A Truthful Online Incentive Mechanism for Nondeterministic Spectrum Allocation

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***Abstract*— Dynamic spectrum access (DSA) is a promising platform to solve the problem of spectrum shortage for which the most challenging issue is spectrum allocation under uncertain availability information, which is referred as a nondeterministic spectrum allocation problem. The nature of such a problem is due to inaccurate spectrum sensing results, which are induced by that power or energy based sensing can be greatly impacted by thermal and environmental noise. For spectrum allocation, auction-based mechanisms have been extensively studied because of channel allocation efficiency, and its potential to achieve bidding truthfulness for secondary uses (SUs). However, most existing spectrum auction mechanisms focus on realizing the truthfulness under certain spectrum availability information. In this paper, we propose FORTUNE, the first truthful online auction mechanism for nondeterministic spectrum allocation by considering uncertain spectrum availability and dynamic spectrum requests. Specifically, we take limited information to compute expected income and losses when interference between primary users (PUs) and SUs occurs, and present a virtual request method for changing of spectrum's actual state. Thorough theoretical analysis proves the truthfulness of FORTUNE. Furthermore, given a sample set with 5%-30% noise in spectrum sensing, FORTUNE achieves not only truthfulness, but also up to 50% higher channel utilization than existing spectrum auction mechanisms.**

***Index Terms*— Dynamic spectrum access (DSA), nondeterministic spectrum allocation, auction, truthfulness.**

I. Introduction

SPECTRUM is a scarce and non-renewable resource, therefore with the increasing demand for wireless communications, the spectrum shortage problem becomes more and more serious. With the potential of increasing spectrum utilization, dynamic spectrum access (DSA) is regarded as a promising platform to solve the spectrum shortage problem. In DSA, wireless devices (i.e., secondary users, SUs) without interference are allowed to dynamically access unoccupied channels, which belongs to primary license holder(i.e., primary users, PUs). Most existing spectrum allocation mechanisms (e.g., [2]–[6]) in DSA assume that an auctioneer has complete knowledge about spectrum state information (e.g., spectrum is available/busy for use by SUs deterministically). However, the complete knowledge about the spectrum state information cannot be obtained all the time. Spectrum allocation problem under uncertain spectrum availability should be discussed, which refers to *nondeterministic* spectrum allocation [1].

Generally speaking, the spectrum state information in DSA is obtained through a spectrum sensing/crowdsensing process. Considering that the spectrum sensing on different spectrum slots may take different time, and power/energy based sensing can be greatly impacted by thermal and environmental noise, inaccurate spectrum sensing reports/results will be induced [7], [8]. In addition, recent studies [9], [10] pointed out that DSA is more inclined to use low power for transmission, leading to the existence of certain errors on spectrum sensing and spectrum states. As a result, the auctioneer will obtain an uncertain spectrum availability (e.g., a channel is available for SUs with a probability of 80%), which cannot be handled by traditional *deterministic* spectrum allocation mechanisms.

Due to good spectrum allocation efficiency and fairness, auction-based mechanisms have been widely studied in DSA where bidders (performed by SUs) submit their requests for temporary use of channels. Then the auctioneer, which is performed by PUs or a third party, determines auction winners and their payments for winning channels. Truthfulness (i.e., Strategy-Proofness) is a critical property in spectrum auction mechanisms, which means each bidder obtains her maximal utility by bidding with her true valuation of bidding spectrum, leading to no incentive to lie about it. For each secondary user, her true valuation of spectrum is closely related to the profits of winning the spectrum [11], for example, revenues gained by a service provider for serving her subscribers [2], [12] or a mobile device for transmitting data [11].

In the last few years, many auction-based spectrum mechanisms have been proposed in dynamic spectrum access. Most of them, (e.g., [12]–[18]) focus on realizing truthfulness for deterministic spectrum allocation with static spectrum requests, which assumed that all spectrum requests are submitted in the beginning. Some online spectrum allocation

Manuscript received December 15, 2019; revised March 18, 2020; accepted March 26, 2020. Date of publication April 10, 2020; date of current version July 10, 2020. This work was supported in part by the National Natural Science Foundation of China under Grant 61972310 and Grant 61972017, in part by the Key Research and Development Program of Shaanxi Province under Grant 2019ZDLGY12-03 and Grant 2019ZDLGY13-06, and in part by the Central University of Finance and Economics Program of the Youth Talent Support Plan under Grant QYP1808. The associate editor coordinating the review of this article and approving it for publication was K. Xue. *(Corresponding author: Yulong Shen.)*

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Digital Object Identifier 10.1109/TWC.2020.2985690

mechanisms (e.g., [3], [4], [19], [20]) discuss deterministic spectrum allocation with dynamic spectrum requests, by considering that SUs submit spectrum requests on different time slots, which is more in accordance with reality. However, the nondeterministic spectrum allocation problem has not been discussed well.

In this paper, we aim to design a spectrum allocation mechanism under uncertain spectrum availability by considering dynamic spectrum requests and spatial reusability. One of the main challenges of our design is how to allocate channels with uncertain spectrum state information, which results in the potential utility loss. The auctioneer allocates the spectrum without knowing their actual states, which may cause interference between a pair of PU and SU. Similar to [21], when interference happens, the auctioneer should compensate that PU and return partial payment to the corresponding SU. Therefore, how to predict utility loss according to the limited information and apply this information to the allocating process is an important issue in nondeterministic spectrum allocation. Another challenge is how to realize the truthfulness in this nondeterministic spectrum auction mechanism with dynamic spectrum requests and spatial reusability. A traditional method to achieve spatial reusability is grouping SUs which can use the same channel simultaneously without occurrence of interference. However, how to compute group bids under uncertain spectrum availability and how to guarantee that each SU in a group cannot obtain a higher utility with a cheating bid are other critical factors in truthful auction mechanisms for nondeterministic spectrum allocation, which cannot be solved by traditional methods.

In this paper, we propose FORTUNE, a truthFul Online spectRum aucTion mechanism under UNcertain spEctrum availability to maintain individual rationality and truthfulness. The main contributions of this paper are as follows:

- To the best of our knowledge, we are the first to design a truthful online auction mechanism with spatial reusability for nondeterministic spectrum allocation.
- We present a new method to take limited information to compute expected income and losses when interference between PUs and SUs occurs, in order to reduce the potential utility losses.
- We propose a virtual request method to deal with the changing actual state of channels which makes our mechanism more applicable to nondeterministic spectrum allocation.
- Theoretical analysis shows that FORTUNE is a truthful and individual rational mechanism which also achieves good efficiency under nondeterministic allocation.

