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Auction-based Spectrum Sharing among Differentiated Channels for Heterogeneous Secondary Networks

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Abstract

To mitigate the explosive and diversified demands for wireless communications, shared access of underutilized spectrum among heterogeneous secondary networks (HSNs) via new technologies such as cognitive radio has been deemed as an effective approach. The development of carrier aggregation technology makes spectrum sharing more promising because differentiated channels from various bands can be aggregated to provide higher throughput and data rate. For instance, LTE-WLAN aggregation (LWA) is one of the emerging technology which aggregates LTE-band and unlicensed band(s) to make good use of spectrum. Owing to the growth of relevant communication technology, it becomes possible for HSNs to share channels form various bands which have different characteristics.

One of the most critical issues in spectrum sharing is interference control between HSNs. Due to the incompatible MAC/PHY layers, it is not easy to achieve over-the-air control. This issue is further complicated by HSNs' diverse requirements on bandwidth and transmission range. In view of above issues, Zhan *et al.*, 2015, considers the problem of a single provider with spectrum bands available for rent to HSNs. They adopt a centralized auction-based framework to coordinate the secondary spectrum sharing and coexistence problem among HSNs through a market mechanism design at network management layer. Their proposed Vickrey-Clarke-Groves (VCG) auction-based design has a highly expressive bidding format with effective region partition that allows HSNs to

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specify various demands for bandwidth and transmission range and achieves the desirable properties of truthfulness, individual rationality and budget balance. However, channels are assumed to be homogeneous in their work, ignoring HSNs' various valuations toward differentiated channels which may lead to bad channel allocation. HSNs' valuations toward channel combinations are also neglected, losing the opportunity for better allocation and higher revenue.

This thesis considers a coexistence network that involves one spectrum provider (SP) sharing unused differentiated channels in a target area to multiple HSNs and addresses the effects of differentiated channels and channel combination. Built on top of Zhan et al's design, specific design challenges are as follows: (C1) How to define the bidding flexibility for HSNs as well as the reserve pricing space for SP to include HSNs' diverse valuations of channels and combinations? (C2) Assure that an new auction design maintains the good economic properties of truthfulness, individual rationality and budget balance.

To address these challenges, this thesis proposes an **U**nilateral **V**CG-based **A**uction for **H**SNs with **D**ifferentiated **C**hannels consideration (UVAH/DC) with three novel designs:

1. **Fully expressive bidding format** that allows HSNs to flexibly specify operating regions, desired channels and combinations and bid offers;

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2. **Reserve prices by SP over packages** that give SP the flexibility of setting bundle reserve prices to capture market preferences; and

3. **Maximum virtual bid generation** that creates virtual bids from SP's reserve prices over bundles which guarantee winning payment is no less than the corresponding reserve price to avoid revenue deficiency.

We prove that UVAH/DC achieves the economic property of truthfulness of HSNs. Individual rationality and budget balance can also be achieved if for any two disjoint packages with reserve price specifications, the reserve price of joint package is either not specified or no less than the sum of disjoint packages' reserve prices. Numerical experimentation over a scenario with 900 instances shows that, compared to Zhan et al's design, UVAH/DC improves, in average spectrum revenue and spectrum rent-out ratio (ROR) by 36.4% and 9.4% respectively. That is, UVAH/DC not only provides stronger incentive for SP to lease underutilized spectrum, but also increases the whole spectrum utilization.

Keywords: Network Management Solution, Market Design, HSNs, Coexistence, Spectrum Sharing, Spectrum Reusability, Differentiated Channels, VCG auction, UVAH/DC, Effective Partition, Package Bidding, Virtual Bid,

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中文摘要

為了減輕對無線通信的爆炸式和多樣化的需求，通過認知無線電等新技術在異構次級網絡（HSN）之間共享未充分利用的頻譜被認為是一種有效的方法。載波聚合技術的發展使得頻譜共享更有前途，因為來自各個頻帶的具差異頻道可以被聚合，以提供更高的資料流通量和數據速率。例如，LTE-WLAN 聚合（LWA）是聚合 LTE 頻帶和非授權頻帶以最佳利用頻譜的新興技術之一。由於相關通信技術的發展，HSN 可以共享具有不同傳播特性的頻道。

頻譜共享中最關鍵的問題之一是 HSN 之間的干擾控制。由於不兼容的 MAC / PHY 層，實現空中控制並不容易。HSN 對帶寬和傳輸範圍的多樣化要求使這個問題進一步複雜化。針對上述問題，Zhan 等人於 2015 年，考慮了一個頻譜提供商的問題，頻譜可用於租用 HSN。他們採用集中式的拍賣框架，通過網絡管理層的市場機制設計，協調 HSN 之間的頻譜次級共享和共存問題。他們提出的基於 Vickrey-Clarke-Groves（VCG）拍賣設計具有高度表現力的招標格式，具有有效的區域劃分，允許 HSN 規定對帶寬和傳輸範圍的各種需求，並實現真實標性質，個人理性和預算平衡的理想屬性。然而，他們的研究中假設頻道是同質的，忽略了 HSN 對具差異頻道的各種估值，這能導致頻道分配不佳。HSN 對頻道組合的估值也被忽視，失去了更好的頻道分配和更高收入的機會。

為了解決具差異頻道和頻道組合的影響，本論文考慮了一個共存網絡，其涉及一個頻譜提供商（SP）將未使用的具差異頻道共享到多個 HSN。建立在 Zhan 設計之上，具體設計挑戰如下：（C1）為了解決 HSN 的不同估值，如何定義投標靈活性以及 SP 設置底標的空間？（C2）設計機制能否在不犧牲頻譜利用的情況下實現良好的經濟性質，包括真實標性質，個人理性和預算平衡？

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為了解決上述挑戰，本文提出了一種以具差異頻道考慮為基礎的單邊 VCG 拍賣（UVAH / DC），具有三種新穎的設計：

1. **全面的招標格式**，允許 HSN 靈活指定經營地區，期望的頻道和組合以及出價;
2. **組合底標**使 SP 能夠靈活地設置底標以捕獲市場偏好;
3. 建立於組合底標，**最大虛擬出價**創建了高於 SP 底標的虛擬出價，確保獲勝付款不低於相應的底標，以避免收入不足。

我們證明 UVAH / DC 實現了 HSN 的真實標性質。如果任何兩個不相交組合具有底標，且聯合組合的的底標未指定或不低於不相交組合底標的總和，也可以實現個人理性和預算平衡。對一個情境下 900 個實例的數值實驗表明，與 Zhan 的設計相比，UVAH / DC 在平均頻譜收入和頻譜出租比（ROR）分別提高了 36.4%和 9.4%。UVAH / DC 不僅為 SP 提供了更大的激勵來租賃未充分利用的頻譜，而且提高了整個頻譜利用率。

關鍵詞：網絡管理解決方案，市場設計，HSNs 共存，頻譜共享，頻譜可重用性，具差異頻道，VCG 拍賣，UVAH / DC，有效分區，組合出價，虛擬出價

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Chapter 1 Introduction

1.1 Background and Motivation

The explosive growth of mobile data has become a significant concern for the development of future wireless networks. Various reports project that worldwide mobile data traffic will increase more than tenfold in the next five to ten years [Eri12][UMT11]. To embrace such growth opportunities, network operators in certain metropolitan areas are planning for 1000-fold increase in network capacity [Qualc]. On the other hand, spectrum scarcity across specific frequency range, from 100MHz to 6GHz with desired propagation characteristics, is a critical concern. These sub-6GHz bands have already been fragmented and assigned to spectrum licensees in an exclusive manner [OfcSA][SIMT15]. How to utilize spectrum resources efficiently and flexibly becomes a key challenge for next generation network.

To resolve the spectrum scarcity in the near future, spectrum sharing is a promising solution [Teh16]. The benefit of spectrum sharing is twofold: first, secondary service providers can obtain spectrum rights leased by incumbents to provide additional capacity for the users, and secondly, spectrum sharing allows improvement of the spectrum utilization. Spectrum sharing schemes from cognitive radio networks [Aky06] to licensed shared access (LSA) [Mus14] have sparked heated discussions. Both the international standardization entities and regulatory bodies focus on certain aspects of spectrum sharing.

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For example, European Telecommunications Standard Institute (ETSI) plans to apply cognitive techniques such as Radio Environment Maps (REMs) [ETS14]. A study from the Third Generation Partnership Project (3GPP) aims to look for methods to efficiently share common E-UTRAN resources according to identified RAN sharing scenarios [3GP14]. For the regulatory bodies, TV white space spectrum sharing have been implemented by FCC and Ofcom [FCCW][OfcTV]. In the recent years, FCC also defines a new spectrum sharing scheme named spectrum access system (SAS) and target 3.55~3.7GHz to improve spectrum efficiency [Soh15].

However, network heterogeneity is one critical issue in spectrum sharing. Dense deployment of heterogeneous secondary networks (HSNs) are essential to achieve 1000x capacity in the upcoming 5G ecosystem. However, subject to incompatible MAC/PHY layers, HSNs cannot communicate with each other which may lead to undesired interference. In addition, even simple energy-based sensing is used for collision avoidance, diverse channelization and coverage make HSNs to detect the existence of each other.

Channels for sharing are also toward heterogeneity which further complicate the spectrum sharing problem. Various bands including TV white space, VHF band, 3.55~3.7GHz and unlicensed band are potential candidates for sharing. How to enable spectrum sharing meeting diverse requirements of HSNs is an important concern. Moreover, the development of carrier aggregation technology makes differentiated channels from various bands can be aggregated to provide higher throughput and data rate

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Requirements of HSNs may not only contain single channel but also channel combinations. The opportunity of channel combination sharing cannot be ignored for future sharing scenario.

In view of the above issues, this research focuses on the spectrum sharing problem among HSNs while differentiated channels are involved. Specifically, HSNs have different requirements on differentiated channels and their combinations. Our goal is to enable harmonic spectrum sharing for theses HSNs while meeting their requirements.

1.2 Literature Review

One way toward spectrum sharing is spectrum sensing, which has been widely studied in the literature of cognitive radio networks. One of important topics in cognitive radio is spectrum sensing. Yucek and Huseyin [Yuc06] gives a comprehensive overview of spectrum sensing algorithm, and presents various aspects including multi-dimensional spectrum sensing and cooperative sensing. [CMB04] discusses the implementation issues of spectrum sharing in cognitive radio, and two key issues of cognitive radio frontend - dynamic range reduction and wideband frequency agility – are also identified.

Another line of research to address the spectrum resource allocation is to apply economic approaches. Pricing [KZM12] or contract [Gao11] can be utilized in spectrum sharing, but among these methods auction draws the most attention. Each auction design

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aims to address some features about spectrum or the networks. [KhA13] studies heterogeneous channel quality and [KhA15] considers auctions in a dynamic setting where secondary users can change their valuations based on their experiences with the channel quality. Literature involves multiple spectrum owners and multiple secondary networks is usually addressed by double auctions. TRUST [ZhZ09] is the first truthful double auction design to address spectrum reuse among secondary networks. The extensions of TRUST to multi-demand and heterogeneous spectrums are studied in [Che13] and [Fen12] respectively. The most relevant research to us is UVAH proposed by Zhan *et al.* [ZCC15]. Zhan's work focuses on coexistence among HSNs, but their contribution is to transform the coexistence problem into resource allocation problem by using auction-based approach. Our research is motivated by their work and we will give a more detailed description for their designs in Chapter 3.1.2.

