

Collusion-Resistant Repeated Double Auctions for Cooperative Communications

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Abstract—Deployment of relay nodes to existing wireless networks recently has received much attention since the channel capacity from sources to destinations through the cooperation of relay nodes is greatly enhanced. However, choosing appropriate relay nodes is critical to maximize the overall network performance. In this paper, we consider the assignment problem of relay nodes in a cooperative wireless network, where physical relay infrastructures and relay supporting services (relay assignment) are independently operated by different selfish entities with each being driven by its own benefit. We first formulate the problem as a repeated double auction by taking into account the benefits of all entities. Specifically, we consider a system that consists of a set of source-to-destination pairs, where the source nodes are grouped into groups and each of them is represented by a group agent. We assume that both the source nodes and the group agents seek opportunities to maximize their own benefits through various means including untruthful bidding and collusion with each other, and so on. To maximize the social benefit of the system that include the benefits of the source nodes, the relay nodes and the auctioneer, we devise an auction which we refer it to as the repeated multi-heterogeneous-item double auction with collusion resistance. We also analytically show that this auction is not only truthful but also collusion resistant. The experimental results indicate that the proposed auction is effective in collusion-resistance.

I. INTRODUCTION

Recently, cooperative communications have exhibited great potentials in improving data rates and data qualities of wireless communications for various types of networks. For example, with the cooperative communication, cell phone carriers can economically enhance their network coverage and data rates through leasing infrastructures from other carriers. However, the main obstacle between the potential capability of data rate enhancement and the wide adoption of cooperative communication is the lack of incentives for wireless nodes to relay data for others. Most existing studies focus on devising mechanisms to tackle this obstacle [9], [8]. These mechanisms provide monetary incentives for relay nodes through the design of auction-based trading rules that can jointly consider the benefits of sellers (relay-holding carriers) and buyers (relay-requesting carriers). However, none of them considers the revenue of the auctioneer who provides relay assignment for relay-holding carriers that are willing to participate the auction if their revenues can be maximized, since they are normally independent entities. For example, according to a report by Australian Communications and Media Authority [1], all three

major cell phone carriers Telstra, Optus and Vodafone in Australia have their own Mobile Virtual Network Operators, which are independent entities operating marketing and billing services on the behalf of them to maximize their own benefits. This raises an important question, that is *how to give an incentive for each selfish entity to encourage it to participate in the trade while jointly maximizing the revenue of the auctioneer too*. The social-welfare maximizing double auction [2] is an appropriate mechanism to address this question, as it takes into account the revenues of buyers, sellers and the auctioneer. This is usually treated as the social-welfare of the system.

Due to the revenue-jeopardizing properties of untruthful and non-collusion-resistant auctions, we aim to design a truthful and collusion-resistant auction for relay assignment with the aim of maximizing the social welfare in the system. The main contributions of this paper are as follows. We first propose a two-phase auction model for the relay assignment problem in cooperative wireless communication systems. We then devise a repeated multi-heterogeneous-item double auction to consider the benefit of each entity in the system jointly. We next analytically show that the proposed auction is not only truthful but also collusion-resistant. We finally conduct experiments by simulation to evaluate the performance of the proposed auction. The experimental results demonstrate that the proposed auction outperforms the other auctions in terms of social-welfare maximization. To the best of our knowledge, the proposed auction is the first collusion-resistant mechanism for relay assignment.

In the remainder of this paper, we first summarize the related work on relay assignment in Section II. We then introduce the network model and the auction model in Section III. We thirdly devise a novel collusion-resistant relay assignment auction and analyze its economic properties in Section IV. We finally present the experimental results in Section V, and we conclude in Section VI.

II. RELATED WORK

Lot of efforts has been taken on the three-terminal cooperative channel model in the past several years. For example, authors in [11] studied the relay node assignment problem by developing an Optimal Relay Assignment algorithm (ORA) through adopting a ‘linear marking’ mechanism. The authors in [10] considered maximizing the total channel capacity of

source nodes in a cooperative network where nodes transmit their data through orthogonal channels (OFDMA) to mitigate channel interference effects by reducing the Relay Assignment Problem (RAP) into the Maximum Weighted Bipartite Matching (MWBM) problem. The authors in [6] addressed the issue of stimulating cooperative diversity in cooperative networks by proposing a pricing game that converges to a Nash Equilibrium. The authors in [8] devised a two-level Stackelberg game to jointly consider the utilities of selfish buyers and sellers. Ren et al. [5] considered a cooperative network consisting of multiple source-destination pairs and a single relay node by devising a compensation framework to incentive relay nodes to relay data for others.