The rest of the paper is organized as follows. In Section II, we briefly introduce the related works. In Section III, we present our auction model and nondeterministic spectrum allocation problem formulation. In Section IV, we present FORTUNE in detail; and next, we prove the individual rationality and truthfulness of FORTUNE in Section V. In Section VI, the performance of FORTUNE scheme is evaluated. Finally, we conclude this paper in Section VII.

II. Related Works

In the last few years, auction has been widely used to design incentive mechanisms for dynamic spectrum allocation (e.g. [2], [12], [14], [16]–[18], [22], [23]). Spectrum reusability, strategy-proofness (truthfulness), online bidding are three major properties of spectrum auction mechanism.

Xia *et al.* proposed VERITAS [24] which is a classic truthful spectrum allocation mechanism. Then the work extended to a truthful double spectrum auction mechanism with spectrum reusability property and ex-post budget balance property in [13]. Zheng *et al.* in [25] introduced a strategy-proof combinatorial auction for spectrum reusability and transmission scheduling. In [11] and [26], the strategy-proof auction mechanisms allow each bidder to submit a bid for a single channel. Xu *et al.* [27] and Wu *et al.* [2] proposed strategy-proof mechanisms for both single-channel and multichannel auctions. SMALL [28] is a double auction mechanism and assumes that PU set a reserved price for each channel. Al-Ayyoub and Gupta [29] and Jia *et al.* [30] have investigated spectrum allocation which maximizes the expected revenue. Dong *et al.* [31], [32] have conducted on preserving primary users' privacy while guarantee the truthfulness of the auction-based spectrum allocation mechanisms.

Above mechanisms were offline and did not take dynamic spectrum requests into consideration, therefore, channels will be requested and assigned for the whole time. In online spectrum auction mechanisms [3], [4], [19], [33], the channels are arriving in a dynamic and random order, and bidders are allowed to request to use the channel according to their demands. Xu *et al.* in [19] proposed an online mechanism based on a simple scenario where is only one channel available. Wang et al. presented THEMIS [33] which is an online mechanism under dynamic spectrum supply. LOTUS [3] and TODA [4] are online double auction for multiple channels.

Spectrum allocation under uncertain availability is a hot topic which has attracted some researchers' interests Shuang *et al.* [34] proposed an online nondeterministic auction mechanism that maximizes social welfare, which allows SUs apply for multiple channels in a single time slot. Nadendla *et al.* [21] designed an optimal auction in the presence of uncertainty in the availability of PU spectrum at the moderator. However, the above studies either are not auction-based mechanisms with truthfulness, or do not consider spatial reusability and dynamic spectrum requests. In this paper, we propose a truthful online spectrum auction mechanism which supports spatial reusability and nondeterministic spectrum allocation.

III. System Model

A. Auction Model

We consider a network where N bidders, denoted as $\mathcal{N} = \{1, \cdots, N\}$, compete for M homogeneous and orthogonal channels, denoted as $\mathcal{M} = \{1, \cdots, M\}$. And let T denote the entire time slot. For each bidder $i \in \mathcal{N}$, her bid $\beta_i = (b_i, a_i, t_i)$ includes the per time slot bid value b_i, the arriving and service starting time $a_i (0 < a_i \leq T)$ and the duration time $t_i (1 \leq a_i + t_i \leq T)$. We assume that each bidder has a valuation function to calculate her per-time slot true valuation

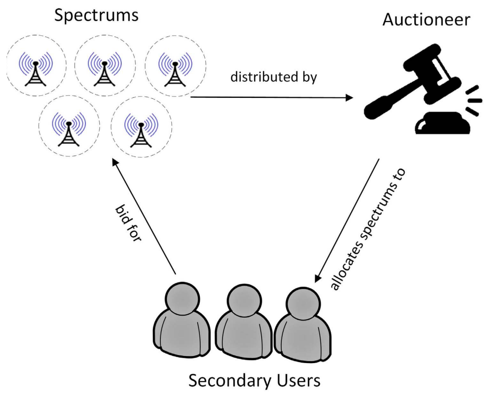


Fig. 1. The process of channel allocation.

v_i for her bidding channels and $b_i = v_i$ means that bidder i bids truthfully. Note that when a bidder find it is profitable, she will manipulate b_i, i.e., $b_i \neq v_i$, to improve her utility.

A conflict graph is used to describe interference between bidders. We use $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ to denote the conflict graph, in which $\mathcal{V}$ is the set of bidders and $\mathcal{E}$ is the set of interference relationships. An edge $(i,j) \in \mathcal{E}$ indicates that interference will occur, if a channel is simultaneously allocated to bidder i and bidder j. The set of interfering neighbors of bidder i is $N(i)$, i.e., $N(i) = \{j|(i,j) \in \mathcal{E}, j \in \mathcal{N}\}$, which also called bidder i's neighbor bidders.

At the beginning of time slot t, an auctioneer, acted by a third party or PU, collects spectrum requests whose required service starting time is t. The spectrum request set with service starting time t is denoted as $\mathcal{R}_t$. Then the auctioneer decides which requests to accept in time slot t. $x_{i,j}(t) = 1$ denotes that channel j is allocated to bidder i at time slot t, otherwise its value is 0. Assume that the per time slot payment of bidder i is p_i and the total payment is pay_i, then the utility of bidder i is

$$u_i = \sum_{j=1}^{m} \sum_{t=0}^{T} x_{i,j}(t)(v_i - p_i). \qquad (1)$$

B. Desired Properties

In this paper, we consider the following important properties:

- **Individual Rationality.** An individual rational auction means that the utilities of bidders with truthful bidding are not less than 0. From Equation 1 it can be inferred that, in an individual rational auction, $b_i \geq p_i$ for each bidder i.
- **Truthfulness.** An auction mechanism is truthful if each bidder can reach her maximum utility when bidding with her true valuation of spectrum, i.e., for any bidder i, $u_i \geq {u_i}'$ holds, in which u_i is the utility when bidding with v_i and ${u_i}'$ is the utility when bidding with ${b_i}' \neq v_i$.

