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ORIGINAL ARTICLE

A truthful auction mechanism for channel allocation in multi-radio, multi-channel non-cooperative wireless networks

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Abstract Due to users' fast-growing demands, wireless spectrum is becoming a more and more scarce resource. However, the state of spectrum usage shows that while large chunks of spectrum are left idle at many places, many emerging wireless applications cannot get enough spectra to provide their services. In contrast to existing truthful mechanisms for channel redistribution, which achieve strategy-proofness at the price of lowered system performance, we propose SHIELD, which not only guarantees strategy-proofness in the process of channel redistribution, but also achieves high system performance. Our evaluation results show that SHIELD outperforms the existing mechanisms, in terms of spectrum utilization and user satisfaction ratio. Here, channel utilization represents the average number of radios allocated to channels, and buyer satisfaction ratio shows the percentage of buyers who get at least one channel in the auction.

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1 Introduction

As the fast development of the communication technologies, the spectrum is becoming a more and more scarce resource. It is expected that global mobile data traffic will increase 26-fold between 2010 and 2015 [6]. To adapt the fast growth of data traffic over wireless links, next generation wireless applications need more spectrum to carry their services. However, traditional spectrum management makes new wireless network applications face the plight of increasingly scarce spectrum resources. Currently, almost every country has a specific department for regulating spectrum usage, e.g., Federal Communications Commission (FCC) [12] in the US and Radio Administration Bureau (RAB) in China [31]. FCC and RAB divide available wireless spectrum into a number of bands and grant the right of using each band within a specified geographical area to a particular business organization or wireless application. Traditional static spectrum allocation has been unable to meet the growing demand for wireless broadband services [13]. On one hand, frequency bands for wireless communications have almost been fully allocated [11]. On the other hand, already allocated spectrum is not fully utilized. For example, measurement results show that in downtown Berkeley, the utilization of spectrum up to 3 GHz is only about 32 %, while for the spectrum of 3–5 GHz, the utilization is less than 1 % [49]. Therefore, to improve the spectrum utilization, we need to find a more efficient mechanism to redistribute the idle spectrum to the wireless applications that need the spectrum resource.

A usual way to implement spectrum redistribution is to use auction, by which the spectrum owner (seller) gets profit through leasing idle spectrum to the wireless applications (buyers) who need the spectrum. In the literature, there are a number of auction mechanisms proposed for dynamic spectrum/channel redistribution, e.g., [43, 55–57]. These auction mechanisms target at guaranteeing strategy-proofness of the spectrum auction. Intuitively, an auction mechanism is strategy-proof, if it is the best strategy for each buyer to truthfully report her valuation of the good as the bid, no matter what the others do, and nobody's individual-rationality is hurt. Two commonly used metrics for evaluating the efficiency of a spectrum auction mechanism are spectrum utilization and buyer satisfaction ratio. Here, spectrum utilization captures the average number of buyers (or radios if the buyers have multiple radios) correspond to each channel, and buyer satisfaction ratio represents the percentage of buyers who get at least one channel in the auction. Although most of existing channel auction mechanisms achieve strategy-proofness, they provide low guarantee for the allocation efficiency in terms of spectrum utilization and buyer satisfaction ratio.

In this paper, we propose SHIELD, which is a strategy-proof and highly efficient channel auction mechanism for multi-radio wireless networks. SHIELD not only guarantees strategy-proofness, but also achieves high performance compared with existing mechanisms. SHIELD divides the buyers into non-conflicting groups, in which every pair of buyers is well separated and can do the transmission on the same channel simultaneously, and gives larger groups higher precedence to be allocated a channel. We also do some improvements for SHIELD and name the mechanism as Fair-SHIELD. Fair-SHIELD achieves fairness in repeated auctions. In this paper, we make the following key contributions.

- First, we model the problem of channel redistribution as a sealed-bid auction and propose a simple but efficient channel auction mechanism, namely SHIELD.
- Second, we prove that SHIELD is a strategy-proof channel auction mechanism.
- Third, we do some improvements for SHIELD and design Fair-SHIELD. Fair-SHIELD can achieve fairness in repeated auctions.
- Forth, we do extensive simulations to compare the performance of SHIELD with existing representative channel auction mechanisms, such as SMALL and VERITAS. Evaluation results verify that SHIELD guarantees strategy-proofness and show that SHIELD outperforms existing representative channel auction mechanisms in terms of spectrum utilization and user satisfaction ratio. We also do simulations to show the performance of Fair-SHIELD, and the evaluation results show that Fair-SHIELD achieves fairness in repeated auctions.

We organize the rest of this paper as follows. In Sect. 2, we present the game model for the problem of channel redistribution and review some important solution concepts from game theory. In Sect. 3, we give the detailed description of SHIELD. In Sect. 4, we show the design of Fair-SHIELD, which can achieve fairness in repeated auctions. In Sect. 5, we illustrate simulation results of our auction mechanism. In Sect. 6, we discuss related works. In Sect. 7, we conclude the paper and point out potential directions for future work.

2 Preliminaries

In this section, we show our game-theoretic model and review some closely related solution concepts from game theory.

2.1 Game-theoretic model

We model the problem of channel redistribution as a sealed-bid auction, in which there are a spectrum seller and a number of buyers, as shown in Fig. 1. The seller holds m idle wireless channels, denoted by $C = \{c_1, c_2, \ldots, c_m\}$. The seller wants to lease her idle channels to buyers to get some profit. A channel can be leased to multiple buyers, who are not conflicting with each other according to an adequate signal-to-interference- and-noise ratio (SINR). Buyers, such as WiFi access points, desperately need the channels to serve their customers. Suppose there are n buyers, denoted by $N = \{1, 2, \ldots, n\}$. Each buyer has a private valuation of a channel, denoted by $v = \{v_1, v_2, \ldots, v_n\}$. Each buyer may equip with a single radio or multiple radios, so a buyer may bid for one or multiple channels. We assume that each channel is of the same value to each buyer. Therefore, we require that each buyer bids equally for each channel she requests. We also assume that the buyers do not cheat about the number of radios she has. Each buyer $i \in N$ has a per-channel valuation v_i. The per-channel valuation can be the revenue gained by the buyer for serving her customers. The channel valuation v_i is private information to the buyer i. In the auction, each buyer submits her sealed per-channel bid b_i together with the number of radios r_i she has to the seller/auctioneer. The seller/auctioneer will decide auction result based on the buyers' bids. Then, we can represent the buyers' bid vector as $b = (b_1, b_2, \ldots, b_n)$, and demand vector as $r = (r_1, r_2, \ldots, r_n)$.

