(r_{max})]dt\Big)^{N-1}\int_{t_1}^{t_2}\frac{R-r_{max}}{N}dt.\end{aligned} \tag{8}$$

According to the property of cumulative distribution function, we have $F(R) \leq 1$. Then we will give the proof of $F(R)$ is not equal to 1.

Assumed that $F(R) = 1$, and since $R \in [r_{min}, r_{max})$, there can be found a ζ definitely, which holds $R + \zeta \in [r_{min}, r_{max}]$. Moreover, we have $F(R + \zeta) \leq 1$. Because $F(R) = 1$, $F(R + \zeta)$ only is equal to 1.

In conclusion, $F(R + \zeta) = F(R) = 1$. Since $F(r)$ is a cumulative distribution function, then $F(R+\zeta)-F(R) = 0$ contracts with the property of this function. Ultimately, we can obtain that $F(R) < 1$.

Since $F(R) \leq 1$ and $R \in [r_{min}, r_{max})$, we can conclude that $\mathscr{X}(r) > 0$ and $\mathscr{X}(r_{max}) < 0$. Relying on the intermediate value theorem, there is at least one solution $r(t)$ in $(R, r_{max}]$ satisfying (5). This completes the proof.

Relying on Lemma 1, the SBS edge clouds' equilibrium bidding strategies can be provided in Theorem 1.

Theorem 1. *Consider that there is a* $\tilde{r}_x(R,t)$ *submitted to* $\{\tilde{r}_1(R,t), \tilde{r}_2(R,t)\}, \cdots, \tilde{r}_K(R,t)$, *then we can obtain the fol-*

lowing bidding strategies $b^*(r_n(t),R,t)$ constitute the SBNE for SBS edge cloud n.

$$b^*(r_n(t),R,t) = \begin{cases} any\ value \in [0, r_{min}], & r_n(t) = r_{min}; \\ r_n(t), & r_n(t) \in (r_{min}, R]; \\ R, & r_n(t) \in (R, \tilde{r}_x(R,t)); \\ R\ or\ \emptyset, & r_n(t) = \tilde{r}_x(R,t); \\ \emptyset, & r_n(t) \in (\tilde{r}_x(R,t), r_{max}]. \end{cases} \quad (9)$$

From (9), in the case of $r_n(t) = r_{min}$, the optimal bidding strategy for SBS edge cloud n is to choose any value in the range $[0, r_{min}]$. When $r_n(t) \in (r_{min}, R]$, $b^*(r_n(t),R,t)$ should be $r_n(t)$. In addition, when $r_n(t) \in (R, \tilde{r}_x(R,t))$, the best strategy for SBS edge cloud n is R. When $r_n(t) = \tilde{r}_x(R,t)$, it may be $R\ or\ \emptyset$. Ultimately, when $r_n(t) \in (\tilde{r}_x(R,t), r_{max}]$, the optimal bidding strategy for SBS edge cloud n should be $\emptyset$.

In conclusion, when the other SBS edge clouds choose their strategies in (9), the optimal strategy for SBS edge cloud n is to adopt $b^*(r_n(t),R,t)$ in (9). To be specific, the proof of Theorem 1 will be given in the following.

Proof. In the following we will give the proof that the bidding strategies $b^*(r_n(t),R,t)$ constitute the SBNE for SBS edge cloud n. For SBS edge cloud n, supposed that all the other SBS edge clouds choose strategy $b^*(r_n(t),R,t)$, and then the following proof will give the maximum utility of SBS edge cloud n, which consists of four cases.

Case I $r_n(t) \in [r_{min}, R]$. Supposed that when time is t, the data offloading rate at SBS edge cloud n satisfies $r_n(t) \in [r_{min}, R]$, then we can obtain the following two situations.

(1) $b_{min}^{-n} \in [0, R]$. In this case, the MBS edge cloud can always find a SBS edge cloud to cooperate with offloading data. If $b_{min}^{-n} < r_n(t)$, then the expectation utility of SBS edge cloud n is $\int_{t_1}^{t_2} r_n(t)dt$. Moreover, when $b_{min}^{-n} = r_n(t)$, the expectation utility of SBS edge cloud n is $\omega b_{min}^{-n} + (1-\omega)\int_{t_1}^{t_2} r_n(t)dt = \int_{t_1}^{t_2} r_n(t)dt$. Hence, bidding $\int_{t_1}^{t_2} r_n(t)dt$ is the optimal strategy of SBS edge cloud n.

To be specific, when $r_n(t) = r_{min}$, we can obtain that $b_{min}^{-n} > r_{min}$ with possibility one. Therefore, for SBS edge cloud n, bidding any value in $[0, r_{min})$ has the equivalent utility with bidding r_{min}. In other words, bidding any value in $[0, r_{min}]$ is the optimal strategy of SBS edge cloud n.

(2) $b_{min}^{-n} = \emptyset$. In this case, If SBS edge cloud n bids, its utility will be $\frac{N-1+\sigma^{SBS}}{N}\int_{t_1}^{t_2} r_n(t)dt$. Since $\frac{N-1+\sigma^{SBS}}{N}\int_{t_1}^{t_2} r_n(t)dt < \int_{t_1}^{t_2} r_n(t)dt$, bidding $r_n(t)$ is one of the optimal strategy of SBS edge cloud n. In addition, when $r_n(t) = r_{min}$, bidding any value in $[0, r_{min}]$ is the optimal strategy of SBS edge cloud n.

As a result, when the other SBS edge clouds choose their strategies in (9), the optimal strategy for SBS edge cloud n is to adopt $b^*(r_n(t),R,t)$ in (9). To be specific, when $r_n(t) = r_{min}$, the optimal bidding price for SBS edge cloud n is any value in the range $[0, r_{min}]$. In addition, in the case of $r_n(t) \in (r_{min}, R]$, the optimal bidding price should be the value of $r_n(t)$.

Case II $r_n(t) \in [R, \tilde{r}_x(R,t)]$. We assume that the data offloading rate at SBS edge cloud n satisfies $r_n(t) \in [R, \tilde{r}_x(R,t)]$. To be specific, we will analyze this case with the following two situations.