The most closely related works to ours are the papers [3], [9]. [3] investigated the relay assignment problem by incorporating fairness and energy efficiency, for which the distributed best response bid updates globally converge to the unique Nash Equilibrium in a completely asynchronous manner. A truthful relay assignment auction, TASC, was devised in [9]. by applying the McAfee double auction for relay assignment problem. However, if collusion-resistance is enforced, these proposed auctions may not be applicable. Several patterns of auction collusion exist: bidding ring collusion, loser collusion and sublease collusion. The bidding ring collusion can be avoided by setting reserve price [9]. One condition required by the sublease collusion is that the product can be subleaseable. In cooperative communications, if a relay node is utilized by a source node to which it should not been assigned to transmit data, the relay node will detect it immediately and stop the data transmission. We thus aim to design an auction that not only guarantees truthfulness but also resists loser collusion.

III. PRELIMINARIES

A. Network model

We consider a wireless cooperative communication system with multiple source-to-destination pairs. Source nodes send their data to relay nodes with the aim of enhancing the Signal-to-Noise-Ratio (SNR) at the destinations. Since wireless channels normally are scarce resources and each relay node has a limited number of communication channels, if all source nodes are in a single group and relay through a single relay node, this will greatly reduce the capacity when orthogonal channels are available (e.g. using OFDMA). To mitigate channel interferences, ideally, the source nodes are divided into groups, and each group is allocated to one relay node. Let $S = \{s_i \mid 1 \leq i \leq N\}$ and $D = \{d_i \mid 1 \leq i \leq N\}$ denote the sets of source nodes and destination nodes, respectively. Denote by $R = \{r_j \mid 1 \leq j \leq J\}$ and $G = \{g_k \mid 1 \leq k \leq K\}$ the sets of relay nodes and groups of source nodes, respectively. Clearly $K \leq N$. Let $\mathcal{D}(s_i, d_i)$ be the Euclidean distance between a source node s_i and a destination node d_i . Given the transmission power of source node s_i , P_{s_i} , the SNR at node d_i is $SNR_{s_i, d_i} = \frac{P_{s_i}}{N_{d_i} \cdot \mathcal{D}(s_i, d_i)^\theta}$, where N_{d_i} is the white noise at node d_i and θ is the path loss factor, which is typically between 2 and 4.

We consider the classic three-terminal amplify-and-forward relay model, in which each connection session consists of two consecutive time frames. In the first time frame, the source nodes send their signals to the destinations; the relay nodes then amplify and forward the overheard signals to their destinations at the second time frame. Let W denote the bandwidth that a relay node could utilize. The channel capacity from a source node s_i to a destination node d_i through a relay node r_j can be represented by

$$C(s_i, r_j, d_i) = \frac{W}{2} \log_2 \left(1 + SNR_{s_i, d_i} + \frac{SNR_{s_i, r_j} \cdot SNR_{r_j, d_i}}{SNR_{s_i, r_j} + SNR_{r_j, d_i} + 1} \right).$$

For the sake of simplicity, in the rest of this paper let $\Gamma_{s_i, r_j, d_i} = SNR_{s_i, d_i} + \frac{SNR_{s_i, r_j} \cdot SNR_{r_j, d_i}}{SNR_{s_i, r_j} + SNR_{r_j, d_i} + 1}$. Then, $C(s_i, r_j, d_i) = \frac{W}{2} \log_2(1 + \Gamma_{s_i, r_j, d_i})$.

B. Auction model and collusion-resistance

Since the relay quality and data transmission requirements by source nodes vary over time, relay nodes are dynamically allocated to groups of source nodes to fully utilize the relaying facilities. To this end, we aim to maximize the system throughput for a given time period T , assuming that T is slotted into equal time slots. A series of repeated multi-heterogeneous-item double auctions is carried out, and each auction proceeds at the beginning of each time slot. Each group has a group agent to represent the source nodes in it. The group agents, as the representatives of their members, compete the relay nodes by participating in the auctions. We assume that the ‘fluctuation’ of the value of relay nodes from the current time slot to the next one is known to everyone. In auctions, each bidder only knows its own bid without any knowledge of the bids of other bidders and the asks of relay nodes.