The seller/auctioneer uses a deterministic channel allocation algorithm to determine the channel allocation $y =$

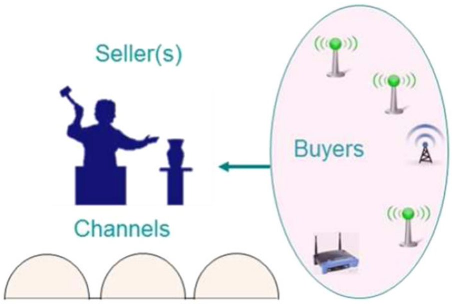

Fig. 1 A simple and ordinal channel auction model, including a seller (auctioneer) and multiple buyers

$(y_1, y_2..., y_n)$ based on the bids. Here, y_i means that buyer i gets y_i channels in the auction. Then, the kth ($k \le y_i$) radio of buyer i can work on the kth channel allocated to i. Each buyer i should pay for the channels she won in the auction with price $p_i = \sum_{k=1}^{y_i} p_i^k$. Here, p_i^k represents the charge to buyer i's kth channel. The utility u_i of buyer i is defined as the difference between her valuation of allocated channels and the charge of using the channels:

$$u_i = \sum_{k=1}^{y_i} u_i^k = \sum_{k=1}^{y_i} (v_i - p_i^k) = v_i \cdot y_i - p_i.$$

Here, u_i^k represents the utility of buyer i gets on the kth channel. We assume that the buyers are rational and always want to maximize their own utilities. In contrast to an individual buyer's objective, our auction mechanism aims to achieve high channel allocation efficiency, in terms of spectrum utilization and buyer satisfaction ratio.

Here, we use an example to show that traditional VCG auction model [7, 18, 36] cannot guarantee strategy-proofness for spectrum auction. VCG auction model sorts the bidders in non-increasing order and then allocates the channels to the bidders one by one using lowest indexed channel in each bidder's available channel set. The charge to bidder i is the bid of the bidder who would get the channel if bidder i is absent. We model the interference among bidders using a conflict graph, which means that two bidders cannot use the same channel simultaneously if there is an edge between each other. Figure 2 shows a simple example to illustrate that the VCG auction violates strategy-proofness. We assume that there are two channels waiting to be leased out. In Fig. 2a, all the bidders bid truthfully and in Fig. 2b, bidder E bids untruthfully. Table 1 shows the utilities of all the bidders when E bids truthfully and untruthfully. We can see that when E bids $b_E = v_E = 4$, he loses in the auction and get utility of 0. When he bids $b_E = 6 \neq v_E$, he wins in the auction and gets the utility of 2. The bidder E can increase his utility by bidding untruthfully. We can see that the traditional VCG auction model cannot guarantee strategy-proofness.

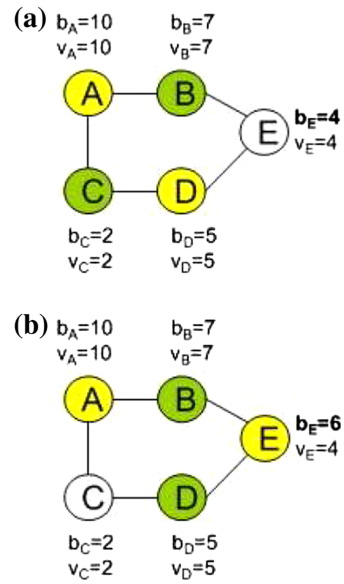

Fig. 2 A simple example which shows that traditional VCG auction model violates strategy-proofness. **a** When E bids truthfully, user A, B, C, D get the channel. **b** When E over bids, user A, B, D, E get the channel

Table 1 Utilities of all the bidders when E bids truthfully (Fig. 2a) and untruthfully (Fig. 2b)

Figure 2a	Figure 2b
$v_A = 10$, $b_A = 10$, $u_A = 6$	$v_A = 10$, $b_A = 10$, $u_A = 8$
$v_B = 7$, $b_B = 7$, $u_B = 3$	$v_B = 7$, $b_B = 7$, $u_B = 7$
$v_C = 2$, $b_C = 2$, $u_C = 2$	$v_C = 2$, $b_C = 2$, $u_C = 0$
$v_D = 5$, $b_D = 5$, $u_D = 1$	$v_D = 5$, $b_D = 5$, $u_D = 3$
$v_E = 4$, $b_E = 4$, $\mathbf{u_E = 0}$	$v_E = 4$, $\mathbf{b_E = 6}$, $\mathbf{u_E = 2}$

Bold is for differences between the two cases

In Sect. 3.1, we will present our strategy-proof channel auction mechanism—SHIELD.

2.2 Solution concepts

We review two important solution concepts from game theory in this section.

Definition 1 (*Dominant strategy* [15, 29]) A strategy s_i is player i's dominant strategy, if for any $s_i' \neq s_i$ and any strategy profile of the other players s_{-i}, her utility satisfies: $u(s_i, s_{-i}) \geq u(s_i', s_{-i})$.

In our game model, each buyer is a player, and s_i is a buyer i's bid.

A dominant strategy of a player is one that maximizes her utility regardless of what strategies the other players choose. Before defining *strategy-proofness*, we review the definition of *incentive-compatibility* and *individual-*

rationality. An auction mechanism is *incentive-compatible* if it is one's dominant strategy for bidding real valuation. *Individual-rationality* means that the buyers can always achieves at least as much utility from participating in the auction as staying outside.

Definition 2 (*Strategy-proof mechanism* [27, 34]) A mechanism is strategy-proof if it satisfies both incentive-compatibility and individual-rationality.

3 Design and analysis of SHIELD

In this section, we present detailed description of our channel allocation auction mechanism, namely SHIELD. SHIELD follows the design methodology of SMALL [43]. However, with a novel winner selection method, SHIELD greatly improves spectrum utilization and buyer satisfaction ratio.

3.1 Design of SHIELD

We now present the design of SHIELD. SHIELD works in three steps: buyer grouping, winner selection and charge determination.

When a buyer i is equipped with r_i radio(s), we use r_i elementary buyer(s) to represent the buyer i (e.g., Fig. 3). We use N' to denote the set of elementary buyers. Therefore, each elementary buyer requests only one channel. Actually, a buyer who is equipped with one radio is an elementary buyer herself. Similar to [43, 56], SHIELD groups the buyers in a bid-independent way. SHIELD models the interference among buyers using a conflict graph. Each node in the graph is an elementary buyer. For each radio equipped by a buyer, we use an elementary buyer to represent it. Each edge in the graph represents that the two elementary buyers who interfere with each other. Since the radios belonging to the same buyer have interference between each other, we connect the nodes/elementary buyers of the same buyer with each other to indicate the confliction. There are also conflicts across nodes/elementary buyers belonging to different buyers; we connect them with each other to represent the conflicts. Then SHIELD divides all the elementary buyers into non-conflicting groups based on the conflict graph. We can use existing graph coloring algorithms (e.g., [42]) to figure out the grouping.

