# Business Modeling for TV White Space Networks

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## ABSTRACT

Database-assisted TV white space network is a promising paradigm of dynamic spectrum sharing, and can effectively improve spectrum utilization and alleviate spectrum scarcity via centralized control of TV white space databases residing in the cloud. In this article, we discuss business modeling for a database-assisted TV white space network, which is very important for wide commercialization of this promising technology. Motivated by several recent business practices, we propose and study two types of different business models: *spectrum market* and *information market*. In the spectrum market model, spectrum licensees, through spectrum brokers acted by databases, lease the underutilized (licensed) TV channels to unlicensed wireless devices for secondary utilization. In the information market model, databases sell the advanced information regarding (unlicensed) TV channels to unlicensed wireless devices in order to enhance the secondary spectrum utilization performance. We outline the corresponding trading mechanism details for both market models, and evaluate the feasibility and performance of both models through theoretical and numerical studies. Numerical results indicate that both the database operator's profit and the total network profit can be significantly improved under properly designed trading mechanisms.

## INTRODUCTION

### BACKGROUND

With the explosive growth of mobile smartphones and bandwidth-hungry wireless applications, radio spectrum is becoming increasingly congested. TVwhite space (TVWS) has recently been recognized as a promising new spectrum opportunity for wireless broadband services, due to its low utilization (at most times and in many areas) and brilliant propagation performance [1]. Specifically, TVWS (also called TV channel) refers to the unused or underutilized broadcast television spectrum (in the UHF/VHF frequency band) at a particular time and location. By allowing unlicensed wireless devices (called white space devices, WSDs) reuse the TVWS in a license-exempt and opportunistic manner, we can effectively improve the spectrum efficiency and alleviate today's global spectrum scarcity. As a consequence, in the United States, the Federal Communications Commission (FCC) has unanimously approved the license-exempt use of TVWS to support new wireless applications [1]. Moreover, Ofcom and the Singapore TVWS pilot group have launched several pilots of TVWS technology in the United Kingdom and Singapore, respectively.[1]

To effectively reuse the TVWS spectrum without harming the interests of licensed devices, spectrum regulators have advocated a *database-assisted* TVWS network architecture [1]. In this architecture, unlicensed WSDs obtain the available TV channel information via querying a certified *geolocation* database residing in the cloud instead of sensing the local spectrum environment as in traditional dynamic spectrum sharing systems. To achieve this, the geolocation database needs to house and periodically update information related to network infrastructures of TV licensees as well as their channel occupations. Figure 1 illustrates such a database-assisted TVWS network architecture. To access any TVWS, WSDs first report their locations to a geolocation database (step 1), and then the database computes and returns the available TV channels that WSDs can use in a certain time period (step 2). In this sense, the database-assisted TVWS network is a typical example of the cloud-enabled virtualized network.[2] As illustrated in Fig. 1, each WSD is an infrastructure-based device (e.g., a base station) operated by a secondary operator, and provides *cellular-based* wireless services to its subscribed end users by using the obtained TV channels.[3]

The database-assisted TVWS network has received wide and enthusiastic support, not only from spectrum regulators, but also from standards bodies and industrial organizations.[4] The geolocation database is no doubt the central network entity in such a network. In the United States, the FCC has temporarily certified several major IT companies including Google, Microsoft, and SpectrumBridge as geolocation database operators. Obviously, the long-term and large-scale commercial deployment of such a database-assisted network requires a proper business model that gives the database operators the opportunity to create and capture sufficient value in order to cover their capital expense (CAPEX) and operating expense (OPEX).

[1] For more details, please refer to Ofcom TV White Space Network Pilot (http://stakeholders.ofcom.org.uk/spectrum/tv-white-spaces/white-spaces-pilot/) and Singapore White Space Pilot Group (http://www.whitespaces.sg/projects.php

[2] Specifically, local computation such as location measurement and identification are performed on a WSD, while complex data processing such as TV channel availability computing, channel scheduling, and business modeling (if needed) are implemented in the white space database residing in the cloud. WSDs and the database communicate with each other through the Internet. Such an architecture can reduce the energy consumption of mobile WSDs and improve system performance.

[3] In addition to this cellular-based network scenario, WSDs can also form networks in ad hoc mode. Nevertheless, in this article, we focus on the cellular-based network scenario.