In the beginning of each auction, each source node submits its bid vector $b_i(t)$ to its group agent based on the valuations of the relay nodes in time slot t . With regard to the valuations, the achieved capacity is an important metric for source node s_i to value different relay nodes, as a higher channel capacity means a higher data throughput and reliability. Therefore, the valuation on r_j can be defined by $v(s_i, r_j) = \alpha \cdot C(s_i, r_j, d_i)$, where $0 \leq \alpha \leq 1$ is a constant which is a private value for each source node and represents its preference on the channel capacity. According to its valuation on relay nodes, source node s_i calculates its bid vector, which may or may not equal to v_{s_i} . Let p_i denote the payment per unit of achieved SNR by source node s_i to its assigned group agent g_k . The utility of source node s_i can be represented by $u(s_i) = v(s_i, r_j) - \Gamma_{s_i, r_j, d_i} \cdot p_i$, which is the gross benefits (valuations of the relay nodes) taken out the payments it has to pay. Each group agent participates in the auction with derived bid $B_k(t)$ after receiving all bids from its members. Winning group agents need to pay for relay services. Let p_k denote the payment of g_k to the auctioneer when g_k wins the auction. The budget of a group agent is then defined as $\Psi_{g_k} = |S_{g_k}^{win}| \cdot p_i(\{b_i \mid \forall s_i \in g_k\}) - p_k$, $\forall s_i \in S_{g_k}^{win}$, where $S_{g_k}^{win}$ is

the set of winning source nodes in group g_k . Each relay node r_j has an ask for its relaying A_j . The payment to relay nodes is defined by $p_a^r(A_1, A_2, \dots, A_J)$, which is a function of the asks. The accumulative social welfare that the auctioneer aims to maximize from the very beginning (time slot 0) to time slot t is $V_t(G, R) = \sum_{\tau=0}^t (\sum_{g_k \in G^{win}(\tau)} p_k - \sum_{r_j \in R^{win}(\tau)} p_a^{r_j})$, where $G^{win}(\tau)$ and $R^{win}(\tau)$ denote the sets of winning group agents and relay nodes in time slot τ .

After each auction, the auctioneer only reveals the winner identities but their bids. It charges source nodes, pays the amount that relay nodes ask and maximizes the surplus of these two values through resisting the revenue-jeopardizing behaviors. The rest of the time slot consists of time frames, and transmissions from sources to destinations through relay nodes occur in every two consecutive time frames.

The economic properties of an auction will determine the efficiency of the auction. *Collusion-resistance* is one important property that does not allow agents to collude with each other, since in some scenarios agents can form coalitions with each other to promote their revenues, they pay their cooperating agents ‘side payments’ as returns. We here consider a more general case where buyers (source nodes and group agents) are ϵ -greedy [7]. That is, with probability $w \cdot \epsilon$, a group agent or a source node seeks to form collusion groups with the others to promote its revenue, where w denotes the unfulfilled percentage of the expected revenue of a buyer. Clearly, a buyer would not seek to promote its revenue when its expected revenue is fully satisfied, i.e. $w = 0$. Let $Pr(s_i)$ and $Pr(g_k)$ denote the probabilities that source node s_i and group agent g_k collude with others, respectively. Let I_t^s and I_t^g denote the incentives for source nodes and group agents who lose the auction at time slot t , respectively. Then, $Pr(s_i) = w_i \cdot \epsilon = \frac{[b_i - I_t^s]^+}{b_i} \cdot \epsilon$ and $Pr(g_k) = w_k \cdot \epsilon = \frac{[(B_k - A(B_k)) - I_t^g]^+}{B_k - A(B_k)} \cdot \epsilon$, where $[x - y]^+$ is $x - y$ if it is not negative; and zero otherwise. A cost-effective method is to limit the number of colluding agents under a pre-defined threshold N_c . Let κ be the percentage that the number of colluding agents exceeds N_c , the collusion resistance is then defined as follows.

Definition 1: An auction is a (N_c, κ, p) -collusion-resistant auction when the probability that the number of colluding group agents X exceeds a given threshold, N_c , by κ percent is bounded by probability p . That is, $Pr[X \geq (1 + \kappa)N_c] \leq p$. In addition to collusion-resistance, truthfulness, budget balance and individual rationality are also important properties of an auction [2].

C. Problem definition

Given a wireless cooperative network with multiple source-to-destination pairs and relay nodes, assume that relaying services are leasing to source nodes periodically, the relay assignment problem is to design an auction such that the social welfare is maximized while the economic properties of individual rationality, budget balance, truthfulness and collusion resistance are met.