(1) Comparison between R and $\emptyset$. When bid R, the utility of SBS edge cloud n can be obtained as follows.

$$\begin{aligned} &U_n^{SBS}(b_n = R, R, t) \\ &= \int_{t_1}^{t_2} (1-(1-F(R))^{N-1}) r_n(t)dt + \int_{t_1}^{t_2} (1-F(\tilde{r}_x(R,t)) \\ &)^{N-1} R dt + \Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n} (F(\tilde{r}_x(R,t)) - F(R))^n (1- \\ &F(\tilde{r}_x(R,t)))^{N-1-n} \frac{R + n r_n(t)}{n+1} dt. \end{aligned} \quad (10)$$

When bid $\emptyset$, the utility of SBS edge cloud n can be obtained as follow

$$\begin{aligned} &U_n^{SBS}(b_n = \emptyset, R, t) \\ &= \int_{t_1}^{t_2} (1-(1-F(R))^{N-1}) r_n(t)dt + \int_{t_1}^{t_2} (1-F(\tilde{r}_x(R,t)) \\ &)^{N-1} \frac{N-1+\sigma^{SBS}}{N} r_n(t)dt + \Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n} (F(\tilde{r}_x(R,t)) \\ &- F(R))^n (1-F(\tilde{r}_x(R,t)))^{N-1-n} r_n(t)dt. \end{aligned} \quad (11)$$

Then we can conclude that

$$\begin{aligned} &U_n^{SBS}(b_n = R, R, t) - U_n^{SBS}(b_n = \emptyset, R, t) \\ &= \int_{t_1}^{t_2} (1-F(\tilde{r}_x(R,t)))^{N-1} \left(R - \frac{N-1+\sigma^{SBS}}{N} r_n(t) \right) dt \\ &+ \Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n} \Bigg(F(\tilde{r}_x(R,t)) - F(R))^n (1-F(\tilde{r}_x(R,t)) \\ &\Bigg)^{N-1-n} \frac{R - r_n(t)}{n+1} dt. \end{aligned} \quad (12)$$

It is simple to realize that $U_n^{SBS}(b_n = R, R, t) - U_n^{SBS}(b_n = \emptyset, R, t)$ is a decreasing function and it is larger than 0. Hence, choose to bid R can obtain a higher utility than biding $\emptyset$.

(2) Comparison between R and any value belongs to $[0, R)$. Assume that there is a value $\xi \in [0, R)$, we will analyze different cases, which are $b_{min}^{-n} \in (\xi, R)$ and $b_{min}^{-n} = R$. The concreted description will be presented in the following.

- $b_{min}^{-n} \in (\xi, R)$. If SBS edge cloud n choose to bid R, the utility is $\int_{t_1}^{t_2} r_n(t)dt$. Moreover, if SBS edge cloud n choose to bid $temp\_a$, the utility is $\int_{t_1}^{t_2} b_{min}^{-n} dt$. Since $b_{min}^{-n} < R \le r_n(t)$, the strategy to bid R is the optimal choice.
- $b_{min}^{-n} = R$. If SBS edge cloud n choose to bid R, the utility is belonged to $(R, r_n(t))$. Furthermore, if SBS edge cloud n choose to bid $temp\_a$, the utility is belonged to R.
- $b_{min}^{-n} = \xi$. If SBS edge cloud n choose to bid R, the utility is $\int_{t_1}^{t_2} r_n(t)dt$. Moreover, if SBS edge cloud n choose to bid $temp\_a$, the utility is $\int_{t_1}^{t_2} b_{min}^{-n} dt$. Since $b_{min}^{-n} < R \le r_n(t)$, the strategy to bid R is the optimal choice.

Therefore, when the other SBS edge clouds choose their strategies in (9), the optimal strategy for SBS edge cloud n is to adopt $b^*(r_n(t),R,t)$ in (9). Specifically, when $r_n(t) \in (R, \tilde{r}_x(R,t))$, the optimal bidding price for SBS edge cloud

n should be the value of R. In the following cases, we will introduce the case when $r_n(t) = \tilde{r}_x(R,t)$, and the analysis is as same as **Case II**, the detailed proof will be negelected.

Case III $r_n(t) = \tilde{r}_x(R,t)$. Similar like the analysis in **Case II**, we can obtain that bidding R has the same utility with bidding $\emptyset$. Consequently, when the other SBS edge clouds choose their strategies in (9), the optimal strategy for SBS edge cloud n is to adopt $b^*(r_n(t), R, t)$ in (9). To be specific, when $r_n(t) = \tilde{r}_x(R,t)$, the optimal bidding price for SBS edge cloud n may be the value of R or not participating in this bidding.

Case IV $r_n(t) \in [\tilde{r}_x(R,t), r_{max}]$. Similar like the analysis in **Case II**, we will consider the two situations when bid R and bid $\emptyset$. We assume that the data offloading rate at SBS edge cloud n satisfies $r_n(t) \in [\tilde{r}_x(R,t), r_{max}]$. To be specific, we will analyze this case with the following situation.

Comparison between R and $\emptyset$. When bid R, the utility of SBS edge cloud n can be obtained as follows.

$$\begin{aligned}
&U_n^{SBS}(b_n = R, R, t) \\
&= \int_{t_1}^{t_2} \left(1 - \left(\int_{\tilde{r}_x(R,t)}^{\infty} f(r_n(t))d(r_n(t))\right)^{N-1}\right) r_n(t)dt + \\
&\int_{t_1}^{t_2} \left(\int_{r_{max}}^{\infty} f(r_n(t))d(r_n(t))\right)^{N-1} Rdt + \Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n} \\
&\left(\int_{\tilde{r}_x(R,t)}^{r_{max}} f(r_n(t))d(r_n(t))\right)^{n} \left(\int_{r_{max}}^{\infty} f(r_n(t))d(r_n(t))\right)^{N-1-n} \\
&\frac{R + nr_n(t)}{n+1} dt \\
&= \int_{t_1}^{t_2} (1 - (1 - F(\tilde{r}_x(R,t)))^{N-1}) r_n(t)dt + \int_{t_1}^{t_2} (1- \\
&F(r_{max}))^{N-1} Rdt + \Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n} (F(r_{max}) - F(\tilde{r}_x(R,t)))^{n} \\
&(1 - F(r_{max})^{N-1-n} \frac{R + nr_n(t)}{n+1} dt.
\end{aligned} \tag{13}$$

When bid $\emptyset$, the utility of SBS edge cloud n can be obtained as follows.

$$\begin{aligned}
&U_n^{SBS}(b_n = \emptyset, R, t) \\
&= \int_{t_1}^{t_2} \left(1 - \left(\int_{\tilde{r}_x(R,t)}^{\infty} f(r_n(t))d(r_n(t))\right)^{N-1}\right) r_n(t)dt + \\
&\int_{t_1}^{t_2} \left(\int_{r_{max}}^{\infty} f(r_n(t))d(r_n(t))\right)^{N-1} \frac{N-1+\sigma^{SBS}}{N} r_n(t)dt + \\
&\Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n} \left(\int_{\tilde{r}_x(R,t)}^{r_{max}} f(r_n(t))d(r_n(t))\right)^{n} \left(\int_{r_{max}}^{\infty} \right. \\
&\left. f(r_n(t))d(r_n(t))\right)^{N-1-n} r_n(t)dt \\
&= \int_{t_1}^{t_2} (1 - (1 - F(\tilde{r}_x(R,t)))^{N-1}) r_n(t)dt + \int_{t_1}^{t_2} (1 - F(r_{max}) \\
&)^{N-1} \frac{N-1+\sigma^{SBS}}{N} r_n(t)dt + \Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n} (F(r_{max}) \\
&- F(\tilde{r}_x(R,t)))^{n} (1 - F(r_{max}))^{N-1-n} r_n(t)dt.
\end{aligned} \tag{14}$$

Then we can conclude that

$$\begin{aligned}
&U_n^{SBS}(b_n = R, R, t) - U_n^{SBS}(b_n = \emptyset, R, t) \\
&= \int_{t_1}^{t_2} (1 - F(r_{max}))^{N-1} \left(R - \frac{N-1+\sigma^{SBS}}{N} r_n(t)\right) dt \\
&+ \Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n} (F(r_{max}) - F(\tilde{r}_x(R,t)))^{n} (1- \\
&F(r_{max}))^{N-1-n} \frac{R - r_n(t)}{n+1} dt.
\end{aligned} \tag{15}$$

According to (15), we can obtain that $U_n^{SBS}(b_n = R, R, t) < U_n^{SBS}(b_n = \emptyset, R, t)$. Therefore, choose to bid $\emptyset$ will obtain a higher utility for SBS edge cloud n.