C. Nondeterministic Spectrum Allocation

1) Sensing Inaccuracy: We assume that auctioneer obtains the state of channels by cooperative sensing [35]. Due to sensing inaccuracy, the final sensed state may be different from the actual state. TABLE II shows the effect of different sensing results on the auctioneer and bidders. Let $P_f(j)$ denote the probability of false alarm for channel j, i.e., the probability that the actual state of channel j is idle but its sensed state is busy. Let $P_m(j)$ denote the probability of misdetection for channel j, i.e., the probability that the actual state of channel j is busy but the sensed state is idle. Let $\pi_0(j)$ be the probability that channel j is idle, therefore the probability of channel j with a idle sensed state is $\pi_0(j)(1-P_f(j))+(1-\pi_0(j))P_m(j)$. Assume that $P_0(j)$ is the probability of channel j with a idle sensed state when its actual state is idle, therefore,

$$P_0(j) = \frac{\pi_0(j)(1 - P_f(j))}{\pi_0(j)(1 - P_f(j)) + (1 - \pi_0(j))P_m(j)}. \qquad (2)$$

As the auctioneer only allocates the channel whose sensed state is idle to bidders, we can know that $P_0(j)$ also is the probability of allocating channel j to bidders without interference. Similar to [21], a compensation strategy is adopted: When the allocation results cause interference between a PU and some bidders on channel j, as a punishment, the auctioneer compensates that PU by c_{inter} and return partial payments to bidders who are allocated with channel j.

2) Changing Actual State: We assume that the actual states of channels change over time, which means the actual state of each channel may change in each time slot. To reduce interference, the auctioneer only allocates channels whose

TABLE I
GLOSSARY OF NOTATION

Notation	Description
T	The total number of time slots
β_i	The request of bidder i submitted to the auctioneer
$\widehat{\beta}_i$	The virtual request of bidder i
b_i	Per time slot bid value of bidder i's request
a_i	Arriving time and service star time of bidder i's request
t_i	Duration time of bidder i's request
v_i	True valuation of bidder i
p_i	Per time slot payment of bidder i
u_i	Utility of bidder i
c_{inter}	Penalty/Cost per interference
$N(i)$	The set of interfering neighbors of bidder i
m_i	Max reusability degree of bidder i
I_i	Interference discount of bidder i
B_i	Average discount bid of bidder i's neighbors
$v_i(t)$	Expected valuation from t to T
$C_i(a_i, t_i)$	Opportunity cost from a_i to $a_i + t_i - 1$
$P_f(j)$	The probability of false alarm for channel j
$P_m(j)$	The probability of misdetection for channel j
$P_0(j)$	The probability that channel j is idle and sensed idle
$\pi_0(j)$	The probability that channel j is idle
$Pr(\tau)$	The probability that bidder requires τ time slots
$\mathcal{R}_t$	The set of requests at time slot t
$\widetilde{\mathcal{R}_t}$	The set of remain requests in time slot t
$\widetilde{\mathcal{C}}_t$	The set of available channels at time slot t
$\widetilde{g}$	The set of groups
σ_l	The group bid of g_l
$\phi_{l,j}$	The expected loss of allocating channel j to g_l
$\psi_{l,j}$	The expected profit of allocating channel j to g_l

TABLE II
EFFECT OF DIFFERENT SENSING RESULTS ON AUCTIONEER AND BIDDER

Player	**Sensed State**	**Actual State**	**Comments**
auctioneer	busy	idle	not allocate
	busy	busy	not allocate
	idle	idle	allocate without interference
	idle	busy	allocate with interference
bidder	idle	idle	use channel without interference
	idle	busy	interference with PU
	otherwise		not use channel

TABLE III
SENSED STATE IN EACH TIME SLOT

channel \ state, time slot	1	2	3	4	5
1	0	0	0	1	1
2	1	1	1	1	1

* 0: idle 1: busy

sensed states are idle to bidders. At the beginning of each time slot, the auctioneer speculates the latest states of all channels, including the channels which have been allocated to bidders. As an idle channel may change into busy in forthcoming time slots, those allocated channels also may cause interference in subsequent time slots. As shown in TABLE III, channel 1 is idle in time slot $1, 2$ and 3, and if the auctioneer in time slot 1 allocates channel 1 to a bidder who requests 4 time slots, interference will occur in time slot 4. We assume that at the beginning of each time slot, when the auctioneer finds that the state of an allocated channel is busy, the auctioneer will allocate another channel for bidders or take it back. To avoid interference, bidders can no longer use that busy channel as long as its sensed state is idle.

3) Impact of Nondeterministic Spectrum Allocation: Most of existing spectrum allocation mechanisms assume that all the spectrum availability information is known before allocation. However, such an assumption cannot be applied to nondeterministic spectrum allocation, for the reason that the auctioneer cannot allocate channels to bidders in advance without considering the changing of channels' actual states. We assume that the auctioneer does not know all the requests before allocation, which means that she should allocate channels to bidders without the information about forthcoming requests. Moreover, for a request whose arriving time is a_i, the auctioneer decides whether to accept this request at time slot a_i.

We conduct simulations to show how nondeterministic spectrum and sensing inaccuracy impact the allocation results. In those simulations, 100 bidders are competing 10 channels, and are randomly distributed in a 2000 × 2000 m^2 square area. The interference range is $425m$, and the total number of time slots is 10. The per time slot bids are randomly from 0 to 2 and the compensation for interference is 5. We perform LOTUS [3], which is an elegant online spectrum allocation mechanism based on deterministic situation, for simulation experiments and run the experiment 100 times in each simulation.

TABLE IV
EXPERIMENTAL RESULTS UNDER NONDETERMINISTIC SPECTRUM ALLOCATION BY LOTUS

time slot	10	20	30	40	50
interference	1.55	2.67	3.59	4.68	5.18
affected requests	9.77	14.58	19.04	23.79	25.93
income	12.817	6.669	5.708	-1.863	-7.193

As shown in TABLE IV, the average number of interference and the number of affected requests increases when the number of total time slots rises up. As a result, the average income of the auctioneer decreases with the increase of total time slots, which means the more allocation the auctioneer makes, the lower income she will obtain. Plus, more interference also means lower spectrum utilization and lower user satisfaction. In a word, existing works cannot be directly applied to the nondeterministic spectrum allocation.

IV. FORTUNE

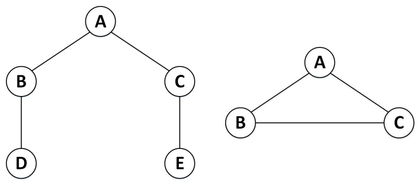
In this section, we will introduce the details of our mechanism named FORTUNE, which is mainly divided into four phases: *screening*, *grouping*, *winner determination* and *virtual request reallocation*.

A. Screening

The auctioneer must decide whether or not to accept a request at time slot t, which means that she cannot know the requests after time slot t in advance. The key to getting a better allocation result is to eliminate requests that have large impacts on the allocation result, which is the main purpose of the screening phase. The reason of the above impacts is that, the interference between two neighboring users leads to only one of them using a specific channel. Furthermore, to avoid interference, when a user is allocated with a channel, her neighboring users cannot use that channel, which resulting in a decrease of spectrum utility. Let $\widetilde{\mathcal{R}_t}$ denote the set of remain requests after the screening phase in time slot t. Note that only requests in $\widetilde{\mathcal{R}_t}$ can proceed to the next phase.