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### SOLUTIONS

Before talking about the business modeling solutions, we first look at the current business practices of SpectrumBridge Inc.,[5] the world's first FCC-certified geolocation database operator in the United States. Specifically, SpectrumBridge offers two different commercial models: *SpecEx* and *White Space Plus*. The formal model, SpecEx, enables TV licensees to lease their licensed but underutilized TV channels to unlicensed WSDs. In this process, the database acts as a spectrum broker to facilitate the trading process (e.g., connecting and matching buyers and sellers). The latter model, White Space Plus, on the other hand, enables the database to sell *information* regarding TV channels to unlicensed WSDs. This is motivated by the fact that the database has more information regarding the quality of TV channels, and such information can potentially be used by unlicensed WSDs to improve their performance. The above discussion actually leads to two different types of business models for TVWS networks, the *spectrum market* and the *information market*, which will be the main focus of this article.

Specifically, the spectrum market and information market target different types of TV channels in TVWS networks: *licensed* and *unlicensed* TV channels. The licensed TV channels are those registered to some TV licensees but underutilized by the licensees. Hence, the licensees can temporarily lease the underutilized (licensed) channels to WSDs for exclusive usage during a short time period. The unlicensed TV channels are those not registered to any TV licensee at a particular location, and hence are a public resource at that location. Unlicensed TV channels are usually assigned by spectrum regulators for public and shared usage among unlicensed WSDs, and not allowed for trading in a spectrum market. Moreover, due to the shared usage by unlicensed WSDs, the quality of unlicensed TV channels is usually not guaranteed. Hence, the database can potentially sell its advanced information regarding the quality of unlicensed TV channels to WSDs.

In this article, we analyze both the spectrum and information markets under *non-competitive* and *competitive* market scenarios. Figure 2 illustrates the taxonomy of TVWS business models in this article. The rest of this article is organized as follows. We begin with an overview of the database-assisted TVWS network as well as the technical and economical issues in this new network. We then provide detailed formulation and analysis of the spectrum and information markets. We further discuss the future challenges and open issues in this area, and conclude the article.

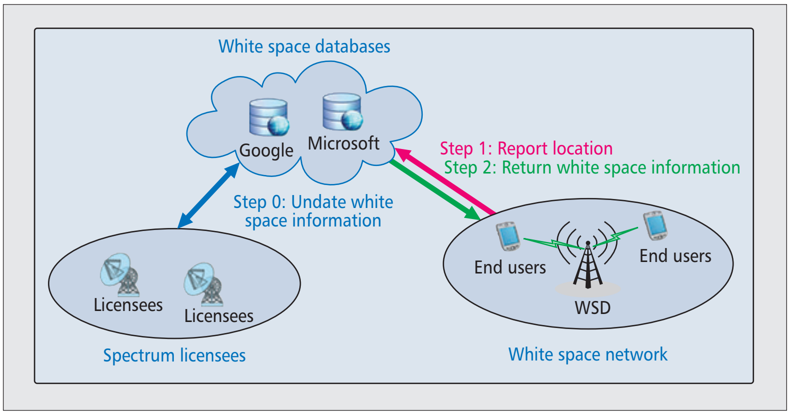


**Figure 1.** Database-assisted TVWS network architecture.

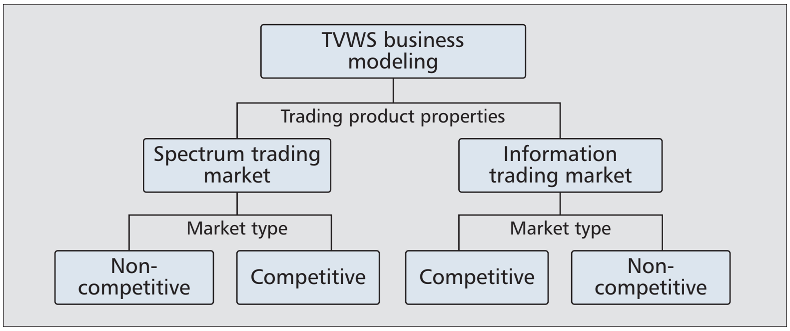


**Figure 2.** Taxonomy of TVWS network business modeling.

## TECHNOLOGY OVERVIEW

In this section, we briefly introduce the TVWS network technology as well as the technical and business model design issues in this new type of network. As shown in Fig. 1, one of the most important features of a database-assisted TVWS network is that unlicensed WSDs obtain the TV channel availability information through querying a geolocation database residing in the cloud, rather than directly sensing the current activity levels in the TV channels. Hence, the geolocation database is the central network entity in such a network.