Relying on the four cases above, when the other SBS edge clouds choose their strategies in (9), the optimal strategy for SBS edge cloud n is to adopt $b^*(r_n(t), R, t)$ in (9). To conclude, we have provided the concrete proof of Theorem 1.

5.3 Equilibrium for $R \in [0, \frac{N-1+\sigma^{SBS}}{N} r_{min}]$

Second, we analyze that when the offloading rate $R \in [0, \frac{N-1+\sigma^{SBS}}{N} r_{min}]$, the optimal bidding strategy is provided in the following theorem.

Theorem 2. *In the case of $R \in [0, \frac{N-1+\sigma^{SBS}}{N} r_{min}]$, the optimal strategy for SBS edge cloud n is to adopt $b^*(r_n(t), R, t) = \emptyset$. In addition, when $R = \frac{N-1+\sigma^{SBS}}{N} r_{min}$, the optimal strategy form is presented as follows.*

$$b^*(r_n(t), R, t) = \begin{cases} any\ value \in [0, R]\ or\ \emptyset, & r_n(t) = r_{min}; \\ \emptyset, & r_n(t) \in (r_{min}, r_{max}]. \end{cases} \tag{16}$$

To conclude, when the other SBS edge clouds choose their strategies in (16), the optimal strategy for SBS edge cloud n is to adopt $b^*(r_n(t), R, t)$ in (16). To be specific, when $r_n(t) = r_{min}$, the optimal strategy for SBS edge cloud n is to choose any value in the range $[0, R]$ or not participate in this bid. In the case of $r_n(t) \in (r_{min}, r_{max}]$, it is the optimal strategy not to participate in this bid.

5.4 Equilibrium for $R \in (\frac{N-1+\sigma^{SBS}}{N} r_{min}, r_{min})$

Third, we discuss the optimal strategy for SBS edge cloud n when $R \in (\frac{N-1+\sigma^{SBS}}{N} r_{min}, r_{min})$. Then we introduce Lemma 2 for the following analysis.

Lemma 2. *There exists at least one solution $r_n(t) \in (r_{min}, r_{max})$ satisfying the following equation.*

$$\begin{aligned}
&\Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n} F^{n}(r(t))(1 - F(r(t)))^{N-1-n} \frac{R - r(t)}{n+1} \\
&dt + \int_{t_1}^{t_2} (1 - F(r(t)))^{N-1} \left(R - \frac{N-1+\sigma^{SBS}}{N} r(t)\right) dt \\
&= 0,
\end{aligned} \tag{17}$$

where $F(r_n(t))$ is the cumulative distribution function of random variable $r_n(t)$. Moreover, the solutions are denoted as $\tilde{r}_1(R,t), \tilde{r}_2(R,t), \cdots, \tilde{r}_L(R,t)$, where $L = \{1, 2, \cdots, L_{max}\}$ which represents the number of solutions and L_{max} is the maximum number of solutions.

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Proof. The function of left hand side of equation is defined as $\mathscr{R}(r(t))$,

$$\mathscr{R}(r(t)) \triangleq \Sigma_{n=1}^{N-1}\int_{t_1}^{t_2} C_{N-1}^{n}F^{n}(r(t))(1-F(r(t)))^{N-1-n}\frac{R-r(t)}{n+1} dt + \int_{t_1}^{t_2}(1-F(r(t)))^{N-1}\left(R-\frac{N-1+\sigma^{SBS}}{N}r(t)\right)dt, \quad (18)$$

where function $\mathscr{R}(r(t))$ is continuous for $r_n(t)$ in (r_{min}, r_{max}). In particular, $F(r_{min}) = 0$ for $r_n(t) \in (-\infty, r_{min}]$, and $F(r_{max}) = 1$ for $r_n(t) \in [r_{max}, +\infty)$. Then we can obtain that

$$\mathscr{R}(r_{min}) = \Sigma_{n=1}^{N-1}\int_{t_1}^{t_2} C_{N-1}^{n}F^{n}(r_{min})(1-F(r_{min}))^{N-1-n}\frac{R-r(t)}{n+1} dt+\int_{t_1}^{t_2}(1-F(r_{min}))^{N-1}\left(R-\frac{N-1+\sigma^{SBS}}{N}r_{min}\right)dt \int_{t_1}^{t_2}\left(R-\frac{N-1+\sigma^{SBS}}{N}r_{min}\right)dt. \quad (19)$$

And since $F(r_{max}) = 1$, we can obtain that

$$\mathscr{R}(r_{max}) = \Sigma_{n=1}^{N-1}\int_{t_1}^{t_2} C_{N-1}^{n}F^{n}(r_{max})(1-F(r_{max}))^{N-1-n}\frac{R-r(t)}{n+1} dt+\int_{t_1}^{t_2}(1-F(r_{max}))^{N-1}\left(R-\frac{N-1+\sigma^{SBS}}{N}r_{max}\right)dt \int_{t_1}^{t_2}\frac{R-r_{max}}{N}dt. \quad (20)$$

Since $\frac{N-1+\sigma^{SBS}}{N}r_{min} < R < r_{min} < r_{max}$, we can conclude that $\mathscr{R}(r_{max}) > 0$ and $\mathscr{R}(r_{max}) < 0$. Based on the intermediate value theorem, there is at least one solution $r(t)$ in $(\frac{N-1+\sigma^{SBS}}{N}r_{min}, r_{min})$ satisfying (17). The proof is completed.

To be specific, the proof of Lemma 2 is provided in the above. Based on Lemma 2, we can obtain the following theorem.

In the following we will give an analysis when $R \in (\frac{N-1+\sigma^{SBS}}{N}r_{min}, r_{min})$, first an optimal bidding strategy will be presented in Theorem 3, then its detailed proof will be described.

