SPECIAL: A Strategy-Proof and Efficient Multi-Channel Auction Mechanism for Wireless Networks

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***Abstract*—Efficient wireless channel allocation is becoming a more and more important topic in wireless networking. Dynamic channel allocation is believed to be an effective way to cope with the shortage of wireless channel resource. In this paper, we propose SPECIAL, which is a Strategy-Proof and EffiCIent multi-channel Auction mechanism for wireLess networks. SPECIAL guarantees the strategy-proofness of the channel auction, exploits wireless channels' spatial reusability, and achieves high channel allocation efficiency.**

I. INTRODUCTION

With the surging deployment of wireless communication devices and the emergence of software-defined radios, the shortage of radio spectrum is becoming a more and more serious problem. Among the best-known market-based allocation mechanisms, auctions are outstanding on both perceived fairness and allocation efficiency [5]. Thus, auction is a natural way to distribute goods, including wireless channels. For example, since 1994, the Federal Communications Commission (FCC) and its counterpart across the world have been using auctions to assign channels. However, designing a feasible channel auction mechanism has its own challenges. The first challenge, which is not only limited to channel auctions but applies to auctions in general, is strategy-proofness meaning that each buyer can maximize her payoff only by reporting true valuation of the good as the bid. The second challenge is the efficiency of the channel allocation. Different from conventional goods, wireless channels have a property of spatial reusability, which means that wireless users that are well geographically separated can use the same channel simultaneously. With this property, the well-known Vickrey-Clarke-Groves auction becomes invalid, because even if a powerful central authority exists, computing the optimal channel allocation is NP-complete in a multi-hop wireless network [2].

In recent years, a number of elegant channel auction mechanisms in wireless network (*e.g.*, [11], [13], [14]) have been proposed to solve the problem of dynamic channel allocation. In these papers, it is commonly assumed that every buyer either bids for only one channel, or bids for multiple channels with the same per-channel price. However, doubling the number of channels, especially contiguous channels, a buyer's valuation does not necessarily double. It has been shown that the saturated throughput is a concave non-decreasing function on channel width [1]. Consequently, according to the saturated throughput on a channel, a buyer's valuation is reasonably expected to be a concave non-decreasing function on the width of the channel she gets. Different buyers may have different valuation functions. Therefore, considering the need for various numbers of channels due to various valuations, it is more reasonable to give the buyers the flexibility to submit various combinatorial bids for contiguous channels.

In this paper, we present SPECIAL, which is a Strategy-Proof and EffiCIent multi-channel Auction mechanism for wireLess networks. As far as we know, we are the first to combine flexible bids with combinatorial auction to study the problem of dynamic channel allocation. Combinatorial auction, in which a large number of items are auctioned concurrently and bidders are allowed to express preferences on bundles of items [7], has the capability of providing the proper expression of the problem of combinatorial wireless channel allocation. Furthermore, SPECIAL is fundamentally different from traditional combinatorial auction, as it allows multiple users that are geographically separated to use the same channel due to spatial reusability. In SPECIAL, all the buyers simultaneously submit their sealed bids for available channels. A bid specifies the maximal price the buyer would like to pay for each combination of contiguous channels. Then, SPECIAL decides the auction winners, channel allocation, and charges based on the bids. SPECIAL exploits wireless channels' spatial reusability, and achieves strategy-proofness.

We make the following contributions in this paper:

- We present a combinatorial auction mechanism, namely SPECIAL, for the problem of channel allocation in multi-hop wireless networks. To the best of our knowledge, we are the first to introduce flexible bids for different numbers of contiguous channels.
- Our analysis shows that SPECIAL is a strategy-proof channel auction mechanism.

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The rest of the paper is organized as follows. In Section II, we present technical preliminaries. In Section III, we describe SPECIAL in detail. In Section IV, we briefly review the related works. Finally, we conclude the paper and point out potential future works in Section V.

II. Technical Preliminaries

In this section, we present our auction model for the problem of combinatorial channel allocation, and review several solution concepts from game theory and mechanism design.