### TECHNICAL ISSUES

There are several technical challenges in developing a database-assisted TVWS network, including:

- How can a geolocation database residing in the cloud be designed and managed?
- How does a geolocation database accurately compute the available TV channels in a particular location?
- How can a database-assisted TVWS network be efficiently deployed and optimized?

Many research works have been devoted to address these technical issues. Gurney *et al.* [2] presented an effective geolocation database design and discussed the TVWS determination issue. Murty *et al.* [3] presented and evaluated a TVWS exploration method using a more accurate propagation model with terrain data. Goncalves *et al.* [4] compared the geolocation database assisted approach with the sensing approach. In [5], Feng *et al.* presented the design and implementation of a multicell infrastructure-based TVWS network. Chen *et al.* [6] studied the TVWS network optimization problem. Zhang *et al.* [7] proposed a vehicle-based measurement framework to enhance the performance of a database. In fact, many of the above technical issues have been well solved. As a result, several geolocation databases (e.g., those deployed by Google, Microsoft, and SpectrumBridge) have been successfully developed, based

[4] These include the IEEE 802.22 WRAN standard (http://www.ieee802.org/22/) and the real world white space database systems deployed by Google (http://www.google.org/spectrum/whitespace/), Microsoft (http://whitespaces.msresearch.us/), and Spectrum Bridge (http://www.spectrumbridge.com/

[5] SpectrumBridge Inc., http://www.spectrumbridge.com/

on which some TVWS trial systems have been launched in the United Kingdom, Singapore, and the United States.

### Economic Issues

In addition to the technical challenges mentioned above, there are also critical economic challenges in commercially implementing a database-assisted TVWS network. In particular, there is a lack of systematical study on the business modeling of such a network, which has become the main bottleneck of the wide commercialization of this new network. Designing a proper business model for the database-assisted TVWS network requires to consider and answer many challenging questions, including:

- Who will be involved in a TVWS business model, and how will they interact with each other? How can the economic role of each involved network be properly defined?
- What kind of services will be supported in a TVWS network, and how can the services exploit the unique characteristics of licensed and unlicensed TV channels?
- How are the proposed business models analyzed and optimized? How can efficient mechanisms be designed to realize the proposed business models, considering the performance as well as the implementation complexity?

Tackling the above questions is challenging due to the following reasons. First, TV channels are heterogeneous in terms of their properties. That is, some channels are licensed to certain TV licensees, while others are unlicensed. The model related to licensed TV channels must involve their licensees, while the model related to unlicensed TV channels does not have this requirement. Second, database operators are heterogeneous in terms of their interests and advantages. Note that the geolocation databases connect the TV licensees to unlicensed WSDs and play a central role in a TVWS business model. Different database operators may lead to very different business models. Moreover, to balance secondary spectrum utilization and primary licensee protection, spectrum regulators have specified strict technical restrictions on the secondary usage of TV channels. This may bring additional challenges in the design of a feasible business model. Several prior studies [8–11] have considered some economics issues in TVWS networks. However, they only focused on the design of the trading mechanism for the licensed TV channels between the spectrum licensees and unlicensed WSDs, without particularly involving the geolocation databases in the market mechanism design.

## Business Models

In this article, we consider two types of different business models motivated by the SpectrumBridge business cases:

- *Spectrum market* for licensed TV channels
- *Information market* for unlicensed TV channels

### The Spectrum Market Model

In the spectrum market model, TV licensees temporarily lease their licensed TV channels to unlicensed WSDs for additional revenue. During this process, the database acts as a spectrum broker, purchasing licensed TV channels from TV licensees in advance and reselling the purchased licensed TV channels to WSDs. WSDs further serve their subscribed end users by using the purchased TV channels. Depending on whether WSDs serve overlapping end users, we discuss both *non-competitive* and *competitive* scenarios for the spectrum market model.