Theorem 3. *In the case of $R \in (\frac{N-1+\sigma^{SBS}}{N}r_{min}, r_{min})$, assuming that there is a $\tilde{r}_y(R,t) \in (R, r_{max})$ subject to $\{\tilde{r}_1(R,t), \tilde{r}_2(R,t), \cdots, \tilde{r}_L(R,t)\}$, we can obtain the following bidding strategies $b^*(r_n(t), R, t)$ constitute the SBNE for SBS edge cloud n,*

$$b^*(r_n(t), R, t) = \begin{cases} R, & r_n(t) \in [r_{min}, \tilde{r}_y(R,t)]; \\ R \text{ or } \emptyset, & r_n(t) = \tilde{r}_y(R,t); \\ \emptyset, & r_n(t) \in (\tilde{r}_y(R,t), r_{max}]. \end{cases} \quad (21)$$

Similar to the analysis of Theorem 1, Theorem 3 presents that when the other SBS edge clouds choose their strategies in (21), the optimal strategy for SBS edge cloud n is to adopt $b^*(r_n(t), R, t)$ in (21). To be specific, the proof of Theorem 3 is provided in the following.

Proof. **Case I** $r_n(t) \in [r_{min}, \tilde{r}_y(R,t)]$. We assume that the data offloading rate at SBS edge cloud n satisfies $r_n(t) \in [R, \tilde{r}_x(R,t)]$. To be specific, we will analyze this case with the following situation.

Comparison between R and $\emptyset$. When bid R, the utility of SBS edge cloud n can be obtained as follows.

$$U_n^{SBS}(b_n = R, R, t) = \int_{t_1}^{t_2}\left(1-\left(\int_{r_{min}}^{\infty} f(r_n(t))d(r_n(t))\right)^{N-1}\right)r_n(t)dt+\int_{t_1}^{t_2}\left(\int_{\tilde{r}_y(R,t)}^{\infty} f(r_n(t))d(r_n(t))\right)^{N-1}Rdt+\Sigma_{n=1}^{N-1}\int_{t_1}^{t_2}C_{N-1}^{n}\left(\int_{r_{min}}^{\tilde{r}_y(R,t)} f(r_n(t))d(r_n(t))\right)^{n}\left(\int_{\tilde{r}_y(R,t)}^{\infty} f(r_n(t))d(r_n(t))\right)^{N-1-n}\frac{R+nr_n(t)}{n+1}dt$$
$$= \int_{t_1}^{t_2}(1-(1-F(r_{min}))^{N-1})r_n(t)dt+\int_{t_1}^{t_2}(1-F(\tilde{r}_y(R,t)))^{N-1}Rdt+\Sigma_{n=1}^{N-1}\int_{t_1}^{t_2}C_{N-1}^{n}(F(\tilde{r}_y(R,t))-F(r_{min}))^{n}(1-F(\tilde{r}_y(R,t)))^{N-1-n}\frac{R+nr_n(t)}{n+1}dt. \quad (22)$$

When bid $\emptyset$, the utility of SBS edge cloud n can be obtained as follows

$$U_n^{SBS}(b_n = \emptyset, R, t) = \int_{t_1}^{t_2}\left(1-\left(\int_{r_{min}}^{\infty} f(r_n(t))d(r_n(t))\right)^{N-1}\right)r_n(t)dt+\int_{t_1}^{t_2}\left(\int_{\tilde{r}_y(R,t)}^{\infty} f(r_n(t))d(r_n(t))\right)^{N-1}\frac{N-1+\sigma^{SBS}}{N}r_n(t)dt+\Sigma_{n=1}^{N-1}\int_{t_1}^{t_2}C_{N-1}^{n}\left(\int_{r_{min}}^{\tilde{r}_y(R,t)} f(r_n(t))d(r_n(t))\right)^{n}\left(\int_{\tilde{r}_y(R,t)}^{\infty} f(r_n(t))d(r_n(t))\right)^{N-1-n}r_n(t)dt$$
$$= \int_{t_1}^{t_2}(1-(1-F(r_{min}))^{N-1})r_n(t)dt+\int_{t_1}^{t_2}(1-F(\tilde{r}_y(R,t)))^{N-1}\frac{N-1+\sigma^{SBS}}{N}r_n(t)dt+\Sigma_{n=1}^{N-1}\int_{t_1}^{t_2}C_{N-1}^{n}(F(\tilde{r}_y(R,t)) - F(r_{min}))^{n}(1-F(\tilde{r}_y(R,t)))^{N-1-n}r_n(t)dt. \quad (23)$$

Then we can conclude that

$$U_n^{SBS}(b_n = R, R, t) - U_n^{SBS}(b_n = \emptyset, R, t) = \int_{t_1}^{t_2}(1-F(\tilde{r}_x(R,t)))^{N-1}\left(R-\frac{N-1+\sigma^{SBS}}{N}r_n(t)\right)dt +\Sigma_{n=1}^{N-1}\int_{t_1}^{t_2}C_{N-1}^{n}(F(\tilde{r}_y(R,t))-F(r_{min}))^{n}(1-F(\tilde{r}_y(R,t)))^{N-1-n}\frac{R-r_n(t)}{n+1}dt. \quad (24)$$

It is simple to realize that $U_n^{SBS}(b_n = R, R, t) - U_n^{SBS}(b_n = \emptyset, R, t)$ is a decreasing function and it is larger than 0. Hence, choose to bid R can obtain a higher utility than biding $\emptyset$.

Case II $r_n(t) = \tilde{r}_y(R,t)$. Similar like the analysis in **Case I**, we can obtain that bidding R has the same utility with bidding $\emptyset$. Consequently, when the other SBS edge clouds choose their strategies in (21), the optimal strategy for SBS edge cloud n is to adopt $b^*(r_n(t), R, t)$ in (21).

Case III $r_n(t) \in [\tilde{r}_y(R,t), r_{max}]$. Similar like the analysis in **Case I**, we will consider the two situations when bid R and bid $\emptyset$. We assume that the data offloading rate at SBS edge cloud n satisfies $r_n(t) \in [\tilde{r}_y(R,t), r_{max}]$. To be specific, we will analyze this case with the following situation.

Case IV $r_n(t) > r_{max}$. Similar like the analysis in **Case I**, we will consider the two situations when bid R and bid $\emptyset$. We assume that the data offloading rate at SBS edge cloud n satisfies $r_n(t) \in [\tilde{r}_y(R,t), r_{max}]$. To be specific, we will analyze this case with the following situation.