A. Auction Model

We model the problem of wireless channel allocation as a *combinatorial channel auction*. In this auction, there is a wireless service provider, called "seller", who possesses the license of a number of wireless channels and wants to lease out regionally idle channels; and there is a set of static nodes, called "buyers", such as WiFi access points and WiMAX base stations, who want to lease channels in order to provide services to their customers. A channel can be leased to multiple buyers, if these buyers can transmit simultaneously and receive signals with an adequate Signal to Interference and Noise Ratio (SINR). Different from existing channel auction mechanisms, our combinatorial channel auction allows buyers to bid for various numbers of contiguous channels.[1] The auction is sealed-bid and private, meaning that the buyers simultaneously submit their bids privately to the "auctioneer" without any knowledge of others, and do not collude.

We assume that the seller has a set of contiguous, orthogonal, and homogenous channels $K = \{1, 2, \ldots, k\}$ to lease out. The available channels are numbered from 1 to k. As is shown in paper [1], contiguous original channels can be combined to get a wider channel. In Figure 1, we present the function of effective saturated throughput of a channel on the multiple of the bandwidth of the original channel. In

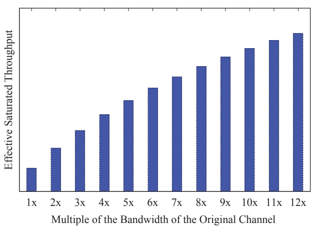


Fig. 1. Effective saturated throughput as a function on the multiple of the bandwidth of the original channel

our auction, a (combined) channel can be leased to one or a group of non-conflicting buyers. (We will define buyer group in Section III-A.)

We denote the set of buyers by $N = \{1, 2, \ldots, n\}$, where each buyer has a unique identification number from 1 through n. We assume that each of the buyers only has a single radio,[2] and can tune its radio to work on an original channel or a wider channel combined by several contiguous original channels. Let v_i^q be buyer i's valuation of a wider channel combined by q $(1 \leq q \leq k)$ contiguous original channels. Then the valuation vector of a buyer i can be denoted as:

$$\vec{v}_i = (v_i^1, v_i^2, \ldots, v_i^k).$$

A buyer's valuation function is private information to the buyer herself and is commonly named *type*. According to Figure 1, we assume that the valuation function is also a concave non-decreasing function, which means

$$\frac{v_i^x}{x} \geq \frac{v_i^y}{y}, \forall i \in N, \forall x, y, s.t.\ x < y \wedge 1 \leq x, y \leq k, \quad (1)$$

In practice, it is more reasonable to give the buyers the flexibility to submit various combinatorial bids for channels. In our combinatorial channel auction, we allow each buyer to submit an independent bid b_i^q for each number q $(1 \leq q \leq k)$ of contiguous channels. Similarly, we denote a buyer i's bid vector by:

$$\vec{b}_i = (b_i^1, b_i^2, \ldots, b_i^k).$$

According to inequation (1), we have

$$\frac{b_i^x}{x} \geq \frac{b_i^y}{y}, \forall i \in N, \forall x, y, s.t.\ x < y \wedge 1 \leq x, y \leq k, \quad (2)$$

when buyers truthfully submit their bids.

In our combinatorial channel auction, the strategy s_i of a buyer $i \in N$ is to report a bid vector, in which $b_i^q = s_i(v_i^q, q)$, based on her channel valuation v_i^q, for each $q (1 \leq q \leq k)$. The strategy profile $\vec{s}$ of all the buyers is represented by the follwoing vector:

$$\vec{s} = (s_1, s_2, \ldots, s_n).$$

According to the notation convention, let $\vec{s}_{-i}$ represent the strategy profile of all the buyers except buyer i.

We assume that all the buyers are rational, and their objectives are to maximize their own utilities. Here, we define the utility of a buyer $i \in N$ as

$$u_i(\vec{s}) = v_i(\vec{s}) - p_i(\vec{s}), \quad (3)$$

where $v_i(\vec{s})$ is player i's valuation on the outcome of the strategy profile $\vec{s}$, and $p_i(\vec{s})$ is a charge for using the allocated channel(s). We assume that a buyer has no preference over different outcomes, if the utility is the same to the buyer herself.