Reserve price is one of our concerns in the auction-based spectrum sharing, and there exist some general results about auctions with reserve price. Myerson [Mye81] showed that reserve-price-based auctions are indeed expected revenue-maximizing in natural, for i.i.d bidders' valuations. Hartline and Roughgarden [HaR09] studied a more general setting of downward-closed single-parameter agent environments with non-identical distributions. They conclude that in many contexts, the VCG mechanism with simple reserve prices is near-optimal in a very practical sense.

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1.3 Problem Scenario of Differentiated Channel Sharing among HSNs

Similar to the problem scenario in Zhan's work, this research focuses on the emerging aspect of coexistence of SP with heterogeneous secondary networks (HSNs) but differentiated channels are involved. As shown in Fig 1-1, the HSNs of our interests may include wireless local area network (WLAN) such as WiFi and wireless wide area networks (WWANs) such as WCDMA and LTE. These HSNs usually belong to different operators and are unable to directly communicate with each other. They usually have different requirements on channel frequency, bandwidth and coverage. Moreover, channels for sharing are assumed to be differentiated in our scenario. For example, it is worthless for a LTE-U network to acquire only 5GHz channel. But the network can work normally if it could acquire 5GHz channel and LTE band simultaneously. Also, HSNs may be interested in multiple combinations at the same time. A LTE network is extremely satisfied if it can get multiple channels to achieve high throughput using carrier aggregation. If multiple channels are impossible, it would be nice to have single channel because the network can still provide acceptable service for users. Differentiated channels lead to HSNs' divergent requirements for channel combinations, making spectrum sharing more complicated.

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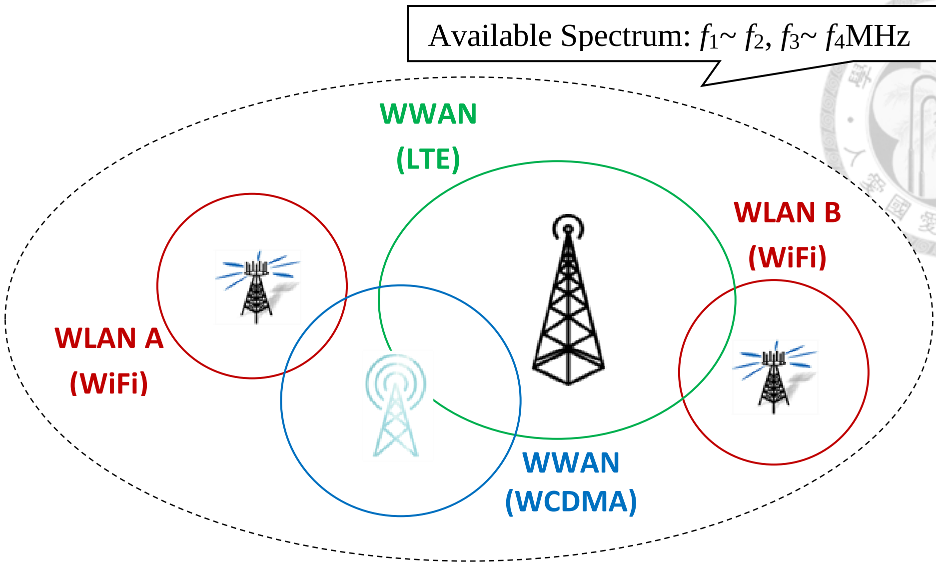

Figure 1-1: A typical coexistence scenario with multiple HSNs

1.4 Organization of Research

The remainder of research is organized as followed. Chapter 2 describes the spectrum sharing problem among HSNs involving differentiated channels and the design challenges when auction-based framework is applied. In Chapter 3, we propose UVAH/DC which can achieve good economic properties with three innovations: fully expressive bidding format , reserve prices over packages and maximum virtual bid generation. Numerical performance evaluations of UVAH/DC are given in Chapter4. Finally, the conclusions and future work are draw in Chapter 5.

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Chapter 2 Differentiated Channels Sharing among HSNs Problem Formulation

The spectrum sharing problem of differentiated channels among HSNs is defined in this chapter. Our distinguished feature differentiated channels, is delineated in Chapter 2.1. Then the spectrum sharing problem is outlined in Chapter 2.2 followed by the auction-based framework in Chapter 2.3 to address this problem. Lastly, Chapter 2.4 depicts the design challenges using auction-based framework when differentiated channels are involved.

2.1 Differentiated Channels

Differentiated channels mean that channels appear different or distinct to HSNs, and HSNs may hold various perspectives toward these channels. This may be caused by channel characteristics or the technology each HSN adopts. Instead of treating all channels identically, HSNs are only interested in part of them. In addition, HSNs' valuations are not only affected by which individual channels they acquire, but also the channel combination they receive at the same time. While technology such as carrier aggregation makes combinations more valuable, other factors induce adverse effects. In the following why channel heterogeneity exists is discussed, and two effects of channel combinations – complementarity and substitutability – are also defined and examined.

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2.1.1 Channel Heterogeneity

One main cause of channel heterogeneity is embedded in various bands. In a practical sharing scenario, available channels may be located on widely separated slices of frequency band, and therefore different channels may have different properties such as propagation characteristics [MaT08]. Federal Communications Commission (FCC) may also identify maximum transmission range for various channels. Moreover, HSNs with different wireless technology have their own suitable channels and lose interests in other channels. Even the value of channels in the same band may be different due to interference. Interference occurs when services use the same channels or adjacent channels. An obvious evidence can be seen in the FCC Incentive Auction, where 600MHz licenses with different interference levels exist in the same regions [FCCDA]. To take into account interference effects on value of license, winning bidders in Incentive Auction also receive an impairment-based discount off the final price for licenses that are subject to impairments [FCC15]. Therefore, channel heterogeneity can exist both in various bands and the same bands.

2.1.2 Channel Complementarity

When a combination harvests additional positive value for HSNs, the channels in the combination are called complements. Let $v_i(A)$ represents HSN-i's value for channel A, channel A and B are regarded as complements [BJV01] for HSN-i if

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$$v_i(A)+v_i(B)<v_i(A\cup B) \quad (1)$$

Complements exist in differentiated channels in several situations. One possibility is that when channels are contiguous, HSNs may be able to utilize the guard band between these channels. For example, one of main goals of Incentive Auction when allocating channels to winning bidders is that FCC would prioritize bidders who wins multiple channels to have contiguous channels. Another possibility is that channel combinations can provide better throughput and data rate because of the technologies such as Carrier Aggregation (CA) or LTE-WLAN Aggregation (LWA). According to Qualcomm's report, carrier aggregation of three 10MHz-blocks can provide 1.5 times higher user rate or 100% capacity gain than blocks without carrier aggregation [QualL]. These factors would make channel combinations more valuable, and be seen as complements from HSNs' perspectives.

2.1.3 Channel Substitutability

Conversely, when a combination harvests additional negative value, the channels in the combination are called substitutes. Channel A and B are regarded as substitutes [BJV01] for HSN-i if

$$v_i(A)+v_i(B)>v_i(A\cup B) \quad (2)$$

Substitutes occur when HSNs think acquiring additional channels is marginally better. For example, HSNs bid channels to slightly increase Quality of Service (QoS) or capacity

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for their services but they are unwilling to pay so much as an individual channel. Another possibility is that although HSNs may only need one channel to provide services, they are under potential interference from adjacent channels. To prevent potential interference, HSNs can acquiring adjacent channels while their willing-to-pay prices are not as high as a single channel. Under above circumstances, HSNs are also interested in channel combinations, but the marginal diminishing value makes these combinations become substitutes.

2.2 Spectrum Sharing of Differentiated Channels among HSNs

Due to the existence of differentiated channels and HSNs, the scenario we consider is one SP shares its unused spectrum channels to multiple competing HSNs in a target area. Available channels are assumed to be differentiated because SP may own channels from various bands. Furthermore, available supply channels may not be identical within the target area. For example, in Fig 1.1, one 3.5GHz channel and one 5GHz channel might be available to WiFi network A while only 3.5GHz channel is available to WiFi network B. Since channels are differentiated, HSNs not only require different channels but also have various evaluation toward channel combinations. Finally, spectrum should be reused by HSNs in different location if they do not interfere with each other.

2.3 Auction-based Framework for Spectrum Sharing

Since self-coexistence of HSNs due to incompatible MAC/PHY layers, we adopt similar methodology as previous work by using broker-based framework. There is an

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broker mandated by the regulator to coordinate the sharing. By doing so, the coexistence between HSNs becomes a resource allocation problem from the broker's viewpoint. Geo-location database is one implementation of broker-based framework [HoD15] and in practice it's widely considered in the context of TV white space, 3.5GHz spectrum sharing in the U.S., and licensed shared access (LSA) in Europe.

To accommodate HSNs' diverse preferences toward differentiated channels and combinations, auction is a potential solution for spectrum management. HSNs can submit bids, indicating the bidding prices for the requested channels, and then the auctioneer will collect all the bids and decide allocation of spectrum resources and corresponding prices. Given that the unused channels vary with time and channel availability ranges from minutes to hours [Sha10], it is reasonable that the auctioneer periodically adopts a single-round auction to allocate spectrum resources to HSNs. By doing so, the SP can quickly adapt resource allocation to potentially volatile spectrum availability. Unlike other economics or business management approaches, auction provides high flexibility for HSNs to express various interest by bidding *packages*, the combinations of channels. The construction of packages in auction is suitable for addressing HSNs' evaluation toward differentiated channels and various combinations effects, e.g. complementarity and substitutability. Therefore, auction-based framework is used to tackle the challenges of HSNs and differentiated channels.

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2.4 Design Challenges of Auction-based Framework Involving Differentiated Channels

Our design aims to maximize total, i.e., total valuation of SP and HSNs. Designing an auction that maximizes the total value of selected bids while achieving high spectrum utilization is not an easy task, especially under the above setting. We have identified two key design challenges including

(C1) How to define the bidding flexibility for HSNs as well as the reserve pricing space for SP to address HSNs' diverse valuations?

HSNs have different valuations toward differentiated channels and their combinations, and how many combinations should be included in bidding format is a long-standing issue. VCG auction [Kri09] is one of the most famous auctions which can allow all kinds of combinations while guarantee good economic properties, but solving VCG auction problem is NP-hard. To ensure the computation efficiency, the number of combinations in bidding format is usually limited in practice [GoH10]. In literature, spectrum allocation problems are either simplified into homogeneous units [ZCL14][ZCC15] or applied with approximation algorithm. Dong *et al*. propose a near-optimal algorithm for spectrum combinatorial auction, but its limitation is HSNs can only bid one combination.