IV. A REPEATED DOUBLE AUCTION FOR RELAY ASSIGNMENT

Although budget-balanced, truthful auctions for relay assignment have been shown to be feasible in general cooperative communications, the non-collusion-resistant characteristic may not be acceptable to the auctioneer when rationally maximizing its budget through resisting the revenue jeopardizing behaviors. In contrast, inspired by maximizing social-welfare auctions and the negative effect of collusion on social-welfare as illustrated in the previous section, we focus on the design of a truthful, collusion-resistant double auction. To meet the truthfulness, we adopt the truthful double auction of [2], in which the truthfulness is achieved through adopting a Trade-Reduction method, in which some trade pairs are sacrificed to guarantee truthfulness. Winner payments are related to the bids of sacrificed agents. This means that collusion only happens if the expected revenues of losers cannot be fulfilled. To meet collusion-resistance, we need to provide some incentives to the losers. The winning source nodes in each auction then transmit their data to the assigned relay nodes in the rest of this time slot. Here, in order to prevent losing source nodes from transmitting data through relay nodes, we assume relay nodes carry out a verification process to punish those losing source nodes transmitting their data.

A. Intra-group and inter-group winner selection

In the intra-group winner selection, each source node s_i submits its bid b_i to its group agent g_k . Having collected the bids of its members, each group agent g_k first calculates a pre group bid B_k^{pre} , which is a function of the minimum bid submitted by its source nodes, i.e., $B_k^{pre} = (|g_k| - 1) \cdot \min\{b_i \mid s_i \in g_k\}$. Group agent g_k then puts all its members except the one with the minimum bid (the loser) to be the winners, and the winners will be charged with the amount that is equal to the bid of the loser, i.e. $\min\{b_i \mid s_i \in g_k\}$. To resist the collusion is to provide a monetary incentive for each loser that equals its expected revenue. We entitle group agents to provide the incentives to the losers of their groups. Each group agent thus needs to extract a portion of the payment by each winning source node in $S_{g_k}^{win}$ as the incentive paid for the loser. The portions are extracted proportionally to the bids of the winning source nodes, as shown in Eq. (1).

$$I^s = \sum_{s_i \in S_{g_k}^{win}} p_i \cdot \frac{b_i}{\sum_{s_i \in S_{g_k}^{win}} b_i}. \quad (1)$$

The winners in group g_k are willing to pay a portion of their payments as the incentives for the loser, since collusions among the source nodes reduce the winner benefits in a group, when the winner benefits of group g_1 in time slot t are reduced in time slot $t + 1$. The final group bid by group g_k is then calculated by $B_k = (|g_k| - 1) \cdot \min\{(b_i - I^s) \mid s_i \in g_k\}$.

In the inter-group winner selection, each group agent g_k first submits its bid B_k to the auctioneer who then calculates an optimal relay assignment \mathcal{A} according to the OPRA algorithm in [10], and let B' denote the bid vector of group agents

under \mathcal{A} . B' and A are then sorted into non-increasing sequence $\langle B'_{m_1}, B'_{m_2}, \dots, B'_{m_K} \rangle$ and non-decreasing sequence $\langle A_{n_1}, A_{n_2}, \dots, A_{n_J} \rangle$, respectively, as what the McAfee auction does. Next, the largest x satisfying $B'_{m_x} \geq A_{n_x}$ is found. If McAfee double auction is applied, the winning matched pairs in \mathcal{A} are the ones whose group agents bid is higher than B'_{m_x} and relay nodes ask is lower than A_{n_x} . Since the relay assignment \mathcal{A} is calculated first, the greater x is, the more pairs in the set of winning pairs will be, thereby leading to more trading and a higher social welfare. To include more matched pairs in \mathcal{A} , the auctioneer needs to find the largest y in sequence $\langle A_{n_1}, A_{n_2}, \dots, A_{n_J} \rangle$ such that $B'_{m_x} > A_{n_y}$. Having found the winners, $G^{win}(t)$ and $R^{win}(t)$ are then determined.

To resist collusions among group agents, we provide incentives for losers. According to our assumption, the probability that a group agent colludes with others will drop significantly if the percentage of its expected revenue is promoted. If the auctioneer dynamically adjusts I^g , the collusions in an auction can be controlled. To this end, the auctioneer sets an incentive according to its current budget and the number of colluding group agents. In other words, the auctioneer should dynamically promote this incentive to limit the number of potential colluding group agents under a tolerable threshold N_c without beyond its budget. Let I_t^g and I_{t-1}^g denote the incentives for losers at time slot t and $t-1$, respectively. Then, we have $I_t^g = I_{t-1}^g + \vartheta \cdot V_t(G, R)$, where $0 \leq \vartheta \leq 1$ is a constant that represents the percentage that the auctioneer draws part of its revenue to provide incentives. It is continuously adjusted by the auctioneer over time in response to the number of colluding agents in one auction. This is a process of reinforcement learning [7]. The group agents whose bids are higher than B'_{m_x} and are not in $G^{win}(t)$ are provided with uniform incentives.