Comparison between R and $\emptyset$. When bid R, the utility of SBS edge cloud n can be obtained as follow

$$\begin{aligned}
&U_n^{SBS}(b_n = R, R, t)\\
&= \int_{t_1}^{t_2} \left(1 - \left(\int_{\tilde{r}_y(R,t)}^{\infty} f(r_n(t)) d(r_n(t))\right)^{N-1}\right) r_n(t) dt +\\
&\int_{t_1}^{t_2} \left(\int_{r_{max}}^{\infty} f(r_n(t)) d(r_n(t))\right)^{N-1} R dt + \Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n}\\
&\left(\int_{\tilde{r}_y(R,t)}^{r_{max}} f(r_n(t)) d(r_n(t))\right)^{n} \left(\int_{r_{max}}^{\infty} f(r_n(t)) d(r_n(t))\right)^{N-1-n}\\
&\frac{R + n r_n(t)}{n+1} dt\\
&= \int_{t_1}^{t_2} (1 - (1 - F(\tilde{r}_y(R,t)))^{N-1}) r_n(t) dt + \int_{t_1}^{t_2} (1 - F(r_{max})\\
&)^{N-1} R dt + \Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n} (F(r_{max}) - F(\tilde{r}_y(R,t)))^{n} (1-\\
&F(r_{max})^{N-1-n} \frac{R + n r_n(t)}{n+1} dt.
\end{aligned} \tag{25}$$

When bid $\emptyset$, the utility of SBS edge cloud n can be obtained as follows

$$\begin{aligned}
&U_n^{SBS}(b_n = \emptyset, R, t)\\
&= \int_{t_1}^{t_2} \left(1 - \left(\int_{\tilde{r}_y(R,t)}^{\infty} f(r_n(t)) d(r_n(t))\right)^{N-1}\right) r_n(t) dt +\\
&\int_{t_1}^{t_2} \left(\int_{r_{max}}^{\infty} f(r_n(t)) d(r_n(t))\right)^{N-1} \frac{N - 1 + \sigma^{SBS}}{N} r_n(t) dt +\\
&\Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n} \left(\int_{\tilde{r}_y(R,t)}^{r_{max}} f(r_n(t)) d(r_n(t))\right)^{n} \left(\int_{r_{max}}^{\infty}\right.\\
&\left. f(r_n(t)) d(r_n(t))\right)^{N-1-n} r_n(t) dt\\
&= \int_{t_1}^{t_2} (1 - (1 - F(\tilde{r}_y(R,t)))^{N-1}) r_n(t) dt + \int_{t_1}^{t_2} (1 - F(r_{max})\\
&)^{N-1} \frac{N - 1 + \sigma^{SBS}}{N} r_n(t) dt + \Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n} (F(r_{max})\\
&- F(\tilde{r}_y(R,t)))^{n} (1 - F(r_{max}))^{N-1-n} r_n(t) dt.
\end{aligned} \tag{26}$$

Then we can conclude that

$$\begin{aligned}
&U_n^{SBS}(b_n = R, R, t) - U_n^{SBS}(b_n = \emptyset, R, t)\\
&= \int_{t_1}^{t_2} (1 - F(r_{max}))^{N-1} \left(R - \frac{N - 1 + \sigma^{SBS}}{N} r_n(t)\right) dt\\
&+ \Sigma_{n=1}^{N-1} \int_{t_1}^{t_2} C_{N-1}^{n} (F(r_{max}) - F(\tilde{r}_y(R,t)))^{n} (1-\\
&F(r_{max}))^{N-1-n} \frac{R - r_n(t)}{n+1} dt.
\end{aligned} \tag{27}$$

According to (27), we can obtain that $U_n^{SBS}(b_n = R, R, t) < U_n^{SBS}(b_n = \emptyset, R, t)$. Therefore, choose to bid $\emptyset$ will obtain a higher utility for SBS edge cloud n. This completes the proof.

5.5 Equilibrium for $R \in [r_{max}, +\infty)$

Ultimately, we analyze the case of offloading rate $R \in (r_{max}, +\infty)$, and the form of SBNE is presented in Theorem 4.

Theorem 4. *When the offloading rate $R \in (r_{max}, +\infty)$, the optimal bidding strategy $b^*(r_n(t), R, t)$ for SBS edge cloud n is provided as*

$$b^*(r_n(t), R, t) = \begin{cases} \textit{any value in } [0, r_{min}], & r_n(t) = r_{min};\\ r_n(t), & r_n(t) \in [r_{min}, r_{max}];\\ \textit{any value in } [r_{min}, R] \textit{ or } \emptyset, & r_n(t) = r_{max}. \end{cases} \tag{28}$$

As a result, when the other SBS edge clouds choose their strategies in (28), the optimal strategy for SBS edge cloud n is to adopt $b^*(r_n(t), R, t)$ in (28). When $r_n(t) = r_{min}$, the optimal price strategy for SBS edge cloud is any value in $[0, r_{min}]$. When $r_n(t) \in [r_{min}, r_{max}]$, the optimal price strategy is $r_n(t)$. Furthermore, when $r_n(t) = r_{max}$, the optimal price strategy for SBS edge cloud is any value in r_{min}, R or giving up bidding.

6 MBS Edge Cloud's Expected Utility Analysis

In this section, we will investigate the optimal expected utility of the MBS edge cloud based the above analysis in Section 4. In addition, we assume that there is a unique solution in (5) and (17) respectively.

In the following we will prove (5) has one solution when $N = 2$. The cumulative distribution function is $F(r(t)) = \frac{r(t) - r_{min}}{r_{max} - r_{min}}$, where $r(t) \in [r_{min}, r_{max}]$. Relying on the expression of (5) and the number of the SBS edge cloud is 2, then the equation can be

$$\frac{r(t) - R}{r_{max} - r_{min}} \frac{R - r(t)}{2} + \frac{r_{max} - r}{r_{max} - r_{min}} \left(R - \frac{1 - \sigma^{SBS}}{2} r(t)\right) = 0. \tag{29}$$

After transformation of equation, we obtain that

$$\frac{\sigma^{SBS}}{2} r(t)^2 - \left(\frac{1 + \sigma^{SBS}}{2}\right) r_{max} r(t) + r_{max} R - \frac{R^2}{2} = 0. \tag{30}$$

Then the left side of equation above can be defined as

$$H(r(t)) \triangleq \frac{\sigma^{SBS}}{2} r(t)^2 - \left(\frac{1+\sigma^{SBS}}{2}\right) r_{max} r(t) + r_{max} R - \frac{R^2}{2}. \quad (31)$$

Because this function is a quadratic, the derivative function of the equation above can be shown as

$$d(H(r(t)))/d(r(t)) = \sigma^{SBS} r(t) - \left(\frac{1+\sigma^{SBS}}{2}\right) r_{max}. \quad (32)$$

Let the derivative function above be equal to zero, we can obtain that in this case the solution of $r_0(t)$ can be

$$r_0(t) = \left(\frac{1+\sigma^{SBS}}{2\sigma^{SBS}}\right) r_{max}. \quad (33)$$

When the solution $r(t) < r_0(t)$, i.e. the derivative function < 0, the quadratic function $H(r(t)))$ is a decreasing function. We will analyze the range of $r(t)$ as follows.

It is obviously that when $r(t) \in [r_{min}, \frac{1+\sigma^{SBS}}{2\sigma^{SBS}} r_{max})$, the quadratic function $H(r(t)))$ decreases with $r(t)$. Since $\frac{1+\sigma^{SBS}}{2\sigma^{SBS}} > \frac{\sigma^{SBS}+\sigma^{SBS}}{2\sigma^{SBS}} > 1$, we can obtain that $r_{min} < r(t) < r_{max} < \frac{1+\sigma^{SBS}}{2\sigma^{SBS}} r_{max}$. Then it can be conclude that $H(r(t)))$ decreases with $r(t)$ in its range.