B. Solution Concepts

We recall several important solution concepts from game theory and mechanism design.

Definition 1 (Dominant Strategy [8]): A dominant strategy of a player is one that maximizes her utility regardless of what strategies the other players choose. Specifically, $s_i^\star$ is player i's

[1] Our model of combinatorial channel auction is a variant of traditional combinatorial auctions, which allow buyers to place bids on any combinations of discrete items. In our model, the buyers bid for contiguous channels, which can be accessed with a single radio.

[2] We note that our channel auction mechanism can be extended to the case of multiple radios by modeling each radio as a virtual buyer [11].

dominant strategy, if for any $s'_i \neq s^\star_i$ and any strategy profile of the other players $\vec{s}_{-i}$, we have

$$u_i(s^\star_i, \vec{s}_{-i}) \geq u_i(s'_i, \vec{s}_{-i}). \tag{4}$$

Definition 2 (Strategy-Proof Mechanism [6]): A direct-revelation mechanism is a mechanism, in which the only strategy available to players is to make claims about their preferences to the mechanism. A direct-revelation mechanism is strategy-proof if it satisfies both *incentive-compatibility* and *individual-rationality*. Incentive-compatibility means reporting truthful information is a dominant strategy for each player. Individual-rationality means each player can always achieve at least as much expected utility from faithful participation as without participation.

In our combinatorial channel auction, the strategy-proofness means that no buyer $i \in N$ can increase her utility by reporting a bid $b^q_i \neq v^q_i$ for any q $(1 \leq q \leq k)$. In other words, it is every buyer's best strategy to simply submit her valuation as the bid in our combinatorial channel auction.

III. Design of SPECIAL and Strategy-Proofness

In this section, we present our design of SPECIAL, and prove its strategy-proofness.

A. Auction Design

The design of SPECIAL is composed of three main components: *buyer grouping and bid integration*, *group-channel allocation*, and *winner selection and charging*.

1) Buyer Grouping and Bid Integration: Considering the spatial reusability of the channels, SPECIAL divides all the buyers into multiple non-conflicting groups. Each group can be assigned with a distinct channel. The assigned channel is either an original channel or a wider channel that is composed of several original contiguous channel. To prevent the buyers from manipulating the auction, here we group the buyers using a bid-independent method. As in [11], [14], SPECIAL uses a conflict graph to capture the radio transmission interference among the buyers. Any pair of buyers, who are in the radio transmission interference range of each other, have a line connecting them in the conflict graph. Then the calculation of bid-independent groups can be implemented by a certain existing graph coloring algorithm (*e.g.*, [9]), such that no two buyers have interference between each other in the same group. We note that the buyers have no control on which group they are in, when the above grouping strategy is used.

We denote the set of buyer groups by $G = \{g_1, g_2, \ldots, g_m\}$, where m is the number of the buyer groups. The buyer groups in G should satisfy: $\bigcup_{1 \leq j \leq m} g_j = N$, meaning that all the buyers are involved, and $g_j \cap g_f = \emptyset, if j \neq f$, meaning that no buyer can be in multiple groups. Figure 2 shows a toy example with 6 buyers (A-F). There exists several feasible grouping results, *e.g.*, $g_1 = \{A, C, E\}$ and $g_2 = \{B, D, F\}$.

From now on, we consider the buyer groups as competitors in the combinatorial channel auction. We now define the integrated group bid for each of the buyer groups. To guarantee the strategy-proofness of the auction, we let the group bid be

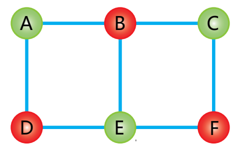


Fig. 2. A toy example with 6 buyers (A-F)

proportional to the smallest bid for each number of contiguous channels in the group, and sacrifice the buyers who may benefit from manipulating the group bid. The sacrificed will not be granted any channel. Two types of buyers have to be sacrificed when computing a group's bid for q contiguous channels:

(1) The buyer who submits the smallest bid for q contiguous channels in the group. In the case of ties, *i.e.*, more than one buyer submit the smallest bid in the group, the tied buyer with smallest identification number will be selected as the sacrificed buyer.
(2) The buyer who can benefit by manipulating her bid for other numbers of contiguous channels than q in order to make herself win q contiguous channels. In Section III-A3, we will present our scheme to identify such cheating buyers in order to achieve strategy-proofness.