It is obvious that if the auctioneer allocates a channel to bidder i, there are $|N(i)|$ bidders cannot use that channel. In return, if the auctioneer allocates a channel to bidder $j \in N(i)$, bidder i cannot use that channel. Such an interactive relationship between bidders and their neighbors is important to allocation results. In order to achieve a higher channel utilization, bidders who have great impacts on their neighbor bidders should be eliminated from the conflict graph, and the corresponding requests are rejected directly.

Therefore, we give a specific discount for each secondary user's bid value, which called *discount bid*. The more impact a SU has on her neighbor bidders, the bigger the discount is, which increase the difficulty of becoming a winner.



(a) (b)

Fig. 2. Two conflict graphs with the same $r_A = 2$ and different impacts.

Next, we are going to discuss how to calculate each secondary user's interference discount, considering her impact on neighbor bidders. Similar to the screening phase in Lotus [3], the geometric property of bidder i in the conflict graph is used to measure the impact on her neighbor bidders. Let r_i denote the ratio of bidder i's neighbors to the average number of her neighbors' neighbors, and we have

$$r_i = \frac{N(i)}{\sum_{j\in N(i)} |N(j)| / N(i))} = \frac{|N(i)|^2}{\sum_{j\in N(i)} |N(j)|}. \tag{3}$$

In general, when r_i is large, it means that allocating a channel to bidder i may has a negative impact on the allocation result. For a higher spectrum utilization, allocating a channel to bidder i's neighbors may be better than allocating it to bidder i. However, it is not enough to only use this value to measure the impact of bidder i to her neighbors. As shown in Fig.2, $r_A = 2$ in both Fig.2(a) and Fig.2(b). In Fig.2(a), bidder B and C can use the same channel simultaneously, which is forbidden in Fig.2(b), because bidder B and C interfere with each other. Therefore, the impact of allocating a channel to bidder A in Fig.2(a) is greater than it is in Fig.2(b). Let m_i denote the max reusability degree of bidder i, which means the maximum number of bidder i's neighbors who can use the same channel simultaneously. For example, $m_A = 2$ in Fig.2(a) and $m_A = 1$ in Fig.2(b). Then the interference discount of bidder i is

$$I_i = \frac{1}{r_i m_i} \tag{4}$$

, and the auctioneer will use the discount bid $I_i * b_i$ to screen the bidders.

As mentioned above, when assigning a channel to a SU, her neighbor bidders cannot use the same channel at the same time. Therefore, when we judge whether a user should be screened out, it does not only depend on the value of discounted bid, but also combines with the condition that whether discount bid greater than the sum of her neighbor bidders' bid. However, as an online model, the auctioneer cannot know all the requests in advance, so we it is critical to anticipate the possible requests. We introduce a SU's *expected valuation* to predict the sum of possible bid for her neighbor bidders, and the expected valuation $v_i(t)$ of bidder i from time slot t to T is as followed:

$$v_i(t) = \begin{cases} \sum_{\tau=1}^{T-t} Pr(\tau)(B_i\tau + v_i(t+\tau)), & t < T \\ \\ Pr(1)B_i, & t = T \end{cases} \tag{5}$$

, in which $Pr(\tau)$ is the probability that bidder i requires τ time slots, and $B_i = \sum_{j\in N(i)} b_j I_j / |N(i)|$ to denote the average discount bid of bidder i's neighbors. Without loss of generality, expected valuation $v_i(t)$ represents that, from time slot t to T, the sum of bid value of potential requests which belongs to bidder i's neighbor bidders.

Thus, we use $v_i(t)$ to calculate the potential loss to auctioneer. If allocating a channel to bidder i at time slot a_i for t_i time slots, its *opportunity cost*, which refers to the potential loss, is

$$C_i(a_i, t_i) = v_i(a_i) - v_i(a_i + t_i). \tag{6}$$

In short, an opportunity cost is used to predict how much loss if allocating a channel to bidder i, because her neighbor cannot use the channel from time slot a_i to $a_i + t - 1$. If $I_i * b_i * t_i \geq C_i(a_i, b_i)$, which means b_i is higher than the potential loss, then the requests of bidder i are able to proceed to the next phase. Otherwise, such requests will be directly rejected.

Algorithm 1 shows the process of screening, in which we will compute the opportunity cost of each bidder according to the conflict graph and their neighbors' bid values (line 3-6). Then we use discount bid and opportunity cost to screen each request (line 7-8).

Algorithm 1: Screening

Input: Time slot t, total time slots T, the conflict graph $\mathcal{G}$, the set of requests $\mathcal{R}_t$

Output: The remaining request $\widetilde{\mathcal{R}_t}$

```
1  R̃_t ← ;
2  for β_i = (b_i, a_i, t_i) ∈ R_t do
3      r_i = |N(i)|^2 / Σ_{j∈N(i)} |N(j)|;
4      I_i = (r_i m_i)^{-1};
5      B_i = Σ_{j∈N(i)} b_j I_j / |N(i)|;
6      C_i(a_i, t_i) = v_i(a_i) − v_i(a_i + t_i);
7      if I_i * b_i * t_i ≥ C_i(a_i, t_i) then
8          R̃_t ← β_i;
9      end
10 end
```

Algorithm 2: Expected Valuation $v_i(t)$

Input: β_i, B_i, t, T

Output: $v_i(t)$

```
τ = 1, v_i(t) = 0;
while τ ≤ T − t do
    if t = T then
        v_i(t) = v_i(t) + Pr(1)B_i;
    else
        v_i(t) = v_i(t) + Pr(τ)(B_i τ + v_i(t + τ));
    end
    τ = τ + 1;
end
```

For the example in Fig.3(a), we assume that there are 4 time slots in total and it is time slot 1 now. $Pr(i) = 25\%$, where $i = 1, 2, \cdots, 4$. A, B, $\cdots$, F are the bidders whose required service starting time is time slot 1, and Fig.Fig.3(a) shows the conflict graph with their bid values and duration time. Sensed state of each channel and the probability of misdetection are shows in TABLE V. The interference cost c_{inter} is 5.

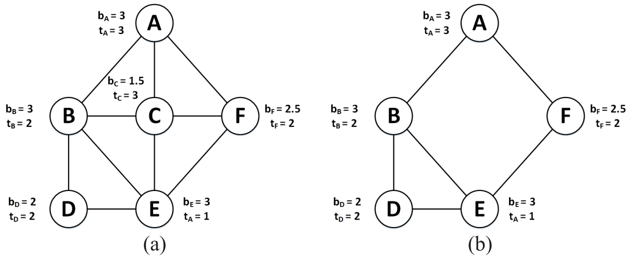


Fig. 3. A simple example.