Figure 3 shows a toy example. In Fig. 3, buyer A is equipped with two radios. Node A^1 and A^2 represent the two elementary buyers of buyer A. Similarly, B^1 and B^2 represent the two elementary buyers of buyer B. C^1 and C^2 represent the two elementary buyers of buyer C. There are seven elementary buyers. There are many possible grouping results, for example $g_1 = \{A^1, C^2\}$, $g_2 = \{A^2, B^1, D\}$ and $g_3 = \{B^2, C^1\}$.

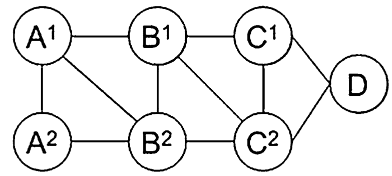

Fig. 3 A simple conflict graph, in which the node represents an elementary buyer and the link between two elementary buyers indicates the confliction

Without loss of generality, we assume that the elementary buyers have been divided into x non-conflicting groups by a given graph coloring algorithm:

$G: \{g_1, g_2, \ldots, g_x\}$.

Next, we discuss the very important step—winner selection. SHIELD sorts the buyer groups according to group size in non-increasing order as follows:

$G': |g'_1| \geq |g'_2| \geq \cdots \geq |g'_x|$.

In case of a tie, each tied group has an equal probability of being ordered prior to the others. SHIELD chooses the first m (or x, if $x < m$) groups as winning groups. Furthermore, SHIELD sets the elementary buyers except the one with the smallest bid in each winning group as winners. In case of a tie, each tied elementary buyer has an equal probability of being selected as a winner. Algorithm 1 shows the pseudocode for the winner selection process.

Algorithm 1 Winner Selection

Input: A set of elementary buyers N', a vector of channel demands r, a vector of bids b, a set of the idle channels C, the number of idle channels m.
Output: A set of winners W, an allocated matrix of channels T.

$sum\_r = \sum_{i=1}^{n} r_i$.
$T = 0^{sum\_r, m}$.
$(G, x) = Grouping(N')$.
$nc = \min\{m, x\}$.
$G' = Sort(G)$ based on group size.
for all $g'_j \in G'$ **do**
  if $nc \geq 0$ **then**
    $nc = nc - 1$.
    for all $i \in g'_j$ **do**
      $T_{ij} = 1$.
    end for
    $WS = g'_j - \{\underset{l \in g'_j}{argmin}(b_l)\}$.
    $W = W \cup WS$.
  end if
end for
return $W and T$.

We note that to achieve strategy-proofness, SHIELD sacrifices a buyer in each winning group. No matter how large the set of buyers is, the number of sacrificed buyers is bounded by m, which is the number of channels for leasing.

Finally, we determine the charges to the winners. The winners in each group are charged equally, and the charge is the smallest bid in that group. For each winner $l \in g'_j$, the payment for her is $\min\{b_q | q \in g'_j\}$. Then the charge p_i to a buyer $i \in N$ is the sum of charges to her winning elementary buyers. We note that since each elementary buyer will not be charged more than her bid. The seller's income is the payments for all the buyers who get the channels:

$$\text{Income} = \sum_{i=1}^{n} p_i.$$

To illustrative clearly, we use Fig. 3 as an example. We can see that $r_A = r_B = r_C = 2$ and $r_D = 1$. We assume that $b_A = 2$, $b_B = 5$, $b_C = 9$, $b_D = 1$ and the number of channels $m = 2$. What is more, we assume the buyers bid truthfully to illustrate the procedure of channel allocation. We use the three steps to allocate the channels to the four buyers.

– The same to above illustration, $g_1 = \{A^1, C^2\}$, $g_2 = \{A^2, B^1, D\}$ and $g_3 = \{B^2, C^1\}$.
– Here, G': $|g_2| \geq |g_3| \geq |g_1|$. There are 2 channels now, and two groups (here, g_2 and g_3) are the winning groups. We assume group g_2 gets channel 1 and g_3 gets channel 2. The elementary buyer with the lowest bid in each group will lose the auction. Here, $b_D < b_{A^2} < b_{B^1} (1 < 2 < 5)$ in group g_2 and $b_{B^2} < b_{C^1} (5 < 9)$, so the elementary buyer D and B^2 will lose in the auction and the elementary buyers A^2, B^1 and C^1 are the winners.
– The payment for each winner is the lowest bid in his buyer group. Here, the payment for elementary buyers A^2 and B^1 is elementary buyer D's bid which is 1. Similarly, the payment for elementary buyer C^1 is elementary buyer B^2's bid which is 5. We can see that $p_A^1 = 0$ and $p_A^2 = 1$, so $p_A = 1 + 0 = 1$. Similarly, $p_B = 1$, $p_C = 5$ and $p_D = 0$.

In this example, buyer A, B and C gets one channel, respectively. We can easily get the utility of each elementary buyer: $u_A = 2 - 1 = 1$, $u_B = 5 - 1$, $u_C = 9 - 5 = 4$ and $u_D = 0$. The seller's income is the payments for all the buyers who get the channels:

$$\text{Income} = \sum_{i=1}^{n} p_i = 1 + 5 + 0 = 6.$$

3.2 Analysis

In this section, we prove that SHIELD is strategy-proof, which means that reporting one's truthful per-channel valuation as a bid is the best strategy of each buyer.

Lemma 1 *SHIELD satisfies incentive-compatibility.*

Proof SHIELD use a bid-independent grouping method to group the elementary buyers. The bid of buyer i will not affect the winning group selection method. Next, we will show that no matter how a buyer bids, she cannot increase her utility by bidding untruthfully. In other words, a buyer cannot increase her utility by misreporting.

If buyer i bids truthfully (i.e., $b_i = v_i$) and gets y_i channel. Then her utility is

$$u_i = \sum_{k=1}^{y_i} u_i^k = \sum_{k=1}^{y_i} (v_i - p_i^k).$$

Let t be the kth one of the elementary buyers generated from buyer i. Suppose $t \in g'_j$. If g'_j is not a winning group, then t cannot be a winner no matter how buyer i bids. We then analyze the case, in which g'_j is a winning group. We prove that buyer cannot increase her utility get from elementary buyer t by bidding untruthfully. We distinguish two cases:

– If $b_i = v_i = \min\{b_s | s \in g_j\}$ when bidding truthfully. In this case, the elementary buyer t would lose in auction or win with a charge equal to her valuation. So $u_i^k = 0$. Let us see the utility get from the elementary buyer t if buyer i bids untruthfully. We further distinguish two cases:

If the bid $b'_i < b_i$, t will also lose in the auction and result in the utility $u_i^k = 0$.