In reality, SP usually has some understanding about market and its price setting may also depend on market valuations. When SP is limited to set reserve prices for individual channels, it fails to capture the market valuations toward composite combinations. As a

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result, SP may also long to set reserve prices over combinations according to market situations. Therefore, the space for reserve pricing is also correlated to HSNs' valuation and bidding format design.

(C2) To assure designed mechanism achieve good economic properties including truthfulness, individual rationality and budget balance.

A critical property of a single-round auction design is truthfulness, which is achieved if every participant can achieve the best outcome to him/herself just by acting according to his/her true preference. It has been theoretically and practically shown that an auction is vulnerable to market manipulation and may lead to poor outcomes if truthfulness is not guaranteed [Kle02]. In addition to truthfulness, a good auction should guarantee individual rationality and budget balance as well. Individual rationality ensures that the SP's revenue is no less than the reserve price so that the SP has incentive to share its unused spectrum. Budget balance guarantees that the auctioneer's revenue is non-negative. The fail of individual rationality may discourage the SP and HSNs from participation, while a successful auction must balance auctioneer's budget. However, Myerson and Satterthwaite [Mys83] have pointed out that no mechanism can be allocation efficient, truthful, individual and budget balanced at the same time. VCG auction is the paradigm of unilateral auction which holds allocation efficiency, truthfulness and individual rationality, but it does not assure budget balance. How to design a mechanism under our problem scenario with desired economic properties is a critical issue.

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Chapter 3 Unilateral Vickrey-Clarke-Groves (VCG)-based Auction for HSNs with Differentiated Channels Consideration (UVAH/DC)

This Chapter substantiates the single-round and unilateral truthful auction of differentiated channels for HSNs. The design shall achieve three economic properties of truthfulness, individual rationality and budget balance. The proposed design is the extension of unilateral VCG-based auction for HSNs (UVAH) which assumes channels are homogenous. Key innovation to address differentiated channels and designed auction clearing algorithm will be given in Chapter 3.2 and 3.3, respectively. Chapter 3.4 proves designed auction achieve desired economic properties.

3.1 Review of Auction Designs

Two auction designs are introduced in this subsection, including the VCG auction, VCG mechanism, and unilateral VCG-based auction for HSNs (UVAH).

3.1.1 VCG Auction and VCG Mechanism

VCG auction is type of seal-bid auction where bidders submit their bidding prices for multiple homogeneous items simultaneously in one round bidding. VCG mechanism,

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which works for heterogeneous goods, is the generalization of VCG auction. Selection of VCG mechanism is due to the assignment following social optimal manner and nice economic property of truthfulness [Kri09]. Theorems by [GrL79] and [Hol79] show that, under weak assumptions, the VCG mechanism is the unique mechanism with truthfulness, efficient outcomes, and zero payments by losing bidders. Because of this, VCG mechanism constitutes a standard way to promoting truthfulness and generates numerous extensions in the past decades.

However, revenue deficiency takes place if there is a single bidder's preferences violate the substitutes condition [AuM06] or the competition is too low. Let's give examples for either case. Consider an auction of two spectrum licenses to three bidders. Bidder 1 is only interested in the package containing both licenses with bid price $2 million. Bidder 2 is interested in the first license and corresponding bid price is $2 million, while bidder 3 wants the second license with bid price also $2 million. By the VCG mechanism, bidder 2 and bidder 3 win the first and second license respectively, but both of their payment is zero! Another example is that, when there is only one bidder to attend the auction, its payment will be also zero. Revenue deficiency is one of the strong reasons why VCG mechanism is rare in practice.

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3.1.2 Unilateral VCG-based Auction for HSNs (UVAH)

To coordinate interference-free spectrum sharing among HSNs while preventing revenue deficiency, Zhan *et al.* [ZCC15] propose **U**nilateral **V**CG-based **A**uction for **H**SNs (UVAH). Held by a third-party auctioneer to fairly enable spectrum sharing, UVAH can accommodate HSNs' diverse requirements on bandwidth and transmission range while allowing SP to specify non-uniform supply in the target area. What makes UVAH a promising way for spectrum sharing are the three designs discussed as followed.

The first design is effective partition of auction regions which address SP's non-uniform spectrum availability within target area. Before the auction is conducted, the auctioneer partitions target area into several small regions. Between any two adjacent regions, a guard region is created to prevent potential interference. Fig 5.1 is an example where target area is partitioned into five small regions. Although the detailed algorithm is not included in UVAH, the partitioned regions should be set to appropriate size because too small regions results in many guard regions while too large regions will be a waste when they are allocated to small networks such as Wi-Fi.

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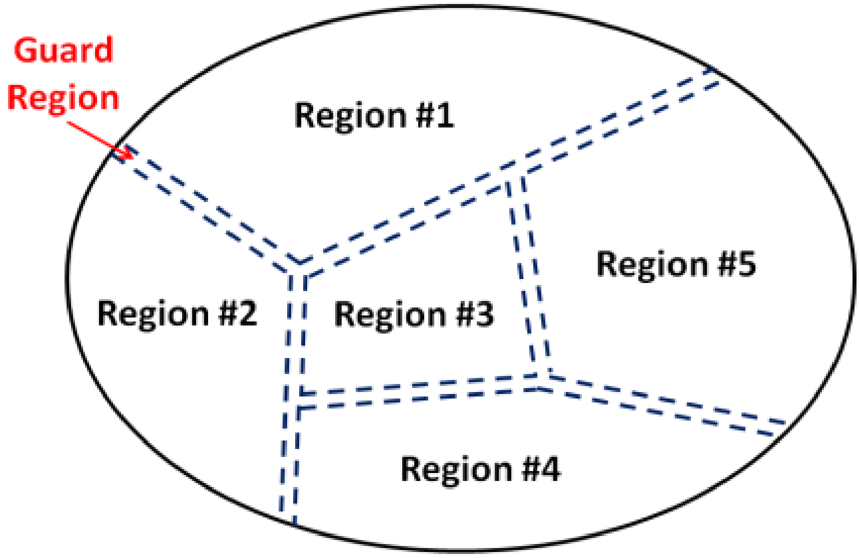

Figure 3-1: Partition of one large target area into multiple small regions [ZCC15]

To allow HSNs specify their diverse demand on bandwidth and transmission range, the second design is the highly-expressive bidding format. Each HSN can bid different amount of supply within every region and combinations between regions. For example, assume that there are two regions, R_1 and R_2, and their available spectrum units are two and one respectively. Given the supply information, up to five packages can be defined as follows:

Package #1: $R_1(1)$;

Package #2: $R_1(2)$;

Package #3: $R_2(1)$;

Package #4: $R_1(1)$ and $R_2(1)$;

Package #5: $R_1(2)$ and $R_2(1)$;

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Such flexibility can provide high bidding flexibility for HSNs depending on their requirements.

The third design is virtual bidders by regions to address revenue deficiency in VCG-based auctions. SP can specify reserve price per channel in each region and the auctioneer would use this information to generate a virtual bidder in each region. For example, there are also two regions R_1 and R_2 with spectrum units two and one respectively. Assume SP' reserve prices per channel in R_1 and R_2 are \$10 and \$8. Virtual bidders and their bids would be generated as followed:

Virtual bidder in R_1: {1 unit: \$10, 2 units: \$20}

Virtual bidder in R_2: {1 unit: \$8}

Then these virtual bidders are introduced to the auction and it can be shown that payment of winning HSNs is higher than the reserve price specified by SP.

UVAH also has three desired economic properties: truthfulness, individual rationality and budget balance. However, spectrum units are assumed to be homogeneous for all HSNs in UVAH, which is apparently not the case in reality. Different bands of spectrum own various physical characteristics such as transmission distance and attenuation. HSNs also have various preference toward differentiated channels depending on the technology they use. In addition, the effect of channel combinations such as complements and substitutes should be further investigated.

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3.2 Innovation of UVAH/DC

To take in the effect of differentiated channels, HSNs should be able to express preference toward differentiated channels and their combinations. Moreover, understanding HSNs have such preference, SP may want to set different reserve prices when HSNs win channel combinations instead of individual channels. Therefore, we extend the methodology in UVAH and introduce UVAH/DC -- **U**nilateral **V**CG-based **A**uction for **H**SNs with **D**ifferentiated **C**hannels consideration.

To mathematically formulate the design problem of UVAH/DC, let us first define notations in Table 3.1.

Table 3-1: Notations for the design of UVAH/DC

$\boldsymbol{R}$	Set of auction regions
r	Region index, $r \in \mathbf{R}$
$\boldsymbol{S_1}$	Set of HSNs that bid spectrum resources
v	Virtual bidder
$\boldsymbol{S}$	Set of all bidder; $\boldsymbol{S} = \boldsymbol{S}_1 \cup v$
i	Bidder index, $i \in \mathbf{S}_1$ for HSN bidders
$\boldsymbol{P}$	Set of packages for bidding
p	Package index, $p \in \boldsymbol{P}$
$\boldsymbol{Q}_p$	Set of channels in package p

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J_r	Amount of available channels in region *r*
J	Amount of available channels in target area
j	Channel index in a region
$U_{r,j}$	Channel j in region *r*
$\theta_{r,j}$	Reserve price of channel *j* in region *r*
θ_p	Reserve price of package-*p*
$\alpha_i(p)$	Bid price of package-*p* submitted by bidder-*i*
$v_i(p)$	Bidder-*i*'s private value toward package-*p*
$x_{i,p}$	Assignment variable. If bidder-*i* is assigned package-*p*, then $x_{i,p} = 1$; otherwise, $x_{i,p} = 0$
$y_{i,r,j}$	Assignment variable. If $U_{r,j}$ is assigned to bidder-*i*, then $y_{i,r,j} = 1$; otherwise, $y_{i,r,j} = 0$

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3.2.1 Fully Expressive Bidding Format

When HSNs have diverse channel requirements and transmission ranges, a fully expressive and flexible bidding format is indispensable. According to the partitions and supply channels in each region, the auctioneer then defines packages for HSNs to bid. Let us take a target area with two regions, R_1 and R_2, for example. The available spectrum units in R_1 and R_2 are two and one, respectively, and can be expressed as set of $\{U_{1,1}, U_{1,2}\}$ and $\{U_{2,1}\}$, respectively. Given the supply information, up to seven packages can be defined as follows:

Package #1: $\boldsymbol{Q}_1 = \{U_{1,1}\}$;

Package #2: $\boldsymbol{Q}_2 = \{U_{1,2}\}$;

Package #3: $\boldsymbol{Q}_3 = \{U_{2,1}\}$;

Package #4: $\boldsymbol{Q}_4 = \{U_{1,1}, U_{1,2}\}$;

Package #5: $\boldsymbol{Q}_5 = \{U_{1,1}, U_{2,1}\}$;

Package #6: $\boldsymbol{Q}_6 = \{U_{1,2}, U_{2,1}\}$;

Package #7: $\boldsymbol{Q}_7 = \{U_{1,1}, U_{1,2}, U_{2,1}\}$.