Moreover, when $r(t) = R$, $H(R)) = \frac{1-\sigma^{SBS}}{2}(r_{max} - R)R > 0$, and $r(t) = r_{max}$, $H(r_{max})) = -\frac{1}{2}(r_{max} - R)^2 < 0$. Based on the above analysis, (5) has only one solution when $N = 2$. In addition, when $N > 2$, we will give the function curve in Section 7.1 to verify its uniqueness.

Remarks: the uniqueness of solution for (17) is proved like (5), therefore the proof is omit in details.

For now, we have obtained the uniqueness of solution for (5) and (17), then in the following subsections the expected compensation $r_{compensation}$ and the expected utility of the MBS edge cloud $\int_{t_1}^{t_2} U^{MBS}(b, R, t)dt$ in different cases of R can be formulated.

6.1 Definition of MBS Edge Cloud's Expected Utility

Definition 2. *First, we define the MBS edge cloud's expected utility as*

$$U^{MBS}(b, R, t) \triangleq E\{U^{SBS}(b^*(r_1, R, t), b^*(r_2, R, t), \cdots, b^*(r_N, R, t)), R\}, \quad (34)$$

where $b^*(r_n, R, t), n \in N$ represents the optimal bidding strategy for each SBS edge cloud under the offloading rate R. Based on the different intervals of offloading rate R, the MBS edge cloud's expected utility has variant forms.

6.2 MBS Edge Cloud's Optimal Expected Utility

The MBS edge cloud's optimal offloading rate should satisfy

$$\begin{aligned} max \int_{t_1}^{t_2} U^{MBS}(b, R, t)dt; \\ s.t.\ b_{max}(R) \le r_{MBS}; \\ t \in t_1, t_2. \end{aligned} \quad (35)$$

Case I $R \in [r_{min}, r_{max})$. Then we compute the probability distribution of b_{min}^{-k}. The cumulative distribution function of b_{min}^{-k} is denoted as $H(\cdot)$ and it can be computed as

$$H(\cdot) = 1 - (1 - F(r_n(t)))^{N-1}, r_n(t) \in [r_{min}, r_{max}]. \quad (36)$$

Therefore, the probability distribution function of b_{min}^{-k} can be computed as

$$h(r_n(t)) = \frac{dH(\cdot)}{dr(t)} = (N-1)f(r_n(t))(1 - F(r_n(t)))^{N-2}, \quad r_n(t) \in [r_{min}, r_{max}]. \quad (37)$$

Then the expected compensation received by SBS edge cloud n. Specifically, SBS edge cloud n is capable of winning the auction under the following three cases:

(1) $r_n(t) \in [r_{min}, R)$ and $b_{min}^{-k} \in [r_n(t), R)$. In this case, SBS edge cloud n is capable of receiving b_{min}^{-k} from the MBS edge cloud.

(2) $r_n(t) \in [r_{min}, R)$ and $b_{min}^{-k} = R\ or\ \emptyset$. In this case, SBS edge cloud n is capable of receiving R from the MBS edge cloud.

(3) $r_n(t) \in [\tilde{r}_x(t), R)$ and $b_{min}^{-k} = R\ or\ \emptyset$. In this case, SBS edge cloud n can receive the expected compensation from the MBS edge cloud depends on the number of the SBS edge clouds bidding R.

Relying on the analysis above, the expected compensation that SBS edge cloud n received is

$$\begin{aligned} r_{compensation} = &\int_{r_{min}}^{R} r(t)g(r(t))F(r(t))dr(t) + RF(R) \\ &(1 - G(R)) + (F(\tilde{r}_x(R)) - F(R))\Sigma_{n=0}^{N-1} C_{N-1}^{n} (F(\tilde{r}_x(t)) \\ &- F(R))^n (1 - F(\tilde{r}_x(t)))^{N-1-n} \frac{R}{n+1}. \end{aligned} \quad (38)$$

Furthermore, we can hold that

$$\begin{aligned} &\frac{1}{N}((1 - F(R))^N - (1 - F(\tilde{r}_x(t)))^N) = \\ &(F(\tilde{r}_x(R)) - F(R))\Sigma_{n=0}^{N-1} C_{N-1}^{n} (F(\tilde{r}_x(t)) - F(R))^n \\ &(1 - F(\tilde{r}_x(t)))^{N-1-n} \frac{R}{n+1}. \end{aligned} \quad (39)$$

Relying on (36), (37) and (39), we can transfer (38) to the following equation:

$$\begin{aligned} r_{compensation} = &(N-1)\int_{r_{min}}^{R} r(t)f(r(t))F(r(t))(1- \\ &F(r(t)))^{N-2}dr(t) + RF(R)(1 - F(R))^{N-1} + \frac{1}{N}R \\ &\left((1 - F(R))^N - (1 - F(\tilde{r}_x(t)))^N\right). \end{aligned} \quad (40)$$

The maximal expected utility of the MBS edge cloud can be concluded as the minimal $r_{compensation}$. Then consider there is N the SBS edge clouds, the total expected compensation can be summarized as

$$\begin{aligned} \widetilde{r}_{compensation} = &N(N-1)\int_{r_{min}}^{R} r(t)f(r(t))F(r(t)) \\ &(1 - F(r(t)))^{N-2}dr(t) + NRF(R)(1 - F(R))^{N-1} + \\ &R\left((1 - F(R))^N - (1 - F(\tilde{r}_x(t)))^N\right). \end{aligned} \quad (41)$$

Considering that the distribution of the SBS edge clouds

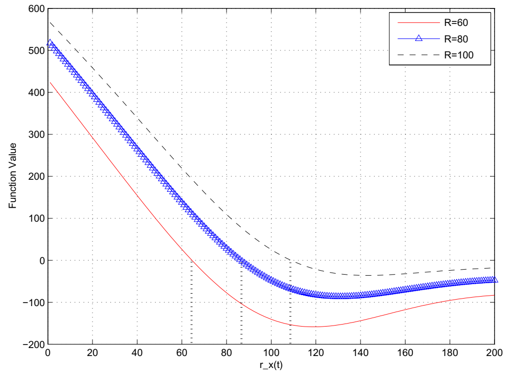

Fig. 3. Function value for different R

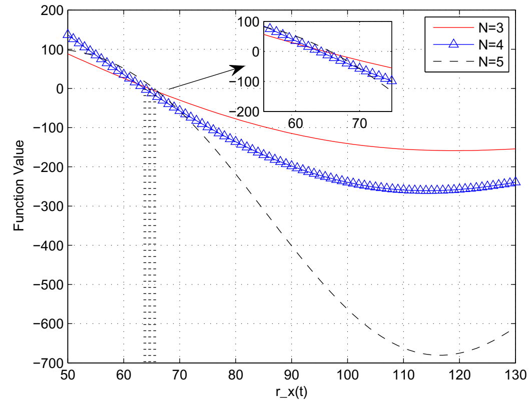

Fig. 4. Function value for different N

offloading rate can be obtained by the MBS edge cloud, moreover, relying on the proof above, no matter how many numbers of the SBS edge clouds, the solution of (5) is only one. In addition, the utility of the MBS edge cloud is defined as (2). Then we can obtain the expected utility of the MBS edge cloud as

$$E\Big(\int_{t_1}^{t_2} U^{MBS}(b,R,t)dt\Big)=\int_{t_1}^{t_2}\Bigg((F(\tilde{r}_x(R,t))^N\sigma^{MBS}R + (1-F(\tilde{r}_x(R,t))^N)R-\tilde{r}_{compensation}\Bigg)dt. \quad (42)$$