If the bid $b'_i > b_i$, the utility on t is 0 when t still loses in the auction. If t wins in the auction, her utility will be $u'^k_i = v_i - p'^k_i$. That means the new lowest bid of the group $\min\{b_s | s \in g_j \backslash \{t\}\} b_i = v_i$.

$$b_i = v_i.$$

$$\begin{aligned} u'^k{}_i &= v_i - p'^k{}_i \\ &= v_i - \min\{b_s | s \in g_j \backslash \{t\}\} \\ &\leq v_i - b_i \\ &= 0. \end{aligned}$$

The utility on t will be non-positive. We can get that, if $b_i = v_i = \min\{b_s | s \in g_j\}$, no matter how i bids, she cannot improve her utility got on t and her utility on t will be no more than 0.

– If $b_i = v_i > \min\{b_s | s \in g_j \backslash \{t\}\}$, buyer t would win in the auction and get the utility $u_i^k = b_i - p_i^k = b_i - \min\{b_s | s \in g_j \backslash \{t\}\}$ if i reports her bid truthfully. If i bids untruthfully, the utility of the buyer will be also u_i^k or will become 0.
– Assume i bids $b'_i > \min\{b_s | s \in g_j\}$, t will win in the auction. Her utility will not change and is still $u'^k{}_i = v_i - \min\{b_s | s \in g_j \backslash \{t\}\} = u_i^k$ because the lowest bid of

the group has not changed. But if she loses the auction her utility will be 0.

We can see that for an elementary buyer t, she cannot improve her utility no matter how i bids , which can be indicated as: $u_i^k \geq u'^k_i$. As we supposed above, the elementary buyer t is the kth one generated from buyer i. For buyer i, her utility is

$$u_i = \sum_{k=1}^{y_i} u_i^k \geq \sum_{k=1}^{y_i} u'^k{}_i = u'_i.$$

The above analysis shows that bidding truthfully is the buyers' dominant strategy when participating in the auction. From the definition of incentive-compatibility, we can draw the conclusion of Lemma 1. □

We next show that SHIELD satisfies individual-rationality.

Lemma 2 *SHIELD satisfies individual-rationality.*

Proof For an elementary buyer t, she can get 0 or higher utility through participating in the auction truthfully. So the utility of the buyer who is equipped with more than one radios can get 0 or higher utility too. That is to say: truthfully participating in the auction is not worse than staying outside, which can be indicated as follows:

$$u_i^k \geq 0 (1 \leq k \leq y_i),$$

$$u_i = \sum_{k=1}^{y_i} u_i^k \geq 0.$$

Then the allocation mechanism satisfies individual-rationality. □

Since SHIELD satisfies both incentive-compatibility and individual-rationality, we can draw the following conclusion from the definition of strategy-proofness.

Theorem 1 *SHIELD is a strategy-proof channel auction mechanism.*

4 Fairness in repeated auctions using fair-SHIELD

We have shown the design of SHIELD used in single-round auction in Sect. 3.1. We now consider the scenario, in which the spectrum can be allocated to buyers repeatedly in multiple-round auctions.

SHIELD sacrifices the buyer with the lowest bid in each winning group to achieve strategy-proofness in a single-round auction. However, in repeated auctions, the buyer with the lowest bid would never get the channel using the same method as used in the single-round auction. Hence, fairness [17] is a very important issue in repeated auctions. Here, fairness means that each buyer can get the channel at least once within certain amount of time in repeated auctions. Unfortunately, SHIELD cannot guarantee fairness in repeated auctions, and it results in starvation. Therefore, SHIELD cannot be directly used in repeated auctions. To achieve fairness, we make some improvements to SHIELD, and we use Fair-SHIELD, to indicate the mechanism used in repeated auctions.

We now show the design of Fair-SHIELD. In repeated auctions, the total utility U_i of each buyer $i \in N$ is the sum of the utilities in all the rounds. We assume that we do the auction for α times, and the utility of a buyer $i \in N$ can be calculated as follows,

$$U_i = \sum_{k=1}^{\alpha} u_i^k.$$

We use the similar method of grouping in Fair-SHIELD as in SHIELD here. First, we sort the groups in non-decreasing order according to the group size.

$$G' : |g'_1| \geq |g'_2| \geq \cdots \geq |g'_x|.$$

In repeated auctions, we allocate the channels to the groups according to the order in G' iteratively. In each round auction, m groups would be selected as winning groups. In the first round, the winning groups are $g'_1, g'_2, \ldots g'_m$; In the second round, the winning groups are $g'_{m+1}, g'_{m+2}, \ldots, g'_{2m}$. In the λth round, the set of winning groups is

$$\{g'_{((\lambda-1)m+j-1) \bmod x+1} | j \in \{1, 2, \ldots, m\}\}.$$

Using this method, all the groups can be selected as winning groups in λ round auctions.

We use the same method as in SHIELD to select winners. In addition, to achieve fairness in repeated auctions, we introduce the concept of virtual bid, which is the product of the bid and a random number, to give any buyer in a winning group some possibility to get the channel. The random number is distributed in (0, 1], and we use $\varphi(i)$ to indicate the random number of buyer i's bid. Here, $\varphi(i)$ is regenerated in each round of auction. Then, the virtual bid b'_i of a player can be defined as follows:

$$b'_i = \varphi(i) \cdot b_i$$

Using the virtual bid, when the auction repeats for multiple-round auctions, the buyers can get the channel at least once in large enough numbers of auction rounds. In other words, Fair-SHIELD can achieve fairness in repeated auctions.

Finally, we determine the charge of the winners in each winning group. We charge the winners with different price in each winning group. Here, we set the charge to the winners in each winning group to be quotient of the lowest virtual bid divided by the random number of the winner's virtual bid. For instance, assume the virtual bid $b'_{min} =$

$\varphi(\tau) \cdot b_\tau$ is the lowest virtual bid and winner i's virtual bid is $b'_i = \varphi(i) \cdot b_i$ in winning group g, then the charge to the winner i in winning group g is as follows:

$$p_i = \frac{b'_{min}}{\varphi(i)} = \frac{\varphi(\tau) \cdot b_\tau}{\varphi(i)} = \frac{\varphi(\tau)}{\varphi(i)} \cdot b_\tau.$$

Intuitively, since the charges to the winners are independent of the winners' bids in each winning group, Fair-SHIELD can also achieve strategy-proofness. The proof is similar to that in Sect. 3.2. So we do not show the details of the proof again.