TABLE V
SENSED STATE OF EACH CHANNEL AND PROBABILITY OF MISDETECTION

channel	1	2	3
time slot 1	0	0	1
time slot 2	0	1	0
P_0	90%	85%	80%

* 0:idle 1:busy

TABLE VI
CORRELATION VALUES USED IN SCREENING

bidder	A	B	C	D	E	F
r_i	0.818	1.230	1.143	0.500	1.230	0.818
m_i	2	2	2	1	2	2
I_i	0.611	0.406	0.438	2.000	0.406	0.550

TABLE VI shows the correlative values used in the screening phase. Now we focus on bidder C, and we can deduce that $B_C = (b_A I_A + b_B I_B + b_E I_E + b_F I_F)/4 = 1.412$, $v_C(1) = 2.630$, $v_C(4) = 0.353$, and $C_C(1,3) = v_C(1) - v_C(4) = 2.277$. Because $I_C * b_C * t_C = 1.971 < C_C(1,3) = 2.277$, the request of bidder C is rejected. Other bidders perform the same process and none of them are eliminated. The new conflict graph is shown in Fig.3(b)

B. Grouping

Due to spatial reusability of spectrum, bidders that using the same channel simultaneously without interference can be organized into a group. We assume that channels are available to all bidders, and groups can be formulated by any graph coloring algorithm which is independent to our design. Note that only bidders whose requests are not rejected in the *screening* phase can be grouped. Assume that bidders in the conflict graph $\mathcal{G}$ are grouped into L independent sets $g_1, g_2, \cdots, g_L$, and the group bid of g_l is

$$\sigma_l = \min_{i \in g_l} b_i * (|g_l| - 1). \tag{7}$$

To ensure that each bidder has no incentive to bid untruthfully, the bidder with minimum bid in each group will be eliminated whether her group becomes a winning group or not (line 8 of Algorithm 3), and a group composed of a single bidder will be eliminated (line 4 in Algorithm 3). These measures are to make all bidders cannot change the group bids by changing their bid values, so that the allocation results are more favorable to themselves.

For the example in Fig.3, by grouping with a greedy algorithm introduced in [13], we have $g_1 = \{A, D\}$, $g_2 = \{B, F\}, g_3 = \{E\}$. g_3 will be eliminated because $|g_3| = 1$. The group bid of g_1 is $\sigma_1 = 2$, and the group bid of g_2 is $\sigma_2 = 2.5$.

Algorithm 3: Grouping

Input: Remaining requests $\widetilde{\mathcal{R}_t}$, conflict graph $\mathcal{G}$
Output: Grouping set $\widetilde{g} = g_1, g_2, \cdots, g_L$
1 Use a graph coloring algorithm to a group set $\widetilde{g}$ which includes L independent groups.
2 **for** $g_l \in \widetilde{g}$ **do**
3   **if** $|g_l| = 1$ **then**
4     $\widetilde{g} = \widetilde{g} \setminus g_l$;
5   **else**
6     $k = \arg\min_{i \in g_l} b_i$;
7     $\sigma_l = b_l * (|g_l| - 1)$;
8     $g_l = g_l \setminus \beta_k$;
9   **end**
10 **end**

C. Winner Determination

The auctioneer determines the winning groups and assigns channels to them in the *Winner Determination* phase (described in Algorithm 4), which consists of two steps: *pre-allocation* (line 2-9) and *risk control* (line 11-22).

In the pre-allocation step, channels are allocated to winning groups, for which the pre-allocation results will be adjusted or optimized later. Let $\widetilde{\mathcal{C}_t}$ denote the set of channels whose sensed states are idle, and those channels in $\widetilde{\mathcal{C}_t}$ are sorted in decreasing order by P_0, which is the probability of allocating a channel to bidders without interference (line 2). Groups are also sorted in decreasing order by their group bids (line 3). Then the auctioneer allocates sorted channels to sorted groups in order (line 6-9). The per time slot payment of each winner is

$$p_i = \frac{\sigma_l}{|g_l|},\ i \in g_l, \tag{8}$$

and no payment is made to losing bidders.

In the risk control step, since the actual state of channels is unknown, the auctioneer should estimate the loss by the probability of misdetection and withdraw some allocation results that are too risky. Loss happens when the auctioneer making an allocation which results in interference between a PU and a bidder. As a punishment, she compensates that PU with c_{inter} and return partial payment back to that bidder. According to Equation 2, as the auctioneer only allocates idle channels, interference happens with a probability of $1 - P_0(j)$ when allocating channel j to bidders. Assume that t_m is the max duration time in group g_l, then the expected loss of allocating channel j to g_l $\phi_{l,j}$ is

$$\phi_{l,j} = \sum_{\tau=1}^{t_m} P_0(j)^{\tau-1}(1 - P_0(j))c_{inter}. \tag{9}$$

The expected profit of allocating channel j to group l $\psi_{l,j}$ for the auctioneer is

$$\psi_{l,j} = \sum_{i \in g_l} p_i t_i - \phi_{l,j}. \tag{10}$$

If $\psi_{l,j} \geq 0$, the auctioneer allocates channel j to bidders in g_l except the bidder with the minimum bid in g_l. Otherwise, the auctioneer does not allocate channel j to group g_l because its expected loss is too high. In Algorithm 4, line 12-15 and Line 16 are the processes of computing expected loss $\phi_{l,j}$ and $\psi_{l,j}$, separately. After that, line 17-22 determine whether to withdraws some allocation results or not. In a word, pre-allocation is the result of intermediate allocation based on group bids and channel states, while this intermediate allocation will turn into final allocation after risk control.