B. Auction Analysis

We first show that the collusion resistance property is met in both the inter-group and intra-group winner selection by the following lemma.

Lemma 1: The proposed auction is $(N_c, \kappa, \left(\frac{e^{\zeta}-1}{\zeta}\right)^\mu)$ -collusion-resistant, where $\zeta = \frac{(1+\kappa) \cdot N_c}{\mu}$.

The proof sketch of Lemma 1: We first show that the source node winner selection process is collusion-resistant and the number of colluding group agents which exceeds the given threshold by κ percentage can be bounded by $\left(\frac{e^{\zeta}-1}{\zeta}\right)^\mu$ where $\zeta = \frac{(1+\kappa) \cdot N_c}{\mu}$ when $N_c \geq \mu$, and by $2^{-(1+\kappa)N_c}$ when $N_c < \mu$. Due to space limitations, the detailed proof is omitted.

We then have the following theorem.

Theorem 1: The proposed repeated double auction is collusion-resistant, individually rational, budget-balanced and truthful.

V. NUMERICAL RESULTS

To evaluate the performance of the proposed auction, we compare the results of three scenarios: in the first scenario, the source nodes and the group agents never seek to collude with the others; in the second scenario, only the source nodes

seek to collude with the other source nodes; and in the third scenario, only the group agents seek to collude with the other group agents. For the sake of convenience, we denote the repeated auctions without collusion resistance under the above scenarios as RDA-WOC, RDA-SC and RDA-GC, respectively.

A. Simulation Environment

We consider a wireless cooperative network in which source nodes are randomly deployed in a $100\text{ m} \times 100\text{ m}$ square region. The bandwidth of all channels is 22 MHz . The transmission range of each node is set to 20 meters. Let the transmission power be 1 Watt for all wireless nodes. The path loss exponent is set to 4 and the noise at destination node is set to 10^{-10} dBs . Source nodes are geographically grouped into 25 distinct groups. Accordingly, the number of group agents is set to 25. Assume that the source nodes that intend to transmit data at each time slot are chosen randomly. Parameters ϵ and ϑ of the auctioneer will vary in most of our experiments.

B. Performance evaluation

1) *Impact of collusions on social welfare:* To confirm the impact of collusions on social welfare, based on the same network topology with 200 source-to-destination pairs, we first initialize a set of 25 0-greedy ($\epsilon = 0$) group agents and 200 0-greedy ($\epsilon = 0$) source nodes for RDA-WOC. We then initialize a set of 25 0-greedy group agents and 200 0.3-greedy source nodes for RDA-SC. We also initialize a set of 25 0.3-greedy group agents and 200 0-greedy source nodes for RDA-GC. We finally initialize a set of 0.3-greedy group agents and 200 0.3-greedy source nodes for RDA-CR. We run the auctions RDA-WOC, RDA-SC, RDA-GC and RDA-CR each for 100 times. Fig.1 (a) plots the social welfare when auctions RDA-WOC and RDA-SC are applied. The observation is that auction RDA-SC reduces the social welfare of the auctioneer. Due to source node collusions, a loser in one group submitted a very low bid for a specific relay node, which consequently reduces the bid of its corresponding group agent for the relay node according to the proposed intra-group winner selection algorithm. Consequently, the social welfare will decrease accordingly. The changes of social welfare is plotted in Fig. 1 (b) when group agents are allowed to collude with each other, from which we can see that the collusions between group agents will also reduce the social welfare as time goes. Collusions among group agents reduce the difference of the sacrificed group agent's bid and the sacrificed relay agent's ask, which plays an important role in reducing the social welfare according to our inter-group winner selection algorithm.

Fig. 1 (c) plots the social welfare delivered by auctions RDA-CR, RDA-SC and RDA-GC. In terms of the social welfare, RDA-CR exceeds both RDA-SC and RDA-GC as the time goes. In our proposed auction RDA-CR, the colluding probability of group agents is reduced through dynamically providing all the losers in one auction with the uniform incentive. Therefore, the social welfare increases as less group agents choose to collude.