***Spectrum Market with Non-Competitive WSDs*** — In the non-competitive scenario, each WSD faces a distinct pool of end users, and there is no competition among WSDs. Hence, we can focus on the interaction between the database and one WSD. The database needs to purchase (reserve) licensed TV channels from the licensees in advance,[6] without knowing the actual demands of WSDs. Therefore, a key problem is *how much should the database reserve for each WSD?* The problem is challenging due to the following factors:

- *Stochastic demand*: Due to the stochastic nature of end users' activities and requirements, the WSD's spectrum demand (from end users) is random, and cannot be accurately predicted in advance. Hence, there is a risk of reservation mismatch (over-reservation or under-reservation).
- *Asymmetric information*: The WSD usually has more information (i.e., less uncertainty) about the end-user demand than the database, due to its proximity to end users. Note that sharing such information with the database can potentially reduce the risk of reservation mismatch. Nevertheless, the WSD may not be willing to share its private information unless it receives sufficient incentives.

In [12], we proposed a *contract-theoretic* spectrum reservation framework to tackle the above challenges. The key idea is as follows. Before reserving , the database announces a reservation contract including a menu of contract items, where each contract item specifies a particular choice of the amount reserved and the corresponding reservation fee; the WSD selects the contract item (i.e., the reservation amount and the corresponding reservation fee) that maximizes its expected profit based on its private demand information. Then the detailed spectrum reservation, trading, and access processes are shown in Fig. 3. Specifically:

1. The database reserves the corresponding amount of TV channels for each reservation period based on the WSD's selection, and charges the WSD the corresponding reservation fee (step 0).
2. The WSD reports the realized actual demand to the database in each access period (step 1).
3. The database sells the corresponding amount of TV channels to the WSD in each access period (step 2).
4. The WSD serves its subscribed end users by using the purchased channels in each access period (step 3).

We studied the optimal contract design systematically in [12]. Specifically, we first characterized the incentive compatibility (IC) and individual rationality (IR) conditions for a feasi-

[6] In order to guarantee the exclusive usage of licensed TV channels by WSDs, the database needs to negotiate with the TV licensees in advance in terms of when and which licensed TV channels can be used by WSDs.

ble contract, which ensure that each WSD discloses its private demand information credibly. Then we further derived the optimal contract that maximizes the database's profit.

Figure 4 presents the performance of the proposed spectrum reservation contract, which significantly outperforms the traditional database-determined reservation scheme (without involving the private information and decision of a WSD) in terms of the total network profit (the first bar group) as well as the database's individual profit (the third bar group). Moreover, the total network profit under the proposed contract is very close to (the gap is less than 3 percent) the centralized benchmark solution, where the database and the WSD make a decision together as an integrated party.