Algorithm 4: Winner Determination

Input: The set of channels $\widetilde{\mathcal{C}}_t$, groups set $\widetilde{g}$
Output: The winner set $\mathcal{W}$
1 // *pre-allocation*
2 $\mathcal{W} \leftarrow$;
3 Sorting $\widetilde{\mathcal{C}}_t$ by P_0 in decreasing order.
4 Sorting $\widetilde{g}$ by σ in decreasing order.
5 **while** $\left|\widetilde{\mathcal{C}}_t\right| \neq 0$ *and* $|\widetilde{g}| \neq 0$ **do**
6   channel j = TOP($\widetilde{\mathcal{C}}_t$);
7     $\widetilde{\mathcal{C}}_t = \widetilde{\mathcal{C}}_t \setminus$ channel j;
8   g_l = TOP($\widetilde{g}$);
9     $\widetilde{g} = \widetilde{g} \setminus g_l$;
10   // *risk-control*
11     $\phi_{l,j} = 0$, τ=1;
12   **while** $\tau \leq t_m$ **do**
13         $\phi_{l,j} = P_0(j)^{\tau-1}(1 - P_0(j))c_{inter}$;
14         $\tau = \tau + 1$;
15   **end**
16     $\psi_{l,j} = \sum_{i \in g_l} p_i t_i - \phi_{l,j}$;
17   **if** $\psi_{l,j} \geq$ **then**
18   **for** *bidder* $i \in g_l$ **do**
19             $\mathcal{W} \leftarrow$ bidder i;
20             $x_{i,j}(t) = 1$;
21   **end**
22   **end**
23 **end**

For the example in Fig.3, because the sensed state of channel 3 is busy, the auctioneer does not allocate channel 3, which means the available channels are channel 1 and channel 2. In the pre-allocation step, the auctioneer allocates channel 2 and channel 1 to g_1 and g_2, respectively.

As $\phi_{1,2} > 0$ and $\phi_{2,1} > 0$, the auctioneer allocates channel 1 to g_1 and channel 2 to g_2. As a result, bidder A wins channel 2 for 3 time slots and bidder B is allocated with channel 1 for 2 time slots.

D. Virtual Request Reallocation

In the beginning of each time slot, if the state of an allocated channel is idle in this time slot, bidders continue to use this idle channel. In contrast, if the state of an allocated channel changes into busy in the beginning of a time slot,the auctioneer needs to specially handle this case. Let $\mathcal{R}'_t$ denote the set of affected requests allocating with idle channels whose states change into busy.

Assume that the auctioneer allocates channel j to bidder i from time slot a_i to $a_i + t_i - 1$, and the state of channel j changes from idle into busy at $a_t(a_i < a_t < a_t + t_i)$. The remain service time will be regarded as a virtual request $\widehat{\beta}_i = (b_i, a'_i, t'_i)$ of bidder i. For the new virtual request $\widehat{\beta}_i$, the per time bid value b_i remains the same, $a'_i = a_t$, and $t'_i = a_i + t_i - a_t$. Moreover, $\widehat{\beta}_i$ will be added in $\mathcal{R}_{a_t}$, and considered as a normal request submitted at a_t. If the virtual request $\widehat{\beta}_i$ wins, bidder i will be allocated with another idle channel from time slot a_t for ${t_i}'$ time slots, unless the new allocated idle channel changes into busy during the new service time. And if a virtual request loses, bidders in it cannot use any channel in the rest of the time. In all, as shown in Algorithm 5, at the beginning of each time slot t, FORTUNE checks all bidders and generates the set of virtual requests $\mathcal{V}_t$, then add $\mathcal{V}_t$ in $\mathcal{R}_t$.

Algorithm 5: Reallocation

Input: The set of affected requests $\mathcal{R}'_{a_t}$
Output: The set of virtual requests $\mathcal{V}_{a_t}$
$\mathcal{V}_{a_t} \leftarrow$;
for $\beta_i = (b_i, a_i, t_i) \in \mathcal{R}'_t$ **do**
    $a'_i = a_t$;
    $t'_i = a_i + t_i - a_t$;
    $\mathcal{V}_{a_r} \leftarrow \widehat{\beta}_i = (b_i, a'_i, t'_i)$;
end

For the above example, at time slot 2, channel 2 changes into busy and channel 3 changes into idle. FORTUNE generates a virtual request $\widehat{\beta}_A = (b_A, a'_A, t'_A)$, in which $b_A = 3$, $a'_A = 2, t'_A = 1 + 3 - 2 = 2$. $\widehat{\beta}_A$ will be added in $\mathcal{R}_2$, and if bidder A wins in time slot 2, she will be authorized to use channel 3 from time slot 2 to 3. Otherwise, she cannot use any channel.

V. Theoretical Analysis

Lemma 1: FORTUNE is individual rational.

Proof: Since no payment are made to losing bidders, their utilities are 0. For each winning bidder i, according to Equation 7 and 8, p_i is the smallest bid value in the group, which means $p_i \leq b_i$. Therefore, $u_i \geq 0$, and FORTUNE is individual rational.

Lemma 2: FORTUNE is truthful.

Proof: Bidder i is untruthful when her bid value is not equal to her true valuation, i.e., ${b_i}' \neq v_i$. As shown in TABLE VII, there are 4 cases for a bidder bidding truthfully or untruthfully, and we prove that any bidder cannot obtain a higher utility by a cheating bid in these four cases. Since the grouping algorithm is independent to bid values, the grouping results with truthful bidding and untruthful bidding are the same in all cases. We assume that $g_{\hat{i}}$ is the group that contains bidder i.

- **Case 1:** Bidder i loses whether she bids truthfully or not, and the utilities are 0 in both cases. As a result, the case does not work.
- **Case 2:** Bidder i loses when she bids untruthfully and the utility is 0. From Theorem 1, $u_i \geq 0$ if bidder i is a winner. Thus, the utility of bidding truthfully is not less than that of bidding untruthfully. Therefore, this is a case of failure.

TABLE VII
THERE ARE 4 CASES FOR A BIDDER TO BID TRUTHFULLY OR UNTRUTHFULLY. THE SIGN $\surd$ MEANS A BIDDER WINS AND THE SIGN X MEANS SHE LOSES

Case	1	2	3	4
The bidder bids untruthfully	X	X	$\surd$	$\surd$
The bidder bids truthfully	X	$\surd$	X	$\surd$

- **Case 3:** There are two situations for this case: when bidder i bids truthfully, $g_{\hat{i}}$ is a losing group, or $g_{\hat{i}}$ is a winning group and bidder i is the bidder with the smallest bid value in $g_{\hat{i}}$. In both two situations, bidder i should increase her bid value and make it not the smallest bid value in $g_{\hat{i}}$. Let bidder k denote the bidder with the smallest bid value in $g_{\hat{i}}$ when bidder i bids $b_i{}'$. For bidder i wins when she bids untruthfully and bidder i loses when she bids truthfully, we can deduce that $b_i{}' \geq b_k \geq v_i$. According to Equation 8, $p_i = b_k$, thus $u_i{}' \leq 0$ when bidder i bids with b_i, which is not more than the utility when bidding with v_i. Therefore, this case fails.
- **Case 4:** This case should consider the probability that interference occurs. As shown in Equation 2, when the auctioneer allocates channel j to bidders, the probability of no interference is $P_0(j)$. For bidder i, before interference occurs, the number of time slots using channel j follows a geometric distribution, and the probability of interference happening is $1 - P_0(k)$. Thus, her expected utility when allocating channel j to her is

$$U_e = \frac{P_0(k)}{1 - P_0(k)}(v_i - p_i). \tag{11}$$

The expected utility depends on not only the difference between true valuation and payment, but also the probability of allocating channel k to bidders without interference. As the p_i depends on the minimum bid value in $g_{\hat{i}}$, which is unchanged no matter which channel bidder i is allocated with. As a result, bidder i's expected utility is positively correlated with $P_0(j)$. And we will prove that bidder cannot obtain a higher $P_0(j)$ by biding untruthfully.