The total number of packages based on our design can be calculated by $2^J - 1$, where $J = \sum_{r \in \mathbf{R}} J_r$ denotes the amount of available channels in the target area. Such a fully expressive design allows HSN-i to bid based on its requirements of channels and transmission range. Our design provides higher flexibility than highly expressive bidding format in UVAH which assumes channels are homogeneous, fullly expressive bidding

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format allows HSNs to value any combinations among differentiated channels, such as complments and substitutes.

3.2.2 Reserve Price over Packages

When SP has some understandings about HSNs's preference toward combinations, SP would like to set reserve prices according to this market information. For example, SP wants to set higher reserve prices for packages containing contiguoues channels because contiguous channels are usually regarded as complements due to the utilization of guard band. Since SP understands HSNs can evaluate any channel combiantion in fully expressive bidding format, SP may want to set reserve prices for packages as well. However, previous works usually focus on reserve prices for individual channels which only assures SP earns the minimum revenue for each channel even though these channels own combination effects are sold out to the same bidder. Therefore in the design of UVAH/DC, SP is allowed to specify reserve prices over packages, the minimum prices it is willing to sell when each package is assigned to a single HSN. In addition, the information of reserve prices would not be revealed to the HSNs.

3.2.3 Maximum Virtual Bid Generation

To prevent the revenue deficiency, we extend the concept of virtual bidders in UVAH because there are two major differences between UVAH/DC and UVAH. First, now SP set the reserve prices not only for individual channels but also for package, so we need to take

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those reserve prices into account. Second, SP may not identified reserve prices for all kinds of packages, it's reasonable to assume SP only set reserve prices for crucial packages. To address the differences, there is only one virtual bidder *v* in UVAH/DC to accommodate various reserve prices over packages, and the virtual bid generation in UVAH/DC contains two steps: first, for each package *p*, if there exists corresponding reserve price θ_p, virtual bid of that package $\alpha_v(p)$ equals θ_p. In the second step, those packages whose reserve prices not set by SP are sorted by cardinality (number of channels) in nondecreasing order, and their virtual bids are generated sequentially as followed:

Then this information is used for the creation of virtual bids. For each package *p*, there is a corresponding virtual bid which is equal to the reserve price $\theta_{r,j}$. For those packages whose reserve prices are not set by SP, their virtual bids are set to the sum of individual channel reserve prices. Therefore, the virtual bids can be calculated as follows:

$$\alpha_v(p) = Max \sum_{\{p_1, p_2 \dots p_n\} \in C_p} \alpha_v(p_i) \tag{3}$$

where C_p is the collection containing all kinds of set partition of package *p*. We want to make sure the virtual bid of a package without reserve price specification is no less than the sum of virtual bids of partitioned sub-packages. In other words, these virtual bids are set like complements. Since maximum function is used for virtual bid generation, this process is named maximum virtual bid generation. A special case of maximum virtual bid generation is that SP only specifies reserve prices of individual channels, and the virtual bids of packages can be easily calculated by summing up the reserve prices of channels contained in those packages. We will show later maximum virtual bid generation is an

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important design to make sure the payment is no less than reserve price for every winning package, i.e., SP's individual rationality.

3.3 Auction Clearing Algorithm

Based on the two innovations, auction clearing algorithm includes bid selection, payment calculation and the settlements between SP and the auctioneer.

3.3.1 Bid Selection

To allocate the spectrum resources to HSNs and virtual bidder with maximum bid offers, an integer programming model of Knapsack Problem (KP) is formulated for selecting a maximum bid offer combination [18]. When an HSN-*i*'s bid for package-*p* equals the virtual bidder-*v*'s bid, the selection priority is given to HSN-*i* in order to achieve higher spectrum utilization. Define the equal set

$$\boldsymbol{S}_e \equiv \{(i,v,p) \in \{1,\ldots,|\boldsymbol{S}_1|\} \times \{v\} \times \{1,\ldots,|\boldsymbol{P}|\} \mid \alpha_i(p) = \alpha_v(p)\} \tag{4}$$

To include the priority setting in the (KP) formulation, we define the adjusted bids for tie-breaking,

$$\hat{\alpha}_i(p) \equiv \begin{cases} \alpha_i(p) + \varepsilon, \text{ if } (i,\ v, p) \in \boldsymbol{S}_e, \text{ where } 1 >> \varepsilon > 0; \\ \alpha_i(p), \text{ otherwise.} \end{cases} \tag{5}$$

The (KP) can then be formulated as

$$\max_{x_{i,p}, y_{i,r,j}} \sum_{i \in \boldsymbol{S}_1} \sum_{p \in \boldsymbol{P}} x_{i,p} \hat{\alpha}_i(p) + \sum_{p \in \boldsymbol{P}} x_{i,p} \alpha_v(p) \tag{6}$$

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with the following three constraints:

Constraint 1: Single package assignment constraint

A bidder's bid offers for different packages are different, but one bidder wins at most one bid of a specific package *p*:

$$\sum_{p \in \boldsymbol{P}} x_{i,p} \le 1, \ \forall i \in \boldsymbol{S}. \tag{7}$$

Constraint 2: Availability constraint

For each region, each channel *j* can be allocated to one HSN at most.

$$\sum_{i \in \boldsymbol{S}} y_{i,r,j} \le 1, \ \forall r \in \boldsymbol{R}, \forall j \in J_r. \tag{8}$$

Constraint 3: Relation between two assignment variables

For bidder-*i* who wins package *p*, the assignment variable $y_{i,r,j}$, which corresponding channel included in *p*, should be 1.

$$\forall i \in \boldsymbol{S}, \ \exists p, \ x_{i,p} = 1 \Rightarrow y_{i,r,j} = 1, \ \forall U_{r,j} \in \boldsymbol{Q}_p. \tag{9}$$

3.3.2 Payment Calculation

After solving (KP) and obtaining the bid selection result, the auctioneer calculates payments of winning HSNs. Payment calculation follows the VCG auction, where a winning HSN pays the opportunity cost of winning the package. Let $B_{\boldsymbol{S}}^{\boldsymbol{P}}$ be the objective

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function value of (KP). Assume that the optimal bid selection of HSNs is $x^*_{i,p}$ and the package allocated to HSN-*i* is k_i. The payment for package k_i that HSN-*i* wins, $\pi_i(k_i)$, is then

$$\pi_i(k_i) = B^{\boldsymbol{P}}_{\mathbf{S}\setminus i} - B^{\boldsymbol{P}\setminus k_i}_{\mathbf{S}\setminus i}, \tag{10}$$

where $B^{\boldsymbol{P}}_{\mathbf{S}\setminus i}$ and $B^{\boldsymbol{P}\setminus k_i}_{\mathbf{S}\setminus i}$ are the maximal values of allocating packages ***P*** and ***P***\\$k_i$ to bidders in **S** other than HSN-*i*, respectively, and $\pi_i(k_i)$ is therefore the opportunity cost of HSN-*i* winning package k_i.

For each allocated package, the commission to the auctioneer is the difference between the HSN's payment and the reserve price of the package multiplied by a fixed commission rate. The reserve price of package *p* is just the virtual bids:

$$RP(k_i) = \alpha_v \tag{11}$$

The commission rate is the sum of the rate for SP, β, and the rate for HSN, γ. Therefore, the commission of allocating package k_i of the auctioneer can be calculated as

$$\sum\nolimits_{i \in \boldsymbol{S}_1} (\pi_i(k_i) - RP(k_i)) \times (\beta + \gamma) \tag{12}$$

Finally, the revenue to the SP is the sum of all HSNs' winning payments minus the auctioneer's commission and can be calculated by

$$(1 - \beta - \gamma)\sum\nolimits_{i \in \boldsymbol{S}_1} \pi_i(k_i) + (\beta + \gamma)\sum\nolimits_{i \in \boldsymbol{S}_1} RP(k_i) \tag{13}$$

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3.3.3 Illustrative Examples and Discussion

Here we give two illustrative examples to explain how UVAH/DC works. The first example emphasizes the difference between UVAH/DC and UVAH, and the second example describes how reserve price over packages may increase SP's revenue.

Example 3.1 Assume there are two channels A and B for two HSNs to bid and there is no region partition for simplicity. SP's reserve prices are {A: \$10, B: \$14, both: \$25}, and HSNs submit bids in fully expressive bidding format as followed:

HSN-1: {A: \$16, B: \$10}

HSN-2: {A: \$7, B: \$15}

In this example, both HSNs are only interested in individual channels. Since SP specifies reserve prices over all packages, the auctioneer introduces a virtual bidder whose bids are exactly SP's reserve prices.

Since UVAH only allows HSNs to bid by units, we assume the bid for one unit in UVAH is the average of A's and B's bid price. In addition, SP can only set reserve price per unit and it is also assumed to be the average of A's and B's reserve price. Therefore, the bids of HSNs and virtual bidder in UVAH become:

HSN-1: {1 unit: \$13}

HSN-2: {1 unit: \$11}

Virtual bidder: {1 unit: \$12, 2 units: \$24}

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The commission rate $(\beta+\gamma)$ is set to 3% in this example. The auction results of UVAH/DC and UVAH are as followed:

UVAH/DC

HSN-1 wins A with payment $10

HSN-2 wins B with payment $14

Auctioneer's revenue is $(\$10+\$14)\times 3\% = \$0.72$

SP's revenue is $(\$10+\$14)\times(1-3\%) = \$23.28$

UVAH

HSN-1 wins 1 units with payment $12

Auctioneer's revenue is $\$12\times 3\% = \$0.36$

SP's revenue is $\$12\times(1-3\%) = \$11.64$

In this example, UVAH/DC leads to higher revenue than UVAH because the former has a finer granularity for bid selection and allocation than the latter. Although HSN-2 has high valuation toward channel B, it cannot express this preference due to the limitation of bidding format. In addition, although channel A is rent-out in UVAH, auctioneer has no idea which channel for allocation is better. In the worst case, auctioneer would allocate channel B to HSN-1, not only HSN-1 needs to pay higher than its valuation, but SP's revenue is less than channel B's reserve price. This allocation mismatch caused by limitation of bidding format will be harmful to desired economic properties.

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Example 3.2 Assume there are two channels A and B for sharing and there is no region partition. Only one HSN attend the auction and its bids are {A: \$10, B: \$14, both: \$30}. SP's reserve prices are {A: \$12, B: \$10}. If SP does not specify reserve price of package {A, B}, the virtual bid of {A, B} will be set to \$22. We assume SP's reserve price of {A, B} is \$28 and discuss of the impact of this reserve price. The auction results with and without reserve price of {A, B} are as followed:

With reserve price of {A, B}

HSN wins {A, B} with payment \$28

Without reserve price of {A, B}

HSN wins {A, B} with payment \$22

We can see that SP can potentially increase its revenue by setting reserve price over packages.

3.4 Proofs of Economic Properties

This section proves the three desirable economic properties of the UVAH/DC: *truthfulness*, *individual rationality* and *budget balance*.