Theorem 2 *Fair-SHIELD is a strategy-proof channel auction mechanism in repeated auctions.*

5 Evaluation results

In this section, we show the evaluation results. Since the channel allocation mechanism SMALL [43] and VERITAS [55] are similar to our mechanism SHIELD (both can work when each buyer is equipped with a single or three radios), we compare the performance of SHIELD with SMALL and VERITAS.

5.1 Metrics

We use the following three metrics to evaluate the performance of the channel auction mechanisms.

- *Utility* Utility is defined as the difference between a buyer's channel valuation and charge. As we mentioned in Sect. 3.2, a buyer may bid truthfully or untruthfully. The utility reflect the impacts of buyers' behaviors including bidding truthfully and untruthfully. We use this metric in our evaluations to verify that no buyer can increase her utility by misreporting.
- *Spectrum utilization* Average number of radios allocated to each channel.
- *Buyer satisfaction ratio* Buyer satisfaction ratio is the percentage of the buyers who get at least one channel in the auction. Buyer satisfaction ratio and spectrum utilization reflect the performance of a channel auction mechanism.

5.2 Evaluation setup

We now show the settings of the evaluation: We use a greedy graph coloring algorithm [41] to implement SHIELD. We assume that there are 6, 12, or 24 idle channels available and evaluate the cases in which every buyer has a single radio or 3 radios. We vary the number of buyers from 20 to 400. The sized terrain area can be 1,000 × 1,000, 1,500 × 1,500 or 2,000 × 2,000 m. The interference range of each node is set to 425 m. We assume that buyers' valuation per channel is randomly distributed in (0, 1].

5.3 Evaluation results

In our first set of evaluations, we show that SHIELD ensures that no buyer can increase her utility by misreporting the per-channel valuation. We set the number of buyers to 200. We randomly choose a buyer to show the results of honest reporting and misreporting. Since the utilities of the buyers when bidding truthfully and untruthfully is the same in most of the cases, to illustrate clearly, we just show the cases in which these two utilities are different. The simulation is repeated more than 1,000 times. Figure 4 shows the results of buyer 55. Evaluation results of other nodes are similar to that of buyer 55 when bidding truthfully and untruthfully. When the two utilities are different, buyer 55 can always get a much higher utility when bidding truthfully. In Fig. 4, we can also get that when buyer 55 bids truthfully, the utility is always nonnegative, while bidding untruthfully can lead to negative utility. Therefore, a buyer cannot increase his utility by misreporting.

In our second set of evaluations, we compare the performance of SHIELD with SMALL and VERITAS, in terms of spectrum utilization and buyer satisfaction ratio. Our evaluation results show that SHIELD performs better than SMALL and VERITAS. When the buyers are extremely sparse, SHIELD performs a little bit worse than VERITAS. The reason for this is that SHIELD sacrifices a buyer in each winning group. As the number of buyers increases, SHIELD performs better than VERITAS. SHIELD always outperforms SMALL regardless of the number of buyers and the size of terrain area.

Figure 5 shows spectrum utilizations of SHIELD, SMALL and VERITAS under the condition that there are 6, 12 and 24 idle channels available. In this evaluation, we set the terrain area to 2,000 × 2,000 m. We can see from Fig. 5 that when the number of buyers is small, SHIELD achieves a little bit lower spectrum utilization than VERITAS. This is because VERITAS does not need to sacrifice any buyer. When the number of buyers is more than a critical value (e.g., 120 in Fig. 5a), SHIELD outperforms VERITAS. This is because non-grouping-based algorithm used in VERITAS fails to fully consider the whole network topology. Figure 5b and c show that, when each is equipped with three radios and the number of buyers is more than 80, SHIELD performs much better than SMALL and

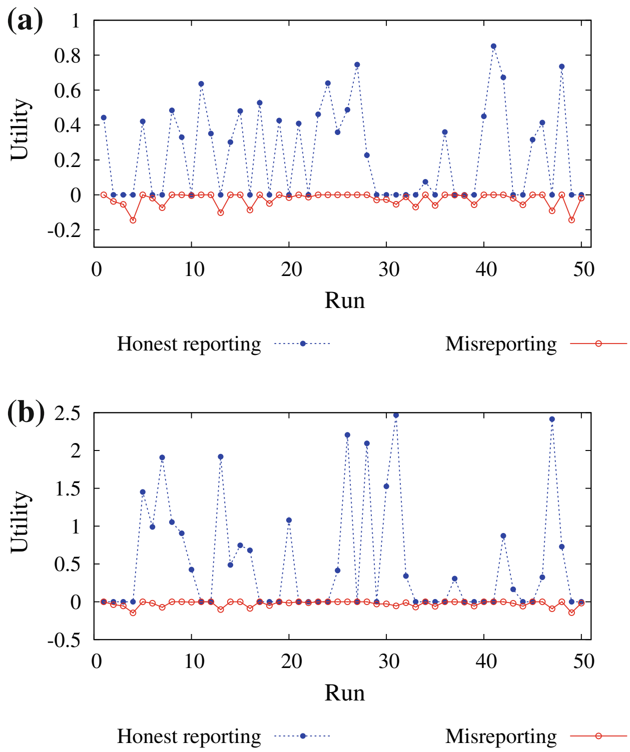

Fig. 4 Utilities of buyer 55 if she bids truthfully and untruthfully when each buyer is equipped with a single radio or three radios in a terrain area of 2,000 × 2,000 m. **a** Each buyer is equipped with a single radio. **b** Each buyer is equipped with three radios