Case II $R\in[0,\frac{N-1+\sigma^{SBS}}{N}r_{min}]$. In this case, the SBS edge clouds work with the MBS edge cloud in the competition mode, and expected utility of the MBS edge cloud is

$$E\left(\int_{t_1}^{t_2} U^{MBS}(b,R,t)dt\right)=\int_{t_1}^{t_2}\sigma^{MBS}r_{MBS}dt. \quad (43)$$

Case III $R\in(\frac{N-1+\sigma^{SBS}}{N}r_{min},r_{min})$. In this case, the SBS edge clouds choose to bid R or $\emptyset$ with possibility, and expected utility of the MBS edge cloud is formulated as

$$E\left(\int_{t_1}^{t_2} U^{MBS}(b,R,t)dt\right)=\int_{t_1}^{t_2}\Bigg((1-F(\tilde{r}_y(R)))^N \sigma^{MBS}r_{MBS}+(1-(1-F(\tilde{r}_y(R)))^N)(r_{MBS}-R)\Bigg)dt. \quad (44)$$

Case IV $R\in(r_{max},\infty)$. In this case, the SBS edge clouds choose to bid $[0,R]$ in the cooperation mode, and expected utility of the MBS edge cloud is formulated as

$$E\left(\int_{t_1}^{t_2} U^{MBS}(b,R,t)dt\right)=\int_{t_1}^{t_2}\Bigg(r_{MBS}-N(N-1)\int_{r_{min}}^{r_{max}} r(t)f(r(t))F(r(t))(1-F(r(t)))^{N-2}d(r(t))\Bigg)dt. \quad (45)$$

6.3 MBS Edge Cloud's Optimal Offloading Rate

The optimal expected utility of the MBS edge cloud is clarified in the following theorem, which satisfying the assumption in Section 4.

Theorem 5. *The optimal offloading rate of the MBS edge cloud is denoted as R^*, which has the following properties.*

Case I *If $r_{MBS}\le\frac{N-1+\sigma^{SBS}}{N(1-\sigma^{MBS})}r_{min}$, offloading rate R^* can be the value from range $[0,\frac{N-1+\sigma^{SBS}}{N}r_{min}]$.*

Case II *If $\frac{N-1+\sigma^{SBS}}{N(1-\sigma^{MBS})}r_{min}<r_{MBS}\le r_{max}$, offloading rate R^* can be any value from $(\frac{N-1+\sigma^{SBS}}{N}r_{min},r_{MBS}]$.*

Case III *If $r_{MBS}>MAX\{r_{max},\frac{N-1+\sigma^{SBS}}{N(1-\sigma^{MBS})}r_{min}\}$, offloading rate R^* can be any value from $(\frac{N-1+\sigma^{SBS}}{N}r_{min},r_{max}]$.*

In the case of $r_{MBS}\le\frac{N-1+\sigma^{SBS}}{N(1-\sigma^{MBS})}r_{min}$, the MBS edge cloud is not capable of providing enough service to the SBS edge cloud. To be specific, $r_{MBS}\le\frac{N-1+\sigma^{SBS}}{N(1-\sigma^{MBS})}r_{min}\Rightarrow(1-\sigma^{MBS})r_{MBS}\le\frac{N-1+\sigma^{SBS}}{N}r_{min}$. Relying on the above analysis, $\frac{N-1+\sigma^{SBS}}{N}r_{min}$ should be the lower bound of the computation offloading rate, which the SBS edge cloud can request from the MBS edge cloud. As a result, when $r_{MBS}\le\frac{N-1+\sigma^{SBS}}{N(1-\sigma^{MBS})}r_{min}$, the MBS edge cloud cannot meet the request from the SBS edge cloud under cooperation mode. Therefore, it chooses $R^*\in[0,\frac{N-1+\sigma^{SBS}}{N}r_{min}]$ in the competition mode.

In the case of $\frac{N-1+\sigma^{SBS}}{N(1-\sigma^{MBS})}r_{min}<r_{MBS}\le r_{max}$, the offloading rate capacity can hold the request from the S-BS edge clouds. Therefore, the MBS edge cloud chooses $\frac{N-1+\sigma^{SBS}}{N}r_{min}$ as the lowest bound of R^*. Moreover, the offloading rate should not be larger than R^*, otherwise, it does not satisfy the SBS edge cloud with the largest bidding value.

In the case of $r_{MBS}>MAX\{r_{max},\frac{N-1+\sigma^{SBS}}{N(1-\sigma^{MBS})}r_{min}\}$, because the maximum bidding value from the SBS edge cloud is r_{max}, the MBS edge cloud always provides enough service ability to meet the SBS edge cloud's request. Meanwhile, the offloading rate choose R^* from the interval of $(\frac{N-1+\sigma^{SBS}}{N}r_{min},r_{max}]$.

7 Numerical Results

We will discuss the influence of parameters on the MBS edge cloud optimal offloading rate, the expected utility of the MBS edge cloud and the SBS edge cloud in this section. Specifically, we verify the effectiveness of our proposed

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scheme in SDN-based ultra dense networks. To be specific, we simulate our proposed scheme in Matlab 2013. We consider one MBS edge cloud and the number of the SBS edge clouds N is determined in the concrete experiment. The timeslot $t \in [0,2]$ and the transmission rate $r_n(t)$ submits to the normal distribution with $\mathscr{N}(r_n(t))$, where the mean value is 125 Mbps and the standard deviation is set as 50 Mbps. In addition, $r_{min} = 50$ and $r_{max} = 200$. The discounting factor of the MBS edge cloud and the SBS edge cloud will be given in the following subsections.

7.1 Uniqueness of $\tilde{r}_x(t)$

In this subsection, we present the proof that the uniqueness of $\tilde{r}_x(t)$ for (5). It includes two part, the first experimental result gives the numerical curve of (5) at the case of different values of R. The second one presents the numerical curve of (5) for different values of N. Relying on the proof, we can conclude that the numerical curve decreases gradually and it has only one solution when this function is equal to zero.