In the winner determination phase, FORTUNE sorts the available channels in decreasing order by P_0 and sorts groups in decreasing order by their group bids. If bidder i wants to use a channel with a higher P_0, she should increase the group bid $\sigma_{\hat{i}}$ to provide $g_{\hat{i}}$ a higher ranking. However, each bidder i has no incentive to alter the group bid $\sigma_{\hat{i}}$, due to the fact that $\sigma_{\hat{i}}$ depends on the minimum bid value in $g_{\hat{i}}$ and the bidder with the minimum bid value is eliminated. Thus, bidder i cannot alter the allocation results and obtain a higher expected utility.

From the above, we prove that FORTUNE is truthful for no bidder can gain a higher utility when bidding untruthfully.

VI. PERFORMANCE EVALUATION

A. Simulation Setup

In our simulations, we deploy bidders following independent uniform distribution in a $2000 \times 2000m^2$ square area. Same as in [2] and [36], the interference range is set to be $425m$, which is 1.7 times the outdoor transmission range $(250m)$ in IEEE 802.11n. If the distance of two bidders' is less than the interference range, they will interfere with each other. At the beginning of each time slot, the probability of a bidder submitting a request is 50%. As for a request $\beta_i = (b_i, a_i, t_i)$, b_i and t_i are randomly distributed in $(0, 2]$ and $(0, 6]$, respectively. The probability of miss detection is randomly distributed in $(0.05, 0.3]$, and at the beginning of each time slot, the probability of a channel changing state is 10%.

The number of bidders N, channels M and total time slots T vary from 50 to 300, from 5 to 40, from 5 to 40, respectively. In the simulations, we vary only one factor while fixing other factors.

We use FORTUNE, LOTUS [3], and Li's design [34], which refer to as 'Base' in the following, to conduct the simulation experiments. In addition, in order to verify the effect of screening, we also added Fortune without screening phase in experiments as a comparison.

B. Efficiency

In the simulations, some metrics are used to evaluate spectrum allocation efficiency, which are as follows:

- *Channel utilization*: The average number of bidders allocated with one channel.
- *Fairness*: The value that determine whether bidders are receiving a fair share of channels.

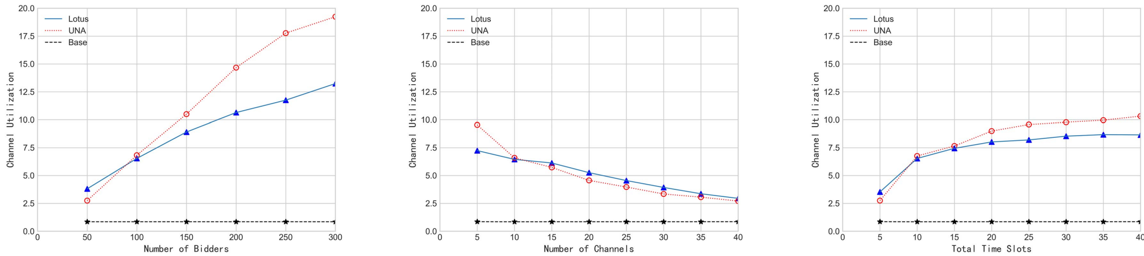
1) Results on channel utilization: The evaluation results on channel utilization are shown in Fig.4.

The relationship between channel utilization and the number of bidders is shown in Fig.4(a). Channel utilization increases with the increase of the number of bidders in both LOTUS and FORTUNE, but the difference between them also increases. For the reason that LOTUS may allocate a channel whose actual state is busy to winning groups, which results in no allocation of some idle channels and the decrease of channel utilization. The channel utilization on the number of channels is shown in Fig.4(b), channel utilization decreases when the number of channels rises up. The reason of it is that the number of bidders is fixed, leading to some idle channels not allocated to bidders. Fig.4(c) shows the channel utilization on the number of total time slots. With the increasing of total time slots, channel utilization gradually tends to be stable, which means that the number of total time slots has little effect on channel utilization. As for Base, it does not consider spatial reusability and a channel is allocated to one bidder in each time slot, which makes channel utilization almost unchanged in all situations. As a result, FORTUNE can obtain a higher utilization than others in nondeterministic spectrum allocation.

2) Results on fairness: We evaluate the fairness by using Jain's fairness index [37], which is defined as

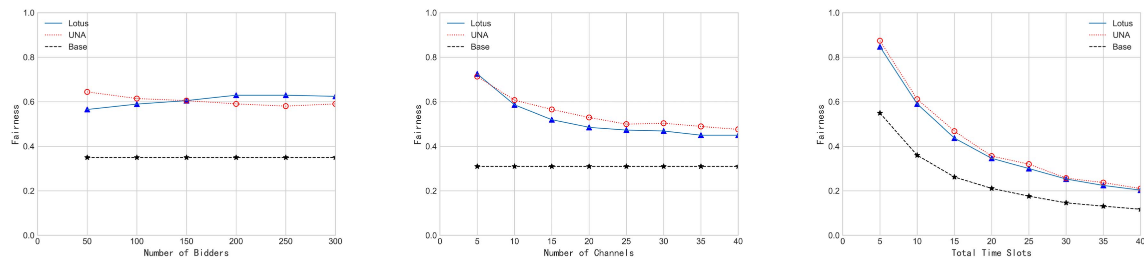
$$J = \frac{(\sum_{i \in W} a_i)^2}{|W| \cdot \sum_{i \in W} a_i^2}, \tag{12}$$

where a_i is the number of channels allocated to bidder i and W is the set of winning bidders. The value ranges from $\frac{1}{|W|}$ (the worst case) to 1 (the best case).