Here, we claim that the number of sacrificed buyers is always no more than two in a buyer group. So we define the integrated group bid (IGB) φ^q_j for each group $g_j \in G$ on q contiguous channels as

$$\varphi^q_j = \max((|g_j| - 2) \cdot \theta^q_j, 0), \tag{5}$$

where

$$\theta^q_j = \min_{l \in g_j}(b^q_l). \tag{6}$$

We denote the IGB vector of group g_j as

$$\vec{\varphi}_j = (\varphi^1_j, \varphi^2_j, \ldots, \varphi^k_j).$$

According to inequation (2), we can get that φ^q_j is also a concave non-decreasing function on q, for every $g_j \in G$.

We note that even if $\varphi^q_j = 0$, the valid winning buyers in group g_j will still be charged when they successfully win q contiguous channels.

2) Group-Channel Allocation: After forming the buyer groups, we present our algorithm that allocates contiguous channels to the buyer groups based on their IGBs.

For ease of comparison between IGBs, we define per-channel integrated group bid (PIGB) ξ^q_j for each buyer group g_j on q contiguous channels:

$$\xi^q_j = \varphi^q_j / q. \tag{7}$$

Similarly, we denote the PIGB vector of group g_j as

$$\vec{\xi}_j = (\xi^1_j, \xi^2_j, \ldots, \xi^k_j).$$

Since φ^q_j is a concave non-decreasing function on q, we can get that ξ^q_j is a non-increasing function on q, such that

$$\xi^x_j \geq \xi^y_j, \ \forall x < y \land 1 \leq x, y \leq k, \ \forall g_j \in G. \tag{8}$$

For the ease of comparison between PIGBs, we define the preference relations as

$$(a, h) \prec (b, j) \Leftrightarrow a < b \vee (a = b \wedge h < j),$$

where a and b are values of PIGBs, and h and j are the identification numbers of buyer groups. In the case of ties,we determine that the group with higher group number has higher priority to be allocated a channel.

Algorithm 1 Algorithm for Group-Channel Allocation GCA()

Input: The set of buyer groups G, the number of available channels k, and a set $\xi = \{\xi_j^q | g_j \in G, 1 \leq q \leq k\}$ of PIGBs.
Output: A vector $\vec{r}$ of numbers of channels allocated to every group, and a channel allocation vector $\vec{ca}$.

```
r⃗ ← 0^m, ca⃗ ← (0,0)^m, k′ ← k
while k′ > 0 do
    ξ_j^q ← max(ξ), r_j ← q
    k′ ← k′ − 1, ξ ← ξ \ {ξ_j^q}
end while
k′ ← 1
for j = 1 to m do
    if r_j > 0 then
        ca_j ← (k′, k′ + r_j − 1), k′ ← k′ + r_j
    end if
end for
return (r⃗, ca⃗).
```

We note that although Algorithm 1 can efficiently allocate the channels to the buyer groups according to their PIGBs, it cannot guarantee strategy-proofness. In the next subsection, we will present a method to strengthen Algorithm 1 in order to achieve strategy-proofness.

3) Winner Selection and Charging: In this section, we consider how to determine winners in each winning buyer group who has been assigned channel(s) and their charges for using the assigned channel(s).

Our analysis shows that there are three cheating actions, say, *preemptive bidding*, *depreciated bidding*, and *retreat for advancing*, through which a buyer may improve her utility. We provide a method to prevent each of the cheating actions, respectively, and strengthen our winner selection and charging scheme step by step to achieve strategy-proofness. In the following, we continue to use the toy example shown in Figure 2 to illustrate the effect of buyers' cheating actions.

a) Preemptive Bidding: The cheating action of preemptive bidding means that a buyer $i \in g_j$ submits a cheating bid vector to make PIGB $\xi_j'^q$ be selected as a winning bid, which would never be a winning group bid if i bids truthfully. Thus, group g_j wins q channels, and so does i.