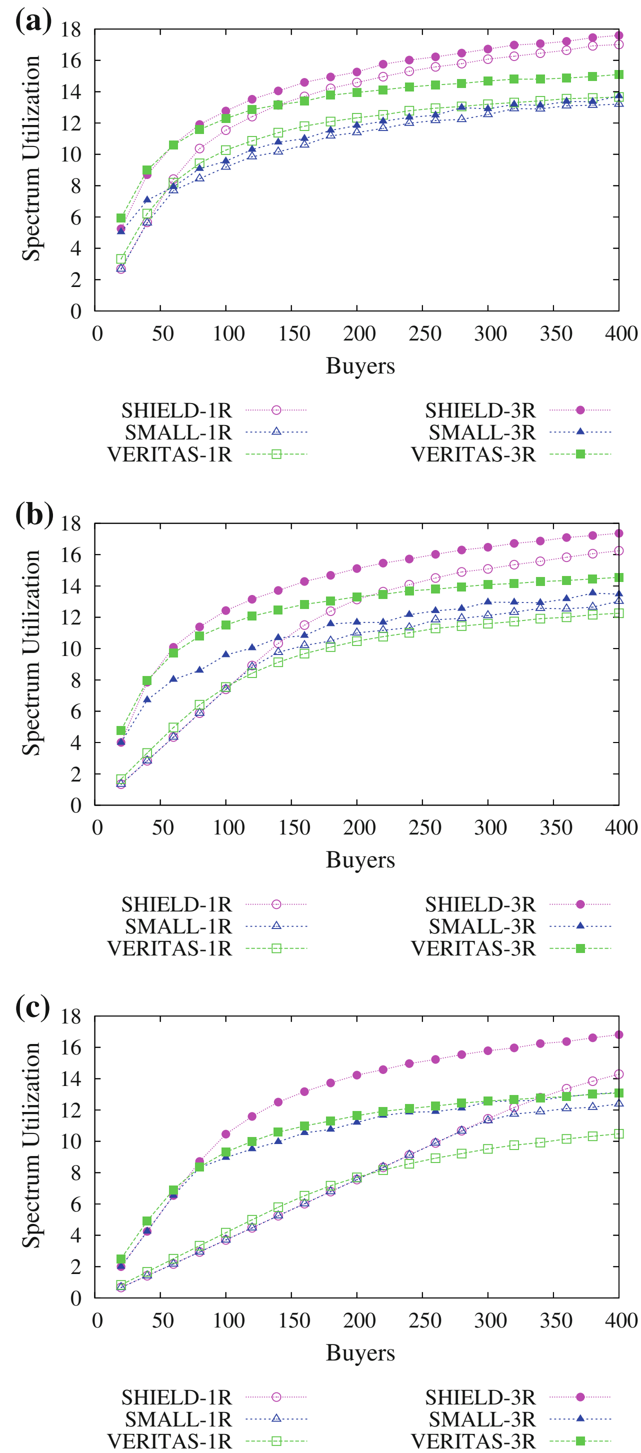

Fig. 5 Spectrum utilizations of SHIELD, SMALL and VERITAS when there are 6, 12 and 24 channels provided. Each buyer is equipped with one radio or three radios, in a terrain area of 2,000 × 2,000 m. **a** There are 6 channels available. **b** There are 12 channels available. **c** There are 24 channels available

VERITAS. SHIELD outperforms better than SMALL in most of the cases.

Figure 6 shows the spectrum utilizations of SHIELD, SMALL and VERITAS in different terrain areas with the same buyer density when each buyer is equipped with a single radio or three radios. We assume there are 80, 180 and 320 buyers that are randomly distributed in the terrain areas when the size of terrain area is 1,000 × 1,000, 1,500 × 1,500, and 2,000 × 2,000 m, respectively. We can see from Fig. 6 that SHIELD always performs not worse than SMALL and VERITAS. Especially when the terrain area is relatively large (1,500 × 1,500, and 2,000 × 2,000 m), SHIELD performs much better than SMALL and VERITAS.

Figure 7 shows the buyer satisfaction ratios of SHIELD, SMALL and VERITAS. In Fig. 7a, b and c, there are 6, 12 and 24 idle channels available, respectively. In each figure, we show the simulation results when each buyer requests only one radio or three radios in 2,000 × 2,000 m terrain area. We can see from Fig. 7 that when the number of buyers is very small, SHIELD performs a little worse than VERITAS. The reason for this is that SHIELD sacrifices a buyer in each winning group. When the number of buyers is a little larger, SHIELD and SMALL outperforms VERITAS. When each buyer is equipped with a single radios, Fig. 7b and c shows that SHIELD and SMALL get nearly the same buyer satisfaction ratios when the number of buyers is less than 125 and 310, respectively. This is

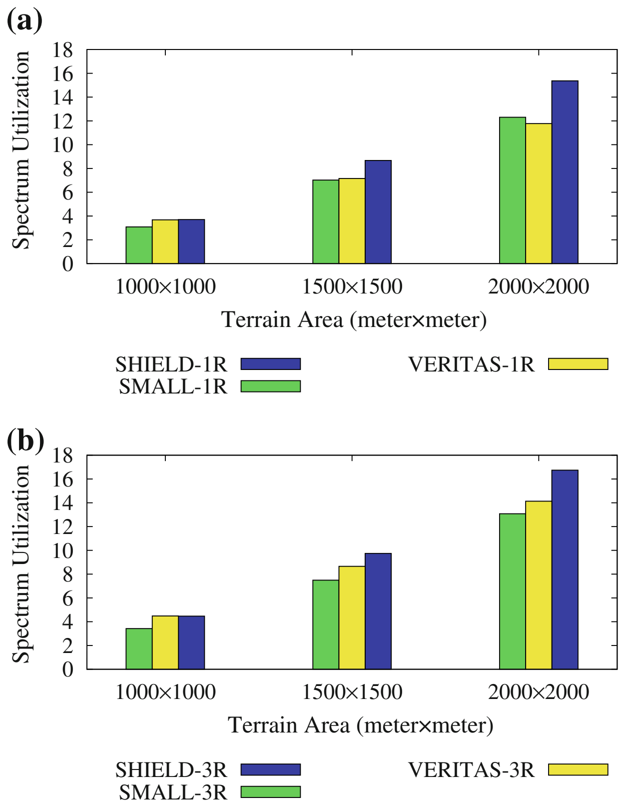

Fig. 6 Spectrum utilizations of SHIELD, SMALL and VERITAS for auctioning 12 channels with the same density of buyers in terrain areas with different sizes, when a buyer is equipped with one radio or three radios. **a** Each buyer is equipped with a single radio. **b** Each buyer is equipped with three radios

because SHIELD and SMALL use the same method of winner selection in one winning group. When each buyer is equipped with three radios, Fig. 7a and b show that SHIELD achieves higher buyer satisfaction ratios than SMALL and VERITAS in most of the cases. Figure 7a and b also show that when the number of buyers is very large, SHIELD and SMALL achieve more closer buyer satisfaction ratio and they both outperform VERITAS.

Figure 8 shows the buyer satisfaction ratios of SHIELD, SMALL and VERITAS for auctioning 12 channels in the same density of buyers in different terrain areas, when a buyer is equipped with one or three radios. We assume there are 80, 180 and 320 when the terrain area is 1,000 × 1,000, 1,500 × 1,500 and 2,000 × 2,000 m, respectively. The buyers are randomly distributed in the terrain area. We can see from Fig. 8 that SHIELD always performs not worse than SMALL and VERITAS. Especially when the terrain area is relatively large (1,500 × 1,500, and 2,000 × 2,000 m), SHIELD performs much better than SMALL and VERITAS.