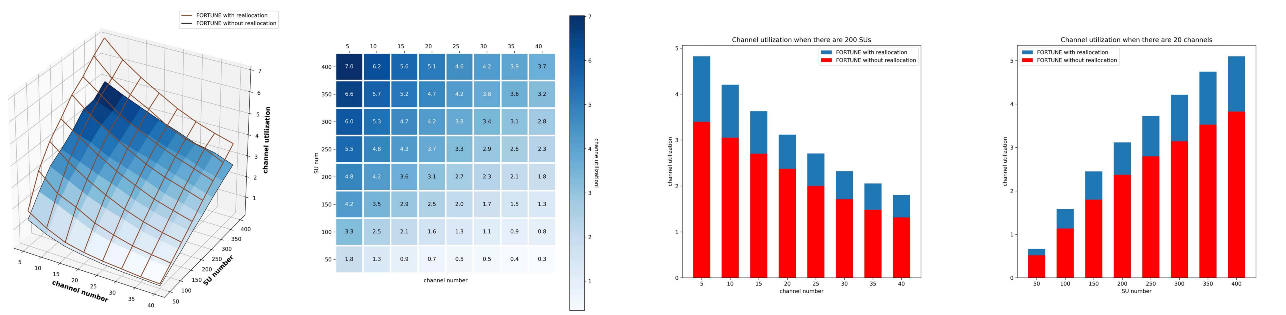
(a) (b) (c)

Fig. 4. Channel utilization of FORTUNE, FORTUNE without screening phase, LOTUS and Base. (a) Effect of the number of bidders. (b) Effect of the number of channels. (c) Effect of total time slots.



(a) (b) (c)

Fig. 5. Fairness of FORTUNE, FORTUNE without screening phase, LOTUS and Base. (a) Effect of the number of bidders. (b) Effect of the number of channels. (c) Effect of total time slots.



(a) Channel utilization in FORTUNE with and without reallocation. (b) Channel utilization with reallocation. (c) The change of channel utilization with respect of channel number. (d) The change of channel utilization with respect of SU number.

Fig. 6. Simulation of FORTUNE with and without reallocation.

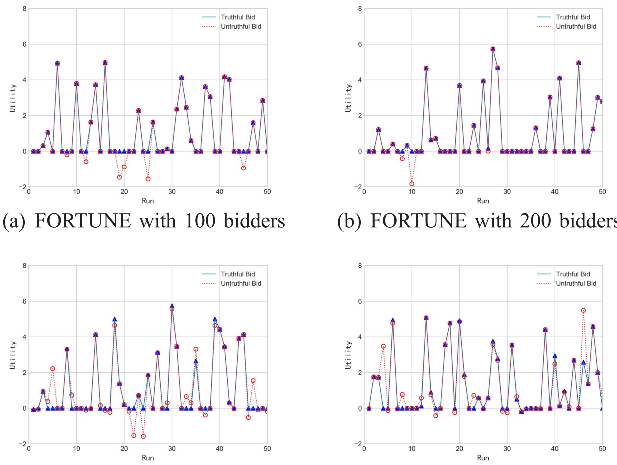
The evaluation results on fairness are shown in Fig.5(a). There is not much difference between FORTUNE and LOTUS, and fairness of them are remarkably higher than that of Base. It is for the reason that Base does not consider spectrum spatial reusability and allocates a channel to one bidder per time slot, thus channels are more likely only allocated to the bidders with higher true valuations.

Moreover, from Fig.4(a) to Fig.5(c), the channel utilization and fairness of FORTUNE with screening are always higher than those of FORTUNE without screening, which verifies the effectiveness of screening phase of FORTUNE.

C. Reallocation

Due to imperfect spectrum sensing, an allocated channel m may turn into busy in the coming time slot t. To avoid Interference, FORTUNE does not allow second users who transmit information on channel m in time slot $t-1$ continue using the same channel in time slot t. For the purpose of improving channel utilization, FORTUNE resets those requests that were stopped in the middle as virtual requests, which is called reallocation in Section IV. In this subsection, we make a simulation to see how much reallocation improves channel utilization.

As shown in Fig.6(a), the channel utilization in FORTUNE with reallocation are higher than without reallocation under different parameters. Fig.6(b) presents the channel utilization of FORTUNE with reallocation under different settings. From Fig.6(c) and Fig.6(d), we can observe that the trend of utilization in different settings is consistent with the previous discussion. It's worth noting that the difference of channel utilization between FORTUNE with and without reallocation becomes smaller as channel number increases, which is in turn when SU number arises. This implies that when the channel is relatively sufficient, the role of reallocation is not very important, otherwise, it plays a key role. Considering that spectrum resources in real life are already very limited, we believe that reallocation will be crucial in nondeterministic spectrum allocation.



(a) FORTUNE with 100 bidders (b) FORTUNE with 200 bidders

(c) LOTUS with 100 bidders (d) LOTUS with 200 bidders

Fig. 7. Utilities by bidding truthfully and untruthfully in FORTUNE and LOTUS.

D. Truthfulness

In this subsection, simulation results are used to verify the truthfulness of FORTUNE.

In simulations of FORTUNE and LOTUS, we randomly select a bidder and record the utilities she obtains by bidding truthful and untruthfully, respectively, while other parameters remain the same. We vary the number of bidders in both mechanisms and run the experiment 50 times in each situation. As shown in Fig.7(a) and Fig.7(b), the selected bidder cannot improve her utility by bidding untruthfully, and obtain the same or lower utilities conversely, which verified the truthfulness of FORTUNE. The results of the same experiments in LOTUS is shown in Fig.7(c) and Fig.7(d), and the selected bidder can gain higher utilities by cheating bids than truthful bids. Simulation results show that FORTUNE is a truthful mechanism under uncertain spectrum availability and LOTUS does not achieve truthfulness.

VII. Conclusion

In this paper, we introduce an online nondeterministic spectrum allocation problem and some challenges it faces. Through simulations, we demonstrate that existing mechanisms designed for deterministic allocation cannot be directly applied to nondeterministic allocation because the auctioneer may gain negative utilities in this scenario. We then proposed FORTUNE, the first truthful online mechanism under uncertain spectrum availability. In order to obtain a higher channel utilization, FORTUNE eliminates some bidders who have large impacts on their neighbor bidders. Then, a sorting and winner determination method is presented to realize the truthfulness of bidders. Evaluation results show that FORTUNE achieves not only truthfulness, but also up to 50% higher channel utilization than LOTUS under uncertain spectrum availability.

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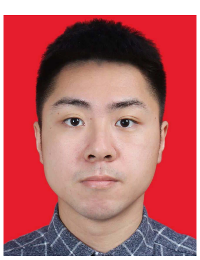

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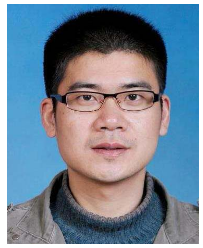

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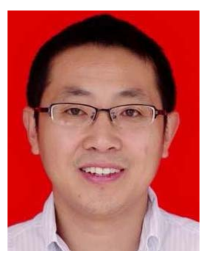

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