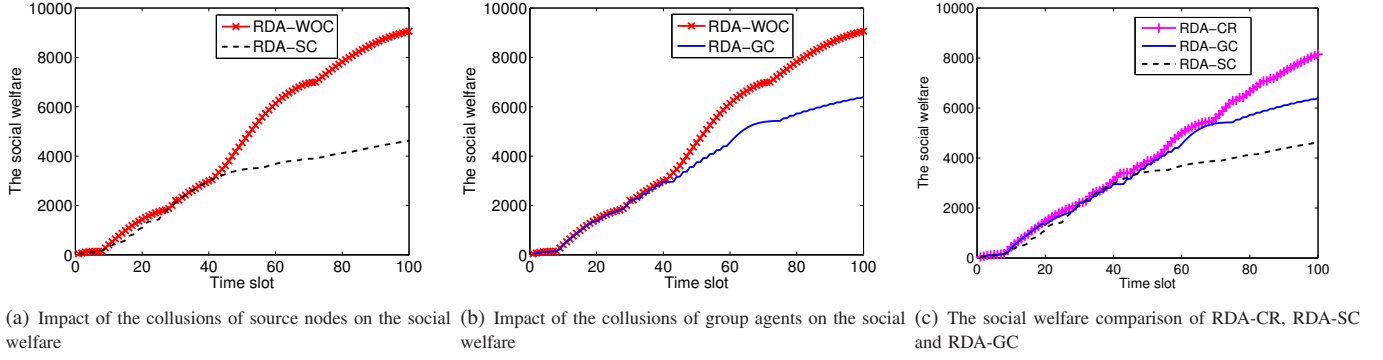


Fig. 1. Impact of the collisions on the social welfare

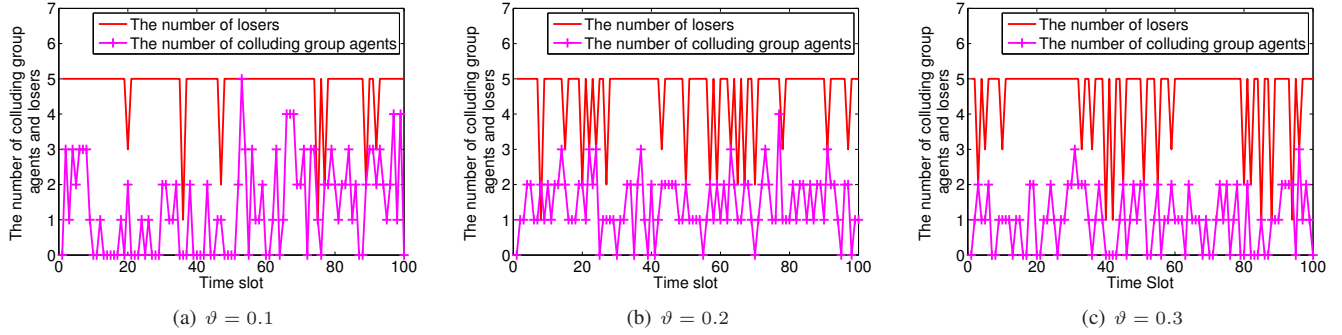


Fig. 2. Impact of ϑ and on the number of colluding agents

2) *Impact of ϑ on the number of colluding agents:* To evaluate the performance of RDA-CR under different sets of group agents with various ϵ , the number of source nodes and group agents are fixed to 200 and 25, respectively. The threshold of colluding number of group agents, N_C , is fixed at 2. We vary ϑ from 0.1 to 0.3 with an increment of 0.1. Fig. 2 plots the number of colluding group agents by varying ϑ . It can be seen from Fig. 2(a) there is the largest number of time slots in which the number of colluding group agents exceeds N_C , this is because that a lower ϑ implies that the losers will receive a lower incentive I^g , and more losers choose to collude with others in order to obtain higher incentives.

VI. CONCLUSION

In this paper, we first devised a truthful and collusion resistant auction mechanism, RDA-CR, which periodically allocates relay nodes to groups of source nodes. Through providing uniform incentives and dynamically adjusting the incentives, the proposed repeated auction enables controlling the number of colluding group agents under a tolerable threshold. We then analytically showed that RDA-CR is not only truthful but also collusion-resistant. Finally, we conducted extensive experiments by simulations to confirm the analytical results, that is, the proposed auction RDA-CR can not only maximize the social welfare with the guaranteed performance but also maintain several economic properties including the individual

rationality, budget balanced, truthfulness, and collusion resistance.

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