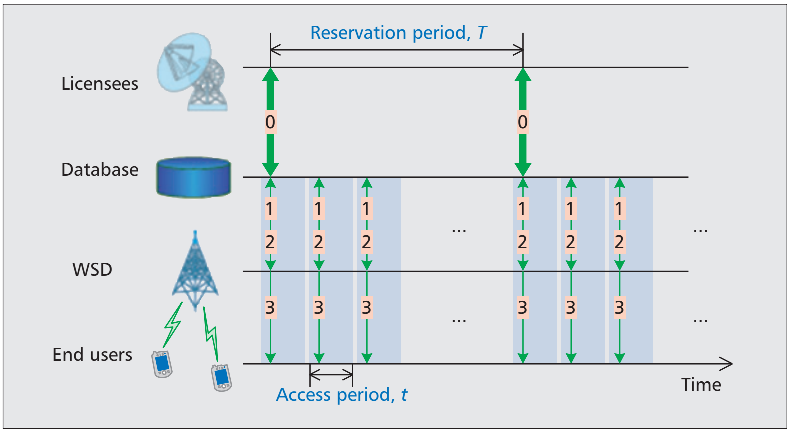


**Figure 3.** The spectrum reservation, trading, and access process in a spectrum market.

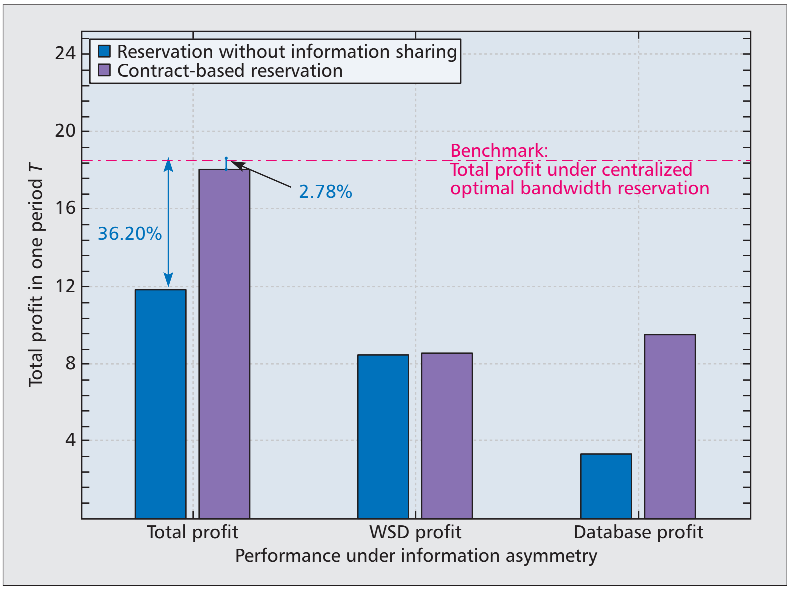


**Figure 4.** Performance of a spectrum reservation contract.

***Spectrum Market with Competitive WSDs*** — In the competitive scenario, multiple WSDs compete for a common pool of end users. Some new questions arise in this scenario:

- How do WSDs interact with each other as well as with end users?
- What is the equilibrium spectrum reservation level and service price for each WSD, taking the competition of other WSDs into consideration?
- What is the optimal wholesale price for the database to maximize its profit or maximize the network profit?

Addressing these questions is challenging due to the stochasticity of end-user demand. Moreover, when the total reserved licensed TV channels are not enough for satisfying all end-user demand, a WSD may further request unlicensed TV channels to serve the excessive end-user demand at a degraded quality of service (QoS) level. It is important to note that although the unlicensed TV channels can be used by WSDs without any payment to the licensees, WSDs may still incur some cost when accessing the unlicensed TV channels. For example, a WSD needs to consume some time and energy to request unlicensed TV channels from the database. Meanwhile, the database also needs to exert some effort to help WSDs use these unlicensed TV channels and accordingly charges WSDs a certain fee.[7] This further complicates the market analysis. In [13], we proposed a three-stage hierarchical model to study such a competitive spectrum market with both licensed and unlicensed TV channels. As illustrated in Fig. 5, the key processes in this model are as follows:

- In stage I, the database determines the *wholesale* prices of both licensed and unlicensed TV channels.
- In stage II, each WSD determines the reservation level of licensed TV channels and the service price.
- In stage III, each end user demands services from the best WSD based on her preferences (e.g., channel conditions to WSDs) as well as WSDs' service prices. If the total end-user demand is larger than the reserved licensed TV channels, a WSD will further purchase unlicensed TV channels for the excess demand.

We study the above three-stage hierarchical model systematically in [13]. Specifically, we first formulate the WSDs' competition in stages II and III as a non-cooperative game, and characterize the game equilibrium analytically by using super-modular game theory. Then we study two different wholesale pricing solutions for the database in stage I: a welfare maximization solution for a *social planning* database and a profit maximization solution for a *profit seeking* database. For a social planning database (e.g., those managed by non-profit organizations such as government regulators), the database operator's objective is to maximize the total network profit or welfare (i.e., the aggregate profit of WSDs and the database operator). For a profit seeking database (e.g., those managed by third-party businesses such as Google, Microsoft, and SpectrumBridge), the database operator's objective is to maximize its individual profit.

Figure 6 presents the performance of the proposed wholesale pricing solutions, where WM denotes the welfare maximization solution and PM denotes the profit maximization solution. The blue (or red) bar in each bar group denotes the network profit under the WM (or PM)

[7] We also denote the service fee charged by the database as the wholesale price.