3.4.1 Truthfulness

Theorem 1: *UVAH/DC is truthful for HSNs.*

Proof:

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Define the utility of HSN-*i* winning package k_i as

$U_i(k_i) \equiv$ *True valuation of* k_i *- Payment for* k_i.

Let $\mathrm{v}_i(p)$ be HSN-*i*'s true valuation for package $p, p \in \boldsymbol{P}$. Let $\alpha_i(p)$ be the bid of package *p* by HSN-*i*, $\underline{\boldsymbol{\alpha}}_i \equiv [\alpha_i(p),\ p \in \boldsymbol{P}]$, and $\underline{\boldsymbol{\alpha}}_{-i} \equiv [\underline{\boldsymbol{\alpha}}_{i'},\ i' \neq i]$. When HSN-*i* bids truthfully, we have $\alpha_i(p) = \mathrm{v}_i(p),\ \forall p \in \boldsymbol{P}$. Let the results of allocating packages ***P*** to ***S*** be that HSN-*i* wins package k_i and other bidders win $\underline{\boldsymbol{k}}_{-i}$, where $\underline{\boldsymbol{k}}_{-i} \equiv [k_{i'}, i' \neq i]$. According to Eq. (8), HSN-*i*'s payment for package k_i is then $p_i(\mathrm{v}_i(k_i), \underline{\boldsymbol{\alpha}}_{-i}(\underline{\boldsymbol{k}}_{-i})) \equiv B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}} - B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}\backslash k_i}$. Now assume that HSN-*i* bids untruthfully with $\alpha_i'(p') \neq \mathrm{v}_i(p)$ and other bidders' bids remain $\underline{\boldsymbol{\alpha}}_{-i}$. Let the auction results be that HSN-*i* wins package k_i' and other bidders win $\underline{\boldsymbol{k}}_{-i}'$. HSN-*i*'s payment for k_i' is $p_i(\alpha_i'(k_i'), \underline{\boldsymbol{\alpha}}_{-i}(\underline{\boldsymbol{k}}_{-i}')) \equiv B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}} - B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}\backslash k_i'}$.

We now prove that given other bidders' bids unchanged, for HSN-*i*, the utility of truthful bidding, $U_i(k_i)$, is no less than the utility of any untruthful bidding, $U_i'(k_i')$:

$$
\begin{aligned}
U_i(k_i) &= \mathrm{v}_i(k_i) - p_i(\mathrm{v}_i(k_i), \underline{\boldsymbol{\alpha}}_{-i}(\underline{\boldsymbol{k}}_{-i})) \\
&= \mathrm{v}_i(k_i) - (B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}} - B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}\backslash k_i}) = \mathrm{v}_i(k_i) + \sum\nolimits_{l \in \boldsymbol{S}, l \neq i} \alpha_l(k_l) - B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}} \\
&= \alpha_i(k_i) + \sum\nolimits_{l \in \boldsymbol{S}, l \neq i} \alpha_l(k_l) - B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}} = \sum\nolimits_{l \in \boldsymbol{S}} \alpha_l(k_l) - B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}} \\
&\geq \sum\nolimits_{l \in \boldsymbol{S}} \alpha_l(k_l') - B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}} = \alpha_i(k_i') + \sum\nolimits_{l \in \boldsymbol{S}, l \neq i} \alpha_l(k_l') - B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}} \\
&= \mathrm{v}_i(k_i') + \sum\nolimits_{l \in \boldsymbol{S}, l \neq i} \alpha_l(k_l') - B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}} = \mathrm{v}_i(k_i') - (B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}} - B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}\backslash k_i'}) \\
&= \mathrm{v}_i(k_i') - p_i(\alpha_i'(k_i'), \underline{\boldsymbol{\alpha}}_{-i}(\underline{\boldsymbol{k}}_{-i}')) = U_i'(k_i').
\end{aligned}
\tag{14}
$$

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3.4.2 Individual Rationality

Theorem 2: *UVAH/DC is individually rational for SP if for any two disjoint packages with reserve price specifications, the reserve price of joint package is either not specified, or no less than the sum of disjoint packages' reserve prices.*

Proof:

Since reserve prices

To achieve rationality of SP, revenue per package must be no less than the reserve price. According to Eq. (8), the payment for HSN-*i* winning package k_i is $\pi_i(k_i) = B_{\mathbf{S}\setminus i}^{\mathbf{P}} - B_{\mathbf{S}\setminus i}^{\mathbf{P}\setminus k_i}$. To prove $\pi_i(k_i) \geq RP(k_i)$, it is equivalent to show

$$B_{\mathbf{S}\setminus i}^{\mathbf{P}} \geq B_{\mathbf{S}\setminus i}^{\mathbf{P}\setminus k_i} + RP(k_i) \tag{15}$$

Note that the left hand side (LHS) in (15) is the maximal value of a (KP) while right hand side (RHS) represents a feasible allocation for the same (KP), but the value in RHS does not necessarily equal to the value of that feasible allocation because $B_{\mathbf{S}\setminus i}^{\mathbf{P}\setminus k_i}$ may or may not already have winning virtual bid. When $B_{\mathbf{S}\setminus i}^{\mathbf{P}\setminus k_i}$ contains virtual bid $\alpha_v(k_v)$, the value of allocation should be recalculated because virtual bidder wins another package $k_v \cup k_i$. Therfore, we discuss following two cases respectively:

(i) $B_{\mathbf{S}\setminus i}^{\mathbf{P}\setminus k_i}$ *does not contain virtual bid*

In this case, the RHS equals to the value of feasible allocation. Furthermore, we know LHS is the maximal value for the (KP), so LHS must be no less than RHS.

(ii) $B_{\mathbf{S}\setminus i}^{\mathbf{P}\setminus k_i}$ *contains virtual bid*

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(15) can be reformulated as

$$B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}} \geq B_{\boldsymbol{S}\backslash(i,v)}^{\boldsymbol{P}\backslash(k_i,k_v)} + RP(k_i) + RP(k_v) \tag{16}$$

But the actual value of allocation in the RHS of (16) is

$$B_{\boldsymbol{S}\backslash(i,v)}^{\boldsymbol{P}\backslash(k_i,k_v)} + RP(k_i \cup k_v) \tag{17}$$

To maintain (16) is true, we must have

$$RP(k_i \cup k_v) \geq RP(k_i) + RP(k_v) \tag{18}$$

Condition (18) means that for any two disjoint packages with reserve price specifications, SP should set the reserve price of joint package no less than the sum of disjoint packages' reserve prices. If the reserve price of joint package is not set, maximum virtual bid generation would guarantee Condition (18) is satisfied. Combined both cases, it can be shown that under the Condition (16), the payment of HSN-*i*'s winning package k_i is

$$\pi_i(k_i) = B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}} - B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}\backslash k_i} \geq RP(k_i). \tag{19}$$

One can find that the payment from the auctioneer to the SP (Eq. (11)) is no less than the reserve price of the package rented out,

$$(1-\beta-\gamma)\sum_{i\in\boldsymbol{S}_1}\pi_i(k_i) + (\beta+\gamma)\sum_{i\in\boldsymbol{S}_1}RP(k_i) \geq \sum_{i\in\boldsymbol{S}_1}RP(k_i). \tag{20}$$

Theorem 3: *UVAH/DC is individually rational for HSNs.*

Proof:

Rationality of HSNs means that payment per package is not higher than the bidding price. Let k_i be the winning package of HSN-*i*. Given that $B_{\boldsymbol{S}}^{\boldsymbol{P}} = \alpha_i(k_i) + B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}\backslash k_i}$, we have

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$$\begin{aligned}\alpha_i(k_i)-\pi_i(k_i)&=\alpha_i(k_i)-(B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}}-B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}\backslash k_i})\\&=(\alpha_i(k_i)+B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}\backslash k_i})-B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}}=B_{\boldsymbol{S}}^{\boldsymbol{P}}-B_{\boldsymbol{S}\backslash i}^{\boldsymbol{P}}\geq 0,\ \forall i.\end{aligned} \tag{21}$$

3.4.3 Budget Balance

Theorem 4: *UVAH/DC is budget balanced if for any two disjoint packages with reserve price specifications, the reserve price of joint package is either not specified, or no less than the sum of disjoint packages' reserve prices.*

Proof:

Under Condition (16), HSN-i's payment for winning package k_i, $\pi_i(k_i)$, is equal to or higher than $RP(k_i)$. By substituting the result into Eq. (10), one can find that the commission to the auctioneer is non-negative when there are bid offers, i.e., budget balanced:

$$[\sum_{i\in \boldsymbol{S}_1}(\pi_i(k_i)-RP(k_i))]\times(\beta+\gamma)\geq 0. \tag{22}$$

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Chapter 4 Numerical Performance Evaluation

The design and economic properties of UVAH/DC auction have been showed in Chapter 3, but what's the performance of UVAH/DC auction and how performance will be influenced by factors is beyond theoretical proofs. There are three issues need to be addressed about UVAH/DC auction:

I1) How will HSNs' valuation toward combinations affect the auction performance? i.e., complementarity and substitutability.

I2) What are the tradeoffs between fully expressive format (FBF) and highly expressive format (HBF)?

I3) How will reserve price affect the economic performance?

In Chapter 4, the performance of UVAH/DC is evaluated. First, the performance indices and parameter settings are summarized in Chapter 4.1. Chapter 4.2 aims to analyze the effects of channel combinations. The tradeoffs between using fully expressive bidding format and highly expressive bidding format discussed in Chapter 4.3. Lastly, since UVAH/DC does not guarantee SP's truthfulness, Chapter 4.4 and Chapter 4.5 describes how market performance is affected by reserve prices of single-channel packages and reserve prices over multi-channel packages respectively.

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4.1 Performance Indices and Parameter Settings

To numerically evaluate the economic performance of UVAH/DC auction, let us define some significant performance indices including total revenue, spectrum rent-our ratio (ROR), SP's surplus and average surplus per HSN, of comparison as follows:

$$\text{Total revenue} \equiv \sum \text{payment from winning HSNs} \tag{23}$$

$$\text{ROR} \equiv \frac{\text{\# of channels allocated to HSNs}}{\text{\# of channels provided by SP}} \tag{24}$$

$$\text{SP's surplus} \equiv \sum (\pi_i(k_i) - \alpha_v(k_i)) \tag{25}$$

$$\text{Average surplus per HSN} \equiv \frac{\sum \text{(valuation-payment)}}{\text{\# of competing HSNs}} \tag{26}$$

For issue I1), ROR, SP's surplus and average surplus per HSN are analyzed because we want to know the influence of HSN's valuation toward combinations from different entities' viewpoints. Besides ROR, total revenue is an important factor to SP's willingness of participation, so we focus on these two indices in I2) and I3).

A baseline scenario is designed for numerical evaluation of UVAH/DC. Since we want to highlight the effect of channel combinations, SP have 4 contiguous channels to share and the target area is not partitioned into multiple regions in the baseline scenario. The reserve price of SP is draw integers uniformly from [10, 15]. The number of HSNs ranges from 1 to 10 and each HSN is interested in two of the channels which are randomly

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picked. The corresponding bidding price for each channel is draw integer uniformly from interval [10, 20]. The combination effects are decided by cases, if there is no complementarity and substitutability, the HSN's bidding price of packages is simply the sum of bidding price for each channel. For simplicity, we assume the commission rate is zero.