Figure 3(a) shows the effect of preemptive bidding. We observe that buyer A's truthful bid $b_A^{\star 3}$ must be the minimum bid in $\{b_A^{\star 3}, b_C^3, b_E^3\}$. So $v_A^3 = b_A^{\star 3} = \theta_1^3$. If we charge every winner in group g_1 the price θ_1^q, where q channel(s) will be allocated to group g_1, then even if buyer A successfully get 3 channels, her utility will be negative or zero, because θ_1^3 will be at least as large as v_A^3.

Formally, we define the charging scheme as follows. If a group g_j wins q contiguous channels, each potential winning buyer $i \in g_j$ is charged a uniform price, which is equivalent to the smallest bid for q contiguous channel in the group. Here, we define the charge of every buyer for using the allocated channels as

$$p_i = \theta_j^q \cdot \eta_i, \tag{9}$$

where η_i decides whether i is selected as a winner or not.

Lemma 1: For any winning group bid ξ_j^q, if we charge each winner $i \in g_j$ with θ_j^q, preemptive bidding can be prevented.

b) Depreciated Bidding: The cheating action of depreciated bidding means that a buyer $i \in g_j$ may submit a lower cheating bid $b_i'^q$ than the truthful one $b_i^{\star q} = v_i^q$, with no influence on the channel allocation. Such a cheating action may decrease the charge to the winners in g_j, if $\xi_j'^q$ is a winning PIGB and $b_i'^q$ appears to be the smallest bid for q channels in the group g_j. As a result, if i is selected as an auction winner, her utility can be increased through depreciated bidding.

Figure 3(b) shows the effect of depreciated bidding. We observe that if a buyer $i \in g_j$ can benefit from depreciated bidding, she must appear to be the one who has the smallest bid for q channels when ξ_j^q is a winning PIGB. Therefore, after allocating q channels to buyer group g_j, the buyer, who has the smallest bid for q channels in the group g_j, should be excluded from the set of winners.

Lemma 2: If ξ_j^q is a winning PIGB, we can prevent depreciated bidding by excluding the buyer $i = \underset{i \in g_j}{argmin}(b_i^q)$ from the winner set. *i.e.*, let $\eta_i = 0$.

c) Retreat for Advancing: The cheating action of retreat for advancing means that if a buyer $i \in g_j$ bids truthfully, PIGB ξ_j^q will be selected as a winning PIGB for group g_j; but if buyer i submits several cheating bids, another PIGB $\xi_j^{q'}$ ($q' < q$) is selected as the final winning PIGB for group g_j. Consequently, buyer i's utility u_i may be increased.

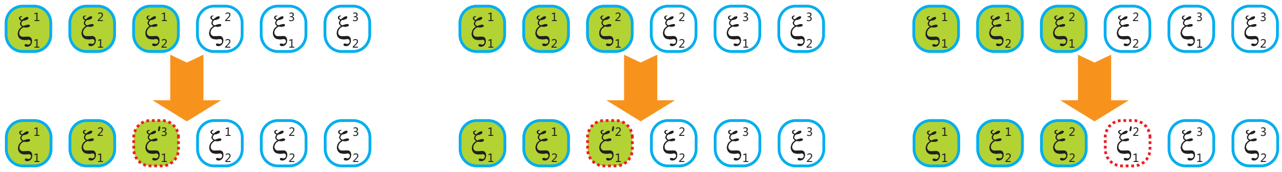
Figure 3(c) shows the effect of retreat for advancing. We can observe that if a buyer $i \in g_j$ benefit from winning $q' + 1$ ($\leq q$) channels instead of q through retreat for advancing, then the auction must exhibit the following two properties:

$$i = \underset{l \in g_j}{argmin}(b_l^{q'+1}), \tag{10}$$

and

$$(\min_{h \neq j}(\xi_h^{r_h}), \underset{h \neq j}{argmin}(\xi_h^{r_h})) \prec \left(\frac{\max\left((|g_j| - 2) \cdot \min\limits_{l \neq i \wedge l \in g_j} (b_l^{q'+1}), 0 \right)}{q' + 1}, j \right) \tag{11}$$

To guarantee strategy-proofness, we have to exclude each such buyer who satisfies the above two criteria from the set of winners in each group.