From Fig. 3, we choose $N = 3, \sigma^{MBS} = 0.3, \sigma^{SBS} = 0.8$, $t \in [0,2]$ and $r_n(t)$ submits to the normal distribution with $\mathscr{N}(r_n(t)) \sim [125Mbps, 2500Mbps^2]$. Moreover, the computation offloading service rate of the MBS edge cloud R is set as $\{60, 80, 100\}$ Mbps, respectively, and it is plot with Fig. 3. We can see that, with the changing values of R, there is an unique solution for (5). In other words, there is only one $\tilde{r}_x(t)$ for this equation at the different cases of R. To be specific, the increase of R results in a higher function value of (5), as well as the zero-point value of $r_x(t)$ increases with a larger R.

As shown in Fig. 4, we choose $R = 60, \sigma^{MBS} = 0.3, \sigma^{SBS} = 0.8, t \in [0,2]$ and $r_n(t)$ submits to the normal distribution with $\mathscr{N}(r_n(t)) \sim [125Mbps, 2500Mbps^2]$. In addition, the number of the SBS edge clouds N is denoted as $\{3, 4, 5\}$ respectively, and it is shown with Fig. 4 for (5) with different N. In other words, the number of the SBS edge clouds doesn't has any effect on the number of $\tilde{r}_x(t)$. Specifically, the zero-point values of three curves are in touching distance. The larger the numerical value of N, the faster the curve descends.

7.2 Impact on Offloading Rate R^*

In this subsection, we implement the experiment to verify the impact of different discounting factors for the SBS edge cloud and the MBS edge cloud. To be specific, we choose the number of the SBS edge clouds as 3, and the distribution of $r_n(t)$ is the same as Section 7.1. As shown in Fig. 5, the discounting factor of the MBS edge cloud is set as 0.3. Moreover, the discounting factor of the SBS edge cloud is denoted as $\{0.1, 0.3, 0.5, 0.7\}$. For different pairs of discounting factors, the offloading rate for the MBS edge cloud R^* is increasing with the change of r_{MBS}.

From Fig. 5, we can see that R^* is constant when r_{MBS} does not exceed $\frac{N-1+\sigma^{SBS}}{N}$. Afterwards, when r_{MBS} is above $\frac{N-1+\sigma^{SBS}}{N}$, R^* increases with r_{MBS}. Specifically, the higher the discount factor of the SBS edge cloud r_{MBS} is, the more R^* the MBS edge cloud is able to provide. It can prove that the difference of r_{MBS} has a great impact on R^*.

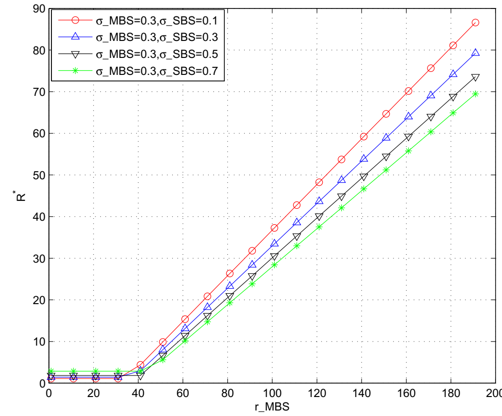

Fig. 5. Impact on offloading rate for different discounting paremters

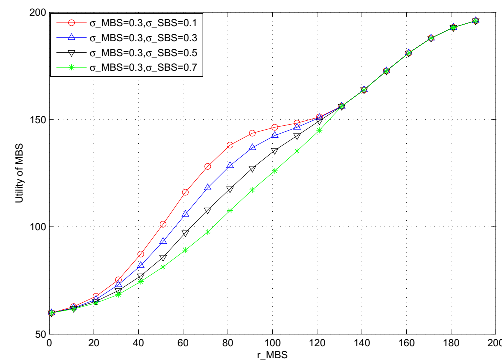

Fig. 6. Utility of the MBS edge cloud for different parameters

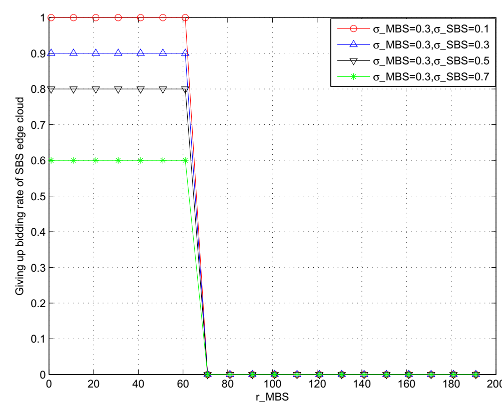

Fig. 7. Giving up bidding rate of the SBS edge cloud for different parameters

7.3 Expected Utility of MBS Edge Cloud

In this subsection, we investigate the expected utility in different parameters. In Fig. 6, we plot the expected utility of the MBS edge cloud against r_{MBS} in the case of different discounting factors. First, we can obviously obtain that, at the first stage, the expected utility of MBS does not change with r_{MBS} is below $\frac{N-1+\sigma^{SBS}}{N}$. Specifically, in the latter stage, with an increase of r_{MBS} the expected utility of the MBS edge cloud increases rapidly. This is because that a higher r_{MBS} enables the MBS edge cloud to set a higher computation offloading rate, which results in a larger possibility of cooperation between the SBS edge cloud and the MBS edge cloud. Moreover, the increase of σ^{SBS} helps deteriorate the expected utility of the MBS edge cloud increases slightly.

7.4 Utility Analysis of SBS Edge Cloud

As shown in Fig. 7, the giving up bidding rate of the SBS edge clouds against r_{MBS} are presented in the case of different parameters. We set the number of SBS as 10, the discount factor of the MBS edge cloud is 0.3, and the discount factor of the MBS edge cloud is chosen from $\{0.1, 0.3, 0.5, 0.7\}$. It is obviously obtained that, with the increase of r_{MBS} the giving up bidding rate of total SBS edge clouds decreases rapidly in the latter stage. In the initial stage, the SBS edge clouds choose to give up bidding because of the low offloading rate when r_{MBS} is below $\frac{N-1+\sigma^{SBS}}{N}$. A larger r_{MBS} helps the SBS edge clouds cooperate the bidding between the SBS edge clouds and the MBS edge cloud in a larger possibility. Furthermore, the increase of σ^{SBS} helps reduce the giving up bidding rate of total SBS edge clouds.

8 Conclusion

In this paper, we have proposed a spectrum sharing and computation offloading scheme for SDN-based ultra dense networks. In this novel network architecture, the proposed scheme was capable of allocating a channel to the MBS edge cloud and the SBS edge cloud for offloading appropriately in cooperative mode and competition mode. In addition, the SBS edge clouds' equilibrium strategies and the optimal offloading rate of MBS edge cloud were analyzed. Finally, the simulation results indicated that our scheme could achieve effective performance. Furthermore, the impact of parameters and expected utility have been discussed. To be specific, the offloading rate for the MBS edge cloud R^* is increasing with the increase of r_{MBS}. The increase of σ^{SBS} helps deteriorate the expected utility of the MBS edge cloud increases slightly and reduce the giving up bidding rate of total SBS edge clouds.

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