UVAH/DC is implemented using python, and to solve such an optimization problem we adopt a commonly available optimization tool suite, IBM ILOG CPLEX™ [ILOG] for solution. The numerical evaluation uses Monte-Carlo simulation that randomly generates HSNs' valuations and SP's reserve price. 1000 testing instances are created for each scenario, with 100 instances for each value of competing HSNs. All the analysis results are averaged over these 100 instances.

4.2 Effects of Channel Combinations

In this subsection, we investigate the influence of combination effects including complementarity and substitutability. Two kinds of channel combinations are considered: contiguous channel combination and non-contiguous one. For any two contiguous channels, additional utility for each bidder is draw integers from interval [0, C_c] ([C_c, 0] if C_c is less than 0). For two non-contiguous channels, additional utility is draw integers from interval [0, C_n]. Complements, due to reuse of guard band or easier implementation of contiguous carrier aggregation, are assumed to have higher impact on contiguous channels

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than non-contiguous channels. However, substitutability in channels is more complicated because the causes of substitutes are quite various, so here we simply assume it has the same influence on these two kinds of channels. Various settings of C_c and C_n are summarized in Table II.

Table 4-1: Definition of Complementarity Levels

Combination Level	C_c	C_n
Substitute Level 2	-10	-10
Substitute Level 1	-5	-5
Neutral	0	0
Complement Level 1	5	0
Complement Level 2	10	5

Complementarity harvests additional value in UVAH/DC which is expected to increase SP's surplus as well as ROR as depicted in Fig 5.1 (a) and (b). From Fig 5.1 (c), we can see average surplus per HSN also increases with complementarity. To see the reasoning, consider a simplified case where two HSNs compete for a specific package and not interested in other ones. The payment of winning HSN is exactly the bid of the other HSN. When effects of complements enlarge, it can be seen as valuations of both HSNs multiplied by a factor which is larger than 1. HSN's surplus, difference of winning bid and payment, also enlarges by this factor. This is a natural result when additional utility is magnified proportionally.

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On the other hand, substitutability is anticipated to decrease SP's surplus, ROR and average surplus per HSN by the similar argument of complementarity. Nevertheless, from Fig 5.1 (c), average surplus per HSN increases with substitutability when HSNs' competition is intense. This is because when multiple HSNs compete for channels and channels are more similar to substitutes, the optimal allocation is probably that each channel is assigned to a HSN. Larger effects of substitutes make little impact on the allocation as a result, but VCG payment reflects substitutes more than total value of selected bids. Consider the following example:

Example 4-1: Assume two HSN to bid for two channels A and B. The virtual bids are (A:$10, B:$10, both:$20), while HSN-1's bids are (A:$15, B:$12, both:$27) and HSN-2's bids are (A:$12, B:$15, both:$27). The results of UVAH/DC are that HSN-1 wins A and HSN-2 wins B with the same payment $12 and surplus $3. If substitutability between A and B reduce both HSNs' valuations from $27 to $25, they still win the same package but their payments become $10 and higher surplus $5.

In the above example, substitutability reduces HSNs' payment while total value of selected bids remains unaffected, and thus increase HSNs' surplus.

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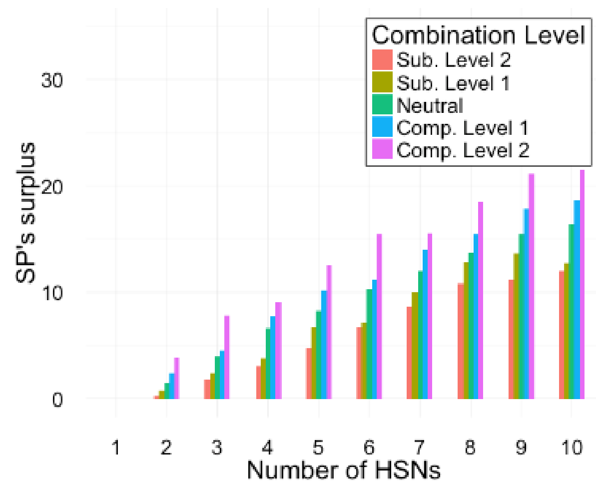

Figure 4-1: Comparison of different combination levels on SP's surplus over different number of HSNs

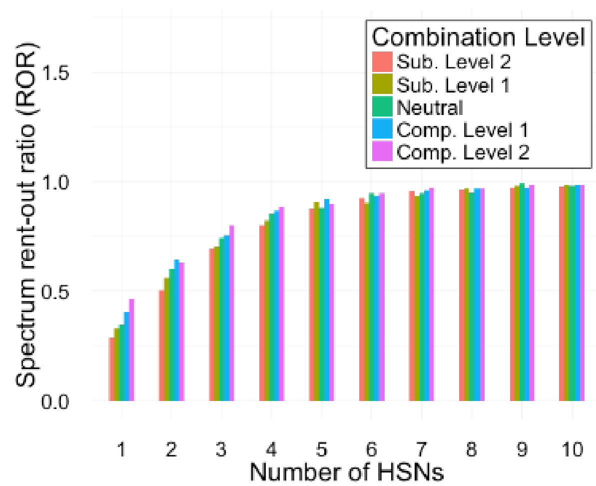

Figure 4-2: Comparison of different combination levels on ROR over different number of HSNs

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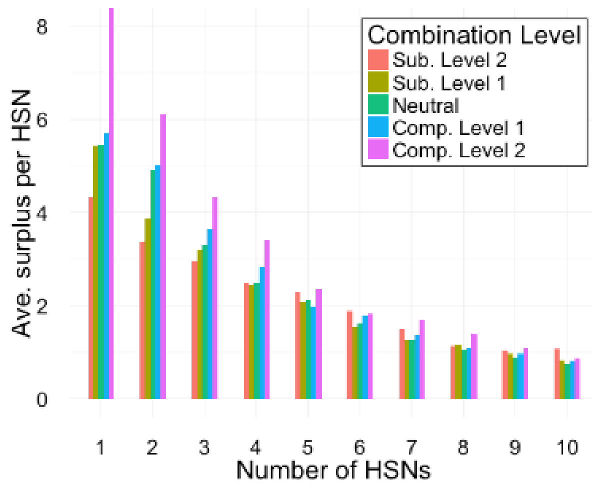

Figure 4-3: Comparison of different combination levels on average surplus per HSN over different number of HSNs

4.3 Revenue and Computation Time Tradeoff of Bidding Flexibility

Design of fully expressive bidding format in (FBF) UVAH/DC gives HSNs more flexibility than highly expressive bidding format (HBF) in [25] which only addresses different amount of homogeneous channels, but to clear the auction with FBF requires longer computation time. Here we analyze the tradeoffs between FBF and HBF using same test cases. Since HSNs with valuations toward differentiated channels may be untruthful when using HBF, it is assumed that bidding price for 1 unit of spectrum in HBF is the average bidding price for each channel in FBF. For example, there are channel A and B for bidding and HSN-1's bids in FBF are (A:$10, B:$14, both: $25), its bids in HBF become (1 unit: $12, 2 units: $25). Likewise, bidding price for multi-unit packages in HBF is also averaged by multi-channel packages in FBF. In addition, now the additional utility among

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any two channels are draw integers from [-10, 10], accommodating complementarity and substitutability at the same time. One thing different from the baseline scenario is that we assume two cases where each HSN's demand is three channels and four respectively.

Using FBF should lead to higher total revenue and ROR because the former has a finer granularity for bid selection and allocation than the latter. Let FBF auction and HBF auction be UVAH/DC using FBF and HBF as bidding format respectively, and note that HBF auction is the UVAH auction in [25]. Fig 5.2 and 5.3 summarizes the results of cases that each HSN's demand is three and four respectively. In the former case, FBF auction leads to 36.4% higher total revenue and 9.4% higher ROR than HBF auction when number of HSNs is greater than 1. The discrepancy is mainly caused by that HBF cannot describe precisely which channels are in HSNs' favorite lists and thus HSNs bid lower when they have more unwanted channels. But even if HSNs are interested in all channels, FBF auction still leads to 11.4% higher total revenue due to better bid selection and allocation. However, the results violate our hypothesis when number of HSNs is only 1. The reason is that auctioneer choose sub-optimal outcome allocating too many channels to HSNs which leads to higher revenue and ROR as following example:

Example 4-2: Assume only one HSN to bid for two channels A and B. The bids of virtual bidders are (A:$10, B:$10, both:$20) and HSN-1's bids are (A:$15, B:$9, both:$24) when using FBF auction. In HBF auction, their bids become (1 unit:$10, 2 units:$20) and (1 unit:$12, 2 units:$24). Auction results are as follows:

FBF auction

HSN-1 wins B and virtual bidder wins A with total revenue $10 and ROR 50%.

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HBF auction

HSN-1 wins both with total revenue \$20 and ROR 100%.

HBF auction has higher total revenue and ROR but actually the allocation in FBF auction is optimal.

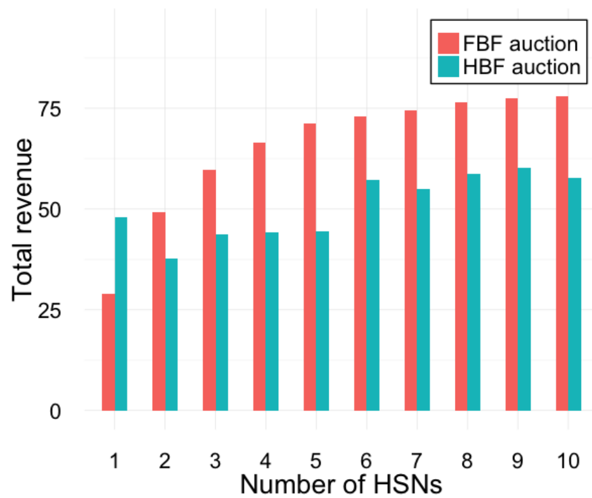

Figure 4-4: Comparison of FBF and HBF auctions with each HSN's demand is three on total revenue over different number of HSNs

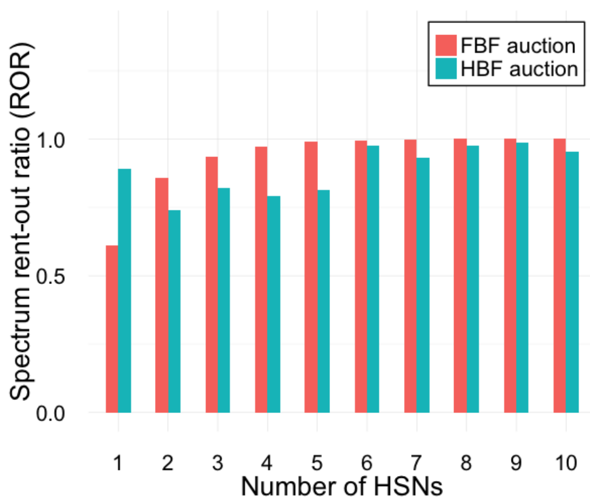

Figure 4-5: Comparison of FBF and HBF auctions with each HSN's demand is three on ROR over different number of HSNs