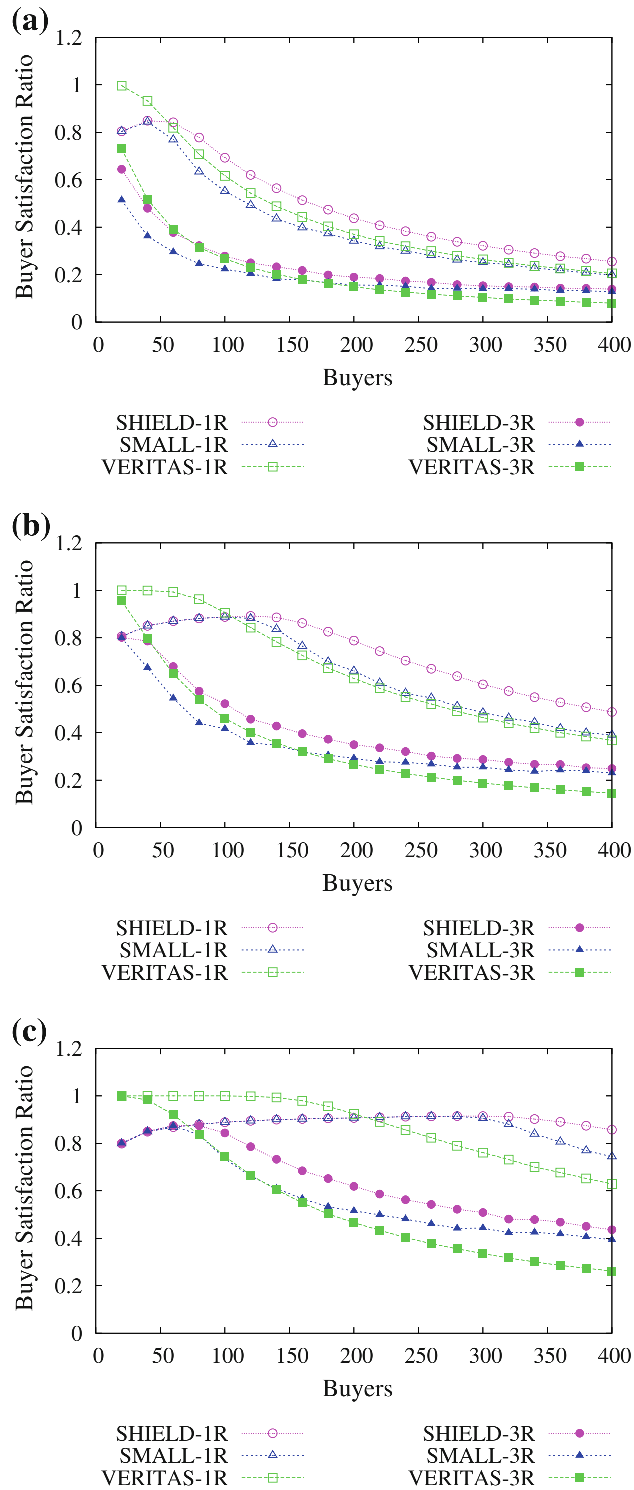

Fig. 7 Buyer satisfaction ratios of SHIELD, SMALL and VERITAS when there are 6, 12 and 24 channels provided. Each buyer is equipped with one radio or three radios, in a terrain area of 2,000 × 2,000 m. **a** There are 6 channels available. **b** There are 12 channels available. **c** There are 24 channels available

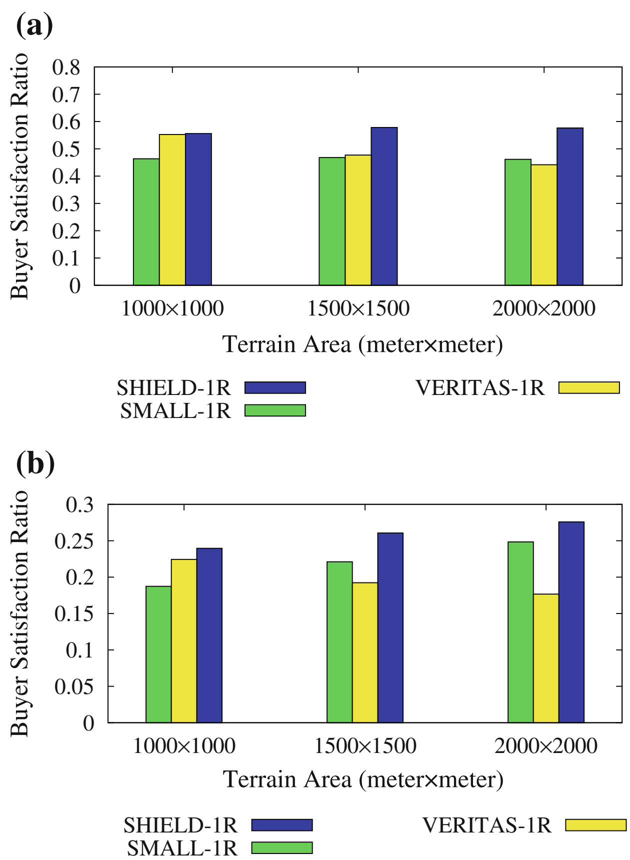

Fig. 8 Buyer satisfaction ratios of SHIELD, SMALL and VERITAS for auctioning 12 channels with the same buyers density in terrain areas of different sizes, when a buyer is equipped with one radio or three radios. **a** A buyer is equipped with a single radio. **b** A buyer is equipped with three radios

In our third set of evaluations, we do some experiments to show that Fair-SHIELD achieves fairness in repeated auctions. Here, we use the buyer satisfaction ratio in repeated auctions to evaluate the performance of Fair-SHIELD. Buyer satisfaction ratio of repeated auctions is the percentage of the all the buyers who get at least one channel in repeated auctions. We assume that there are 200 buyers, and 12 idle channels waiting to be leased out. We evaluate the cases in which each buyer is equipped with one or three radios. The size of the terrain area is 2,000 × 2,000 m.

Figure 9 shows the performance of Fair-SHIELD, when each buyer is equipped with one or three radios. We can see from Fig. 9 that Fair-SHIELD achieves very high buyer satisfaction radio in repeated auctions. When each buyer is equipped with a single radio, Fair-SHIELD achieves more than 50 % buyer satisfaction ratio if the auction repeats only once. What is more, Fair-SHIELD achieves more than 90 % buyer satisfaction ratio if the auction repeats more than 2 times. When the auction repeats more than 24 times, Fair-SHIELD achieves nearly 100 % buyer satisfaction ratio.