(a) Preemptive bidding. A buyer in group g_1, who can only get 2 channels by bidding truthfully, may get 3 channels by submitting an untruthful bid for 3 channels.

(b) Depreciated bidding. A buyer in group g_1 can increase her utility by submitting an untruthful bid that is lower than any others' bids in the group and her own valuation for 2 channels.

(c) Retreat for advancing. A buyer in group g_1 may get her utility increased, by submitting an untruthful bid for 2 channels to make group g_1 wins 1 channel instead of 2 channels won when bidding truthfully.

Fig. 3. Illustrations of cheating actions. All PIGBs are sorted in non-increasing order, among which truthful PIGBs are indicated by solid-border round corner squares, and untruthful ones caused by cheating bids are represented by dashed-border round corner squares.

Lemma 3: For every buyer group $g_j \in G$, if there exists buyer $i \in g_j$ satisfying the condition 10 and 11, we can exclude such buyers from winners to prevent the cheating action of retreating for advancing. *i.e.*, let $\eta_i = 0$.

Algorithm 2 Algorithm for Winner Selection WIN()

Input: The set of buyer groups G, the number of available channels k, and a set $\xi = \{\xi_j^q | g_j \in G, 1 \leq q \leq k\}$.

Output: A set W of winners in the combinatorial channel auction.

$W \leftarrow \emptyset, pm \leftarrow 0, \xi' \leftarrow \xi$
$(\vec{r}, \vec{ca}) \leftarrow GCA(G, k, \xi')$
for all $r_j > 0$ **do**
  $T \leftarrow g_j \setminus \{\underset{i \in g_j}{argmin}(b_i^{r_j})\}$
  if $r_j < k$ **then**
    $pm \leftarrow \underset{i \in g_j}{argmin}(b_i^{r_j+1})$, $d \leftarrow \underset{h \neq j}{argmin}(\xi_h^{r_h})$
    if $(\xi_d^{r_d}, d) \prec \left(\frac{\max((|g_j|-2)\cdot \min_{l \neq pm \wedge l \in g_j}(b_l^{r_j+1}),0)}{r_j+1}, j\right)$ **then**
      $T \leftarrow T \setminus \{pm\}$
    end if
  end if
  $W \leftarrow W \cup T$
end for
return W.

Finally, we use Algorithm 2 to summarize our method to determine winners.

B. Strategy-proofness

Theorem 1: SPECIAL is a strategy-proof combinatorial channel auction mechanism.

Due to limitation of space, we do not present the proof in this paper.

IV. Related Work

In this section, we review the works on channel allocation involved with selfish participants. Earlier, Felegyhazi et al. [3] studied Nash Equilibria in a static multi-radio multi-channel allocation game. Later, Wu et al. [12] designed a mechanism for the multi-radio multi-channel allocation game, converging to strongly dominant strategy equilibrium. Recently, a number of strategy-proof auction-based spectrum allocation mechanisms (*e.g.*, TRUST [14], VERITAS [13], and SMALL [11]) for multiple collision domains have recently been proposed to solve the channel allocation problem. A min-max coalition-proof Nash equilibrium channel allocation scheme has been proposed in [4] to study the multi-radio channel allocation problem in multi-hop wireless networks. In [10], Wu et al. have studied the problem of adaptive-width channel allocation.

V. Conclusion and Future Work

In this paper, we have modeled the spectrum allocation problem as a combinatorial auction, and proposed a strategy-proof and efficient spectrum allocation mechanism, called SPECIAL. For future work, one interesting direction is to extend SPECIAL to be resistant to collusion.

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