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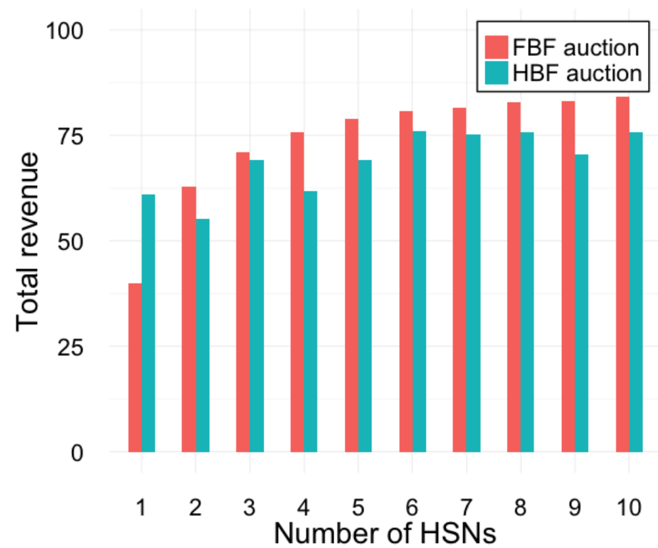

Figure 4-6: Comparison of FBF and HBF auctions with each HSN's demand is four on total revenue over different number of HSNs

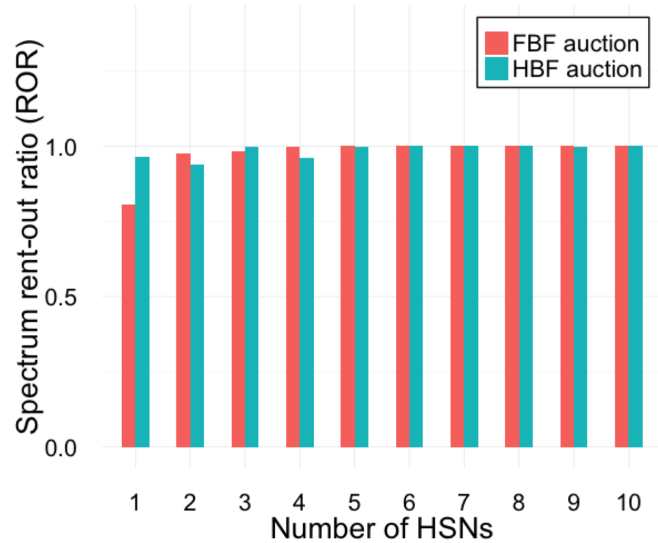

Figure 4-7: Comparison of FBF and HBF auctions with each HSN's demand is four on ROR over different number of HSNs

Now the computation time of clearing UVAH/DC and UVAH is evaluated under different number of HSNs, supply channels and partition of the auction regions. The

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parameters of regions and channels per region we consider are (2, 3), (2, 4), (3, 3). The computation efforts of both auctions come from allocation and payment by solving (MKP)s. If we use numeration to look for optimal solution of (MKP), then the computation complexity for enumeration in worst case is $(|\mathbf{P}|+1)^{N+1}$, where $|\mathbf{P}|$ is the total amount of packages and $(N+1)$ represents the number of HSNs and virtual bidder. The computation complexity for payment calculation is $N(|\mathbf{P}|+1)^{N}$. So the total time complexity of clearing the UVAH/DC is $O(N|\mathbf{P}|^{N})$. Although dynamic programming has been applied to 0-1 Knapsack Problem [27], its complexity is pseudo-polynomial which is actually exponential. We can see from Fig 5.4 that the computation time of both UVAH/DC and UVAH grows exponentially with number of packages and HSNs, and UVAH/DC requires more computation effort than UVAH. But the rewards of longer computation time are HSNs' truthfulness, prevention the HSNs to acquire unwanted channels, and finer granularity for bid selection and allocation.

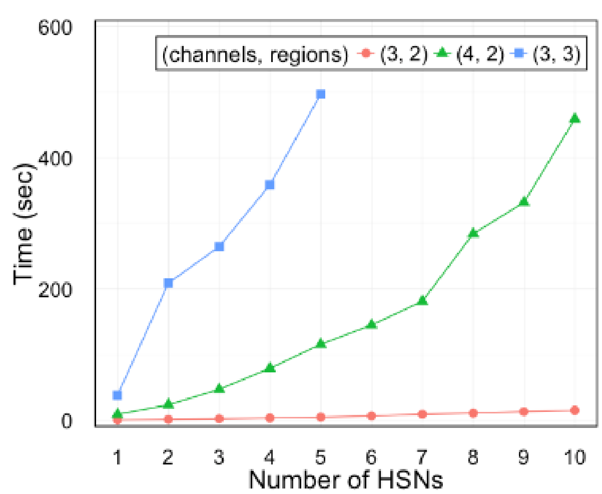

Figure 4-8: Computation time analysis of UVAH/DC over different number of HSNs

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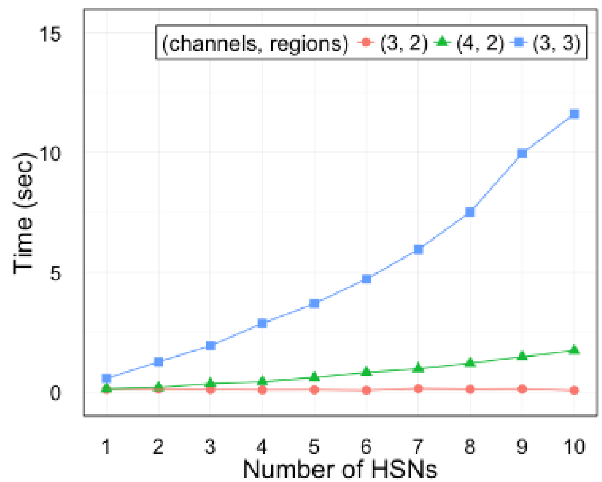

Figure 4-9: Computation time analysis of UVAH over different number of HSNs

4.4 Effects of Single-channel Package Reserve Prices

How SP set reserve price to maximize total revenue is a crucial question because UVAH/DC does not guarantee SP's truthfulness. SP can strategically set the reserve price for each channel and packages. In this subsection, the impact of single-channel package reserve prices is analyzed first. Two potential way to increase SP's ways are discussed as followed: setting reserve price correlated to market preference and increase/decrease reserve prices monotonically.

To simulate the correlation between market preference and SP's reserve prices, the generation of valuations and reserve prices are modified. SP's reserve price for individual channel is draw from $N(15,\sqrt{6})$, and market preference for each channel is also draw from the same distribution. Due to some knowledge about market conditions, SP may set reserve price according to such information. Therefore, we make correlation exists in

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random numbers generated from both distributions by applying Cholesky decomposition. Afterwards, HSNs' valuations for each channel are the corresponding market preference added by a random variable $N(0, \sqrt{6})$. It's assumed that no combination effects exist in HSNs' valuation, and SP would not specify reserve prices for multi-channel packages.

The results of different levels of correlation on total revenue are summarized in Fig 4-10. Total revenue increases with the correlation between SP's reserve prices and market preference, and the phenomenon becomes more salient under high competition between HSNs. The reason is that when SP have more information about market conditions, it can set proper reserve prices to extract more HSNs' surplus. This scenario can be analogous to a monopoly market, when the monopolist has sufficient information about demand, it can set suitable price to maximize its revenue.

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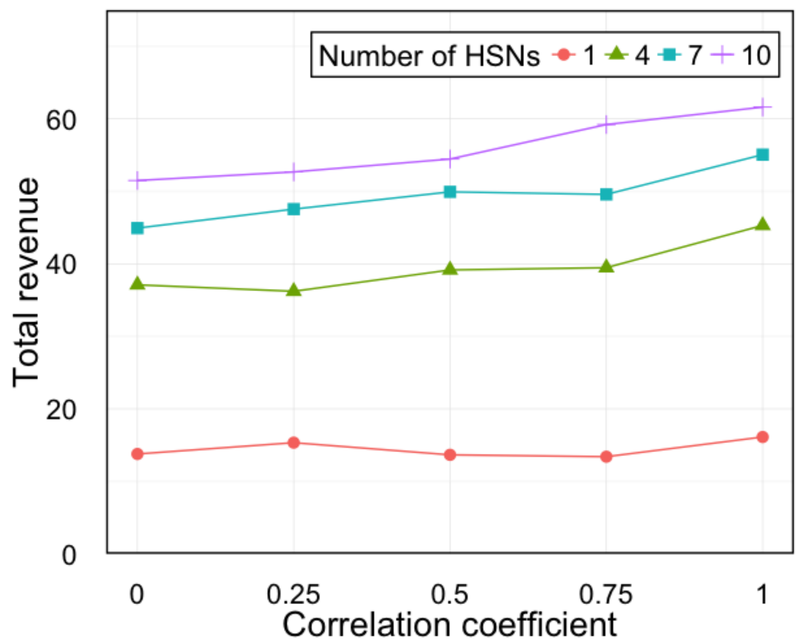

Figure 4-10: Comparison of the impact over various correlation coefficients

Now the effects of increasing/decreasing reserve prices monotonically are analyzed. Before the analyses, there are two intuitively clear properties when SP increases reserve price:

P1) ROR is monotonically non-increasing, and

P2) per-channel revenue is monotonically non-decreasing.

However, its effect on total revenue is not so obvious. We define reserve price premium per channel as the deviation to realization of random distribution. For example, if reserve price premium per channel is $2, it means that SP increases reserve prices for each channel by $2. We would like to know the influence of reserve price premium on total revenue.

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As we can see from Fig 4-11, positive reserve price premium leads to lower total revenue, which comes from the dramatic decrease of ROR by setting reserve price too high. On the other hand, negative reserve price premium also leads to lower total revenue under low competition between HSNs, but total revenue remains almost the same under high competition. When number of HSNs is small, revenue is highly related to reserve price owing to the design of virtual bids. So decreasing reserve price causes lower revenue, but the impact also decreases as number of HSNs increases. To see as a whole, different reserve price premium does not increase total revenue apparently, and little benefits can be acquired by HSNs.