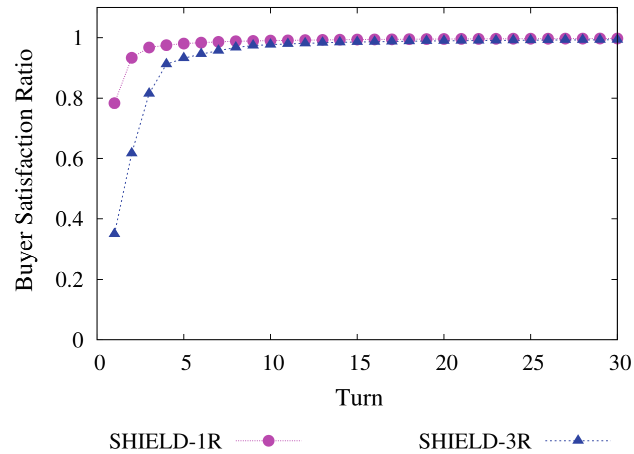

Fig. 9 Buyer satisfaction ratios of Fair-SHIELD, when each buyer is equipped with one or three radios

The reason for this is that we use virtual bid to determine the winners in each winning group, and this method lets all the buyers have the possibility to get channels when the auction repeats for many enough times. When each buyer is equipped with three radios, the evaluation results are similar. In general, Fig. 9 shows that Fair-SHIELD achieves very high satisfaction ratio in repeated auctions.

6 Related works

In this section, we review the related works on channel allocation with cooperative participants and non-cooperative participants.

6.1 Existing works with cooperation participants

Generally, channel assignment schemes in cellular networks can be categorized as fixed channel assignment (FCA), dynamic channel assignment (DCA) and hybrid channel assignment (HCA), which is a combination of FCA and DCA. Many works have been done for wireless LANs(WLANs). For example, Mishra et al. [28] explored the use of channel hopping to improve the fairness and performance of overlapping 802.11 network deployments.

Many works about the channel allocation problems have also been done in wireless mesh networks. For instance, Kodialam and Nandagopal [23, 24] considered the problem of optimal channel assignment, scheduling and routing using a linear programming technique. Rad et al. [30] formulated joint channel allocation, interface assignment and MAC problem. On the optimal problem of the network throughput, Alicherry et al. [2], Raniwala et al. [32] and Kodialam et al. [24] took the routing into account with channel allocation.

The spectrum allocation problem and improvement on this problem have been researched in many other wireless networks too. Kyasanur and Vidya [25] proposed a flow-based routing and channel assignment approach for a single interface in ad hoc networks. Vedantham et al. [35] investigated the granularity of channel assignment decisions that gives the best trade-off in terms of performance and complexity in ad hoc networks. Ding et al. [9]studied distributed routing, relay selection and spectrum allocation in cognitive and cooperative ad hoc networks. Authors in [22, 51] study the spectrum management problem in use of cognitive radio.

6.2 Existing works with non-cooperative participants

The related works showed in above section requests the users to cooperate with each other, while an another category of works considers the case with non-cooperative participants. Related works in this section can be divided into two sub-categories including static auction and online auction.

6.2.1 Static auction

Felegyhazi et al. [14] studied Nash equilibria in static multi-radio multi-channel allocation game. After that Wu et al. [45] proposed a strongly dominant strategy equilibrium to improve the performance of channel allocation, and the scheme achieves the optimal system throughput in single-hop wireless networks. Han et al. [21] presented a distributed algorithms for simultaneous channel allocation of individual links and packet-scheduling, in software-defined radio (SDR) wireless networks.

In recent years, Zhou et al. proposed TRUST [56] and VERITAS [55], which are based on spectrum auction and achieve truthfulness. TRUST is a general framework for truthful double spectrum auction, which takes both buyers and sellers into account and achieves good performance. VERITAS focuses on the buyers and the circumstances, under which buyers request multiple channels. The most closely related work is SMALL [43], which also focuses on the buyers except that it lets the seller to set reserve price to protect her interest.

Gao et al. [16] studied the problem of competitive channel allocation among devices which use multiple radios in the multi-hop system. Xu et al. [46] designed an efficient channel allocation algorithm in different cases, such that the social efficiency can be approximately maximized. Xu et al. also designed a polynomial-time approximation scheme to maximize the social efficiency. Wang et al. [40] proposed a competitive spectrum sharing scheme based on the auction theory in cognitive radio networks. Mahmoud and Gupta [1] designed a polynomial-time truthful spectrum auction that offers a performance guarantee on the expecter revenue for Bayesian setting. Yang et al. [48] designed a truthful auction mechanism for the cooperative communication, named TASC. TASC is individually rational and budget-balanced, where wireless node can trade relay services. Wu et al. [44] studies the problem of adaptive-width channel allocation from a game-theoretic perspective and achieve higher system-wide throughput than that when system is in NE.

6.2.2 Online auction

Many works have been done for online auctions. Hajiaghayi et al. [19] considered online auctions with a limited supply and presented value and time strategy-proof mechanisms with constant efficiency and revenue competitiveness. Hajiaghayi et al. [20] gave a characterization for the online allocation rules that are truthfully implementable. Recently, Li [26] used a game-theoretic model to increase the rebate incentive mechanism. Wang et al. [37] proposed TODA which is a truthful online double auction for spectrum allocation in wireless networks. Xu et al. [47] designed an efficient spectrum channel allocation and auction method for online wireless channel scheduling to decide whether to grant each user's exclusive usage and how much will be charged. Deek et al. [8] proposed a truthful online spectrum auction design called Topaz. Topaz can distribute spectrum efficiently while discouraging bidders from misreporting their bids or time report.

Game-theoretic methods are also used in studying the media access problems in wireless networks, and there are also other works on strategy-proofness in wireless networks. There are many examples including wireless sensor networks [5, 50] and ad hoc networks [3, 4, 10, 33, 38, 39, 52–54].

7 Conclusion and future work

In this section, we draw our conclusion and discuss the future work. In this paper, we have proposed SHIELD, which is a strategy-proof and highly efficient channel auction mechanism for multi-radio wireless networks. We have proven its strategy-proofness and have implemented SHIELD. We have made some improvements for SHIELD and implemented Fair-SHIELD in repeated auctions. Our evaluation results have shown that SHIELD can achieve higher performance compared with existing channel auction mechanisms, and Fair-SHIELD can achieve fairness in repeated auctions. For future work, it will be interesting to investigate the problem of the collusion resistance in designing wireless channel auction mechanisms.

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