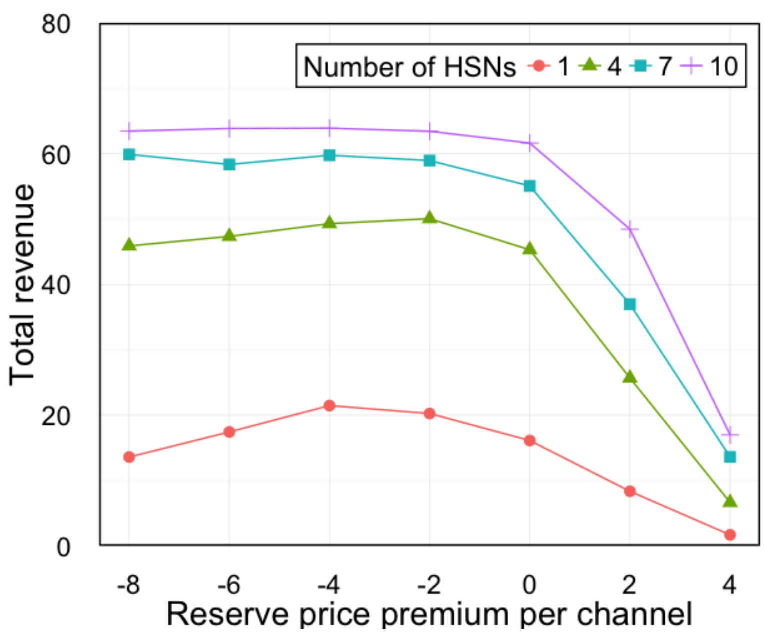

Figure 4-11: Comparison of different reserve price premium on total revenue

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4.5 Effects of Multiple-channel Package Reserve Prices

We analyze effects of multiple-channel package reserve prices in this subsection. Reserve prices over packages are designed to guarantee the minimum rent-out price is no less than the corresponding reserve price. SP with reserve prices over packages is expected to have higher revenue. To check that in numerical evaluations, we extend the scenario settings in Chapter 4.4 where market preference and reserve price toward two-channel packages are draw from $N(40,\sqrt{6})$, which is a complement scenario. HSNs' valuation toward two-channel packages are draw from $N(0,\sqrt{6})$ added by corresponding market preference. The correlation between market preference and reserve price is set to 1 for both single- and two-channel packages.

To our surprise, the usage of reserve prices over packages decrease total revenue instead which is shown on Fig 4-12. To go into details of instances, we found that there are two adverse effects of this design. First, although design of reserve price over packages guarantees SP's individual rationality, it also largely decreases the rent-out probability as depicted in Fig 4-13. For instance, two HSNs are interested in channel A and B respectively, and both their bids are higher than the corresponding reserve price. However, if SP specifies reserve price on package {A, B} which is higher than the sum of HSNs' bids. UVAH/DC would reserve this package for SP. The other side effect is that irrelevant package reserve price may also prevent a package to be rent-out even though HSNs' bid is higher than that package. We explain via an example:

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Example 4.3: Consider there are three channels A, B and C to be shared, and only one HSN attend the auction and it is only interested in package {A, B} with bid $40. Part of the virtual bids generated from SP's reserve prices are summarized in Table 4-2. It should be noted that the HSN's bid $40 is higher than the corresponding virtual bid $30. However, since UVAH/DC adopts maximum virtual bid generation, the virtual bid of {B, C} is too high and also induce high virtual bid of {A, B, C}. As a result, the package {A, B} won't be rent-out to the HSN even though its bid is higher than reserve price due to irrelevant virtual bid {B, C}.

In conclude, to truly exploit the design of reserve price over packages, the issues of low rent-out probability of single channels and irrelevant virtual bids should be addressed in future work.

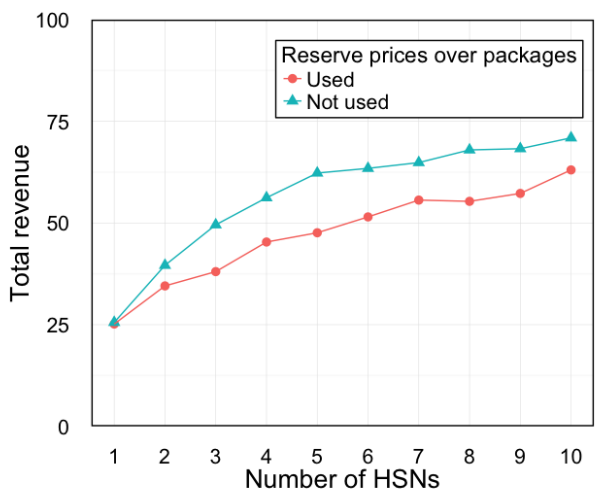

Figure 4-12: Comparison of whether or not using reserve prices over packages on total revenue under complement scenario

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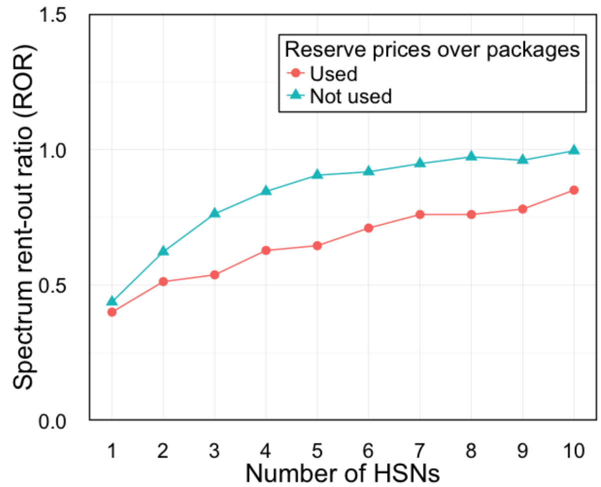

Figure 4-13: Comparison of whether or not using reserve prices over packages on ROR under complement scenario

Table 4-2: Virtual bids in Example 4.3

Package	{A}	{C}	{A, B}	{B, C}	{A, B, C}
Virtual Bids	10	10	30	50	60

Although we have shown that SP should set reserve prices similar to complements to guarantee its individual rationality, it may still be beneficial for SP to set like substitutes because the rent-out probability would increase. To inspect the possibility, we look into a substitute scenario where market preference and reserve price toward two-channel packages are draw from $N(30, \sqrt{6})$. In addition, instead of using maximum virtual bid generation, minimum virtual bid generation is applied to highlight the impact of substitute reserve pricing. From Fig 4-14, we can see reserve pricing over packages leads to slightly higher revenue than reverse prices over packages are ignored when competition is not high, due to higher ROR depicted in Fig 4-15. Although reserve pricing over packages without restrictions would harm the individual rationality theoretically, it may still advantageous in some real situations.

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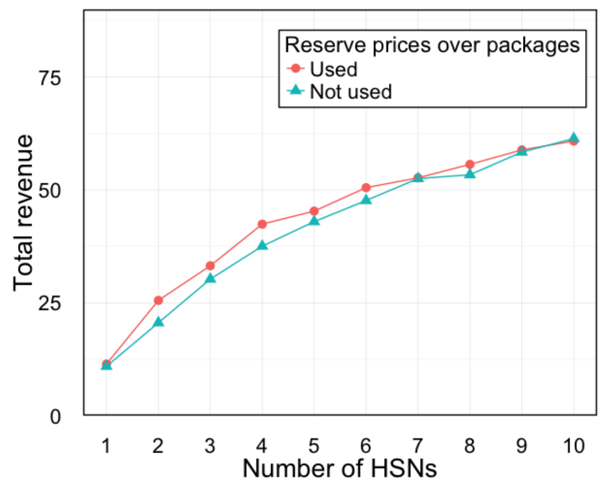

Figure 4-14: Comparison of whether or not using reserve prices over packages on total revenue (minimum virtual bid generation) under non-obvious scenario

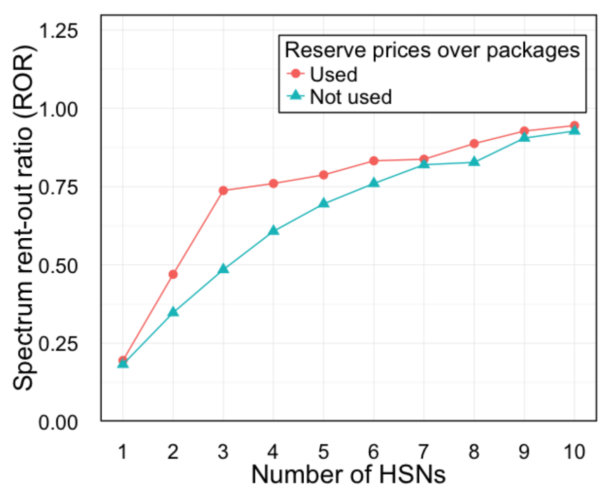

Figure 4-15: Comparison of whether or not using reserve prices over packages on ROR (minimum virtual bid generation) under non-obvious scenario

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Chapter 5 Conclusions and Future Work

5.1 Conclusions

Various local and global reports project that worldwide mobile data traffic will increase more than tenfold in the next five to ten years. Exploitation of underutilized spectrum is therefore an effective alternative to meet the explosive mobile data traffic. When HSNs are allowed to operate in the same underutilized spectrum, the coexistence issue becomes a critical issue. This thesis considered a coexistence network that involved one SP sharing unused spectrum resources to multiple HSNs. To address the spectrum sharing problem of coexistence HSNs, this thesis adopted a single-round auction, UVAH/DC, with three novel designs. Firstly, a fully expressive package bidding format allows HSNs to freely specify the operating regions, channel and channel combinations. The second one is reserve prices over packages which provide SP flexibility to set reserve price for each package. The last one is maximum virtual bid generation derived from the SP's reserve price over packages which resolves the revenue deficiency of VCG. UVAH/DC exploits spectrum availability by enabling spatial reuse while achieving good economic properties including truthfulness, individual rationality and budget balance. Numerical experimentation also shows that, compared to Zhan's design, UVAH/DC improves spectrum revenue and spectrum rent-out ratio (ROR) by 36.4% and 9.4% respectively, making it a practical solution to enable differentiated channel sharing among HSNs.

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5.2 Future Work

The directions of future research are listed as followed.

(1) Enable the flexibility of reserve pricing over packages while not sacrificing ROR.

In Chapter 4.5, we showed reserve prices over packages cause lower ROR and revenue when market preference is toward complementarity. This negative side effect violates our initial intention allowing SP to better capture market preference. How to maintain the flexibility of reserve pricing over packages while not sacrifice ROR remains an issue. One possibility is new auction design under relaxation of SP's individual rationality. Definition of SP's individual rationality in this thesis is that payment of each winning package must be no less than the corresponding reserve price. However, another possible definition is that total revenue of winning packages should be no less than the sum of corresponding reserve prices, which means auctioneer can sacrifice SP's individual rationality for some packages but remain it as a whole. Nevertheless, VCG-based auctions cannot achieve this kind of individual rationality, and the auction algorithm must be redesigned.

(2) Design a computationally feasible algorithm for large-scale UVAH/DC.

Since UVAH/DC needs to solve several (MKP)s, this problem is NP-hard and becomes computationally infeasible for large number of regions, channels and HSNs. If large-scale auction-based spectrum sharing is not impossible, UVAH/DC would become inappropriate to achieve time efficiency and efficient auction algorithm should be designed. Approximate algorithms are potential ways to make large-scale UVAH/DC into practice. Based on VCG auction, Shi et al. [Shi14] propose an approximate, computationally efficient auction

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framework which guarantee good competitive ratio (the bound of approximate solution over optimal solution). Their work will be helpful to design an approximate algorithm for UVAH/DC.

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