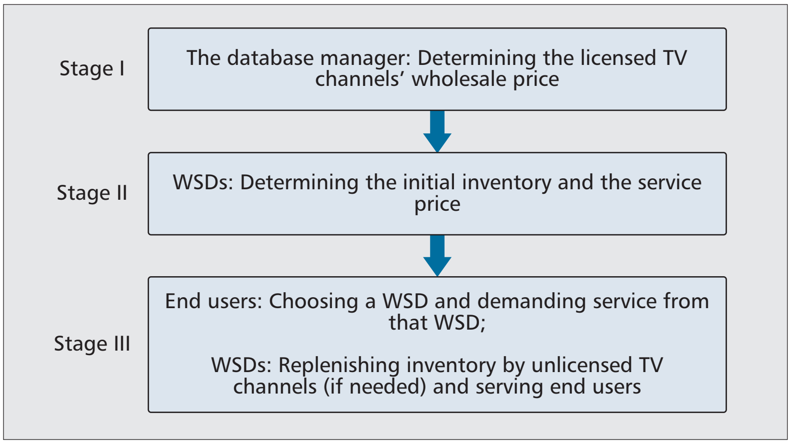


**Figure 5.** Three-stage hierarchical model.

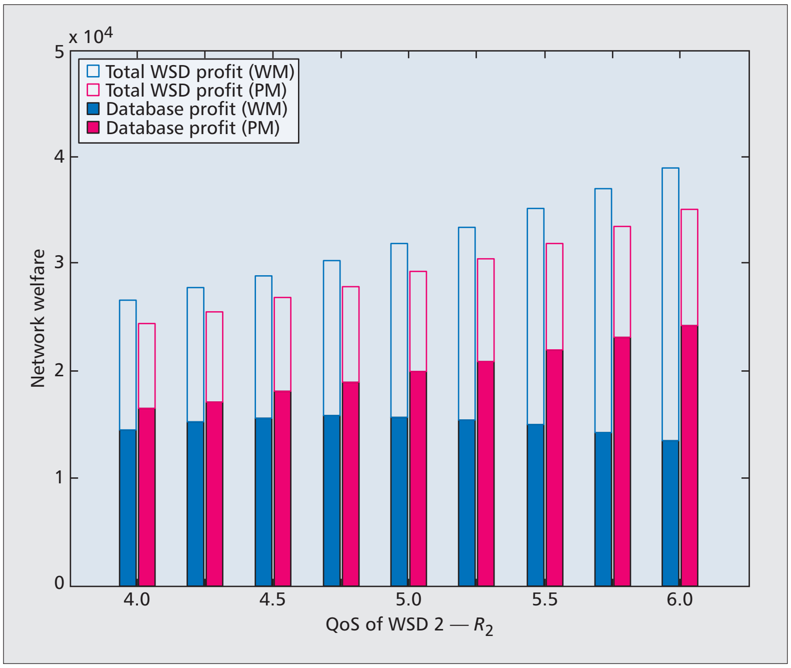


**Figure 6.** Performance of welfare maximization and profit maximization wholesale pricing solutions.

scheme, where the database operator's profit is denoted by the solid bar, and the total WSDs' profit is denoted by the hollow bar. In this numerical simulation, we consider a market with two competitive WSDs, where the QoS of WSD 1 is fixed at $R_1 = 4$, while the QoS of WSD2 changes from $R_2 = 4.0$ to 6.0. We can see that under both WM and PM schemes, the network profit increases with the QoS provided by WSD 2 ($R_2$). This is because a higher QoS can potentially attract more end users. Moreover, the network profit under the PM scheme is less than that under the WM scheme. This implies that maximizing the database's individual profit may lead to certain network profit loss from the system perspective.

## The Information Market Model

In the information market model, the database sells advanced information regarding the quality of unlicensed TV channels to unlicensed WSDs for profit. This model is motivated by the fact that the geolocation database knows more information regarding the quality of unlicensed TV channels than unlicensed WSDs, and such information can potentially be used by WSDs to improve their performance.

In the following, we formulate and analyze the information market systematically. To do this, we need to answer the following questions explicitly:

- *Information definition*: What kind of information can be traded in the information market? How are the quality and/or quantity of information defined?
- *Information evaluation*: How will WSDs evaluate the information? Will the same information have different values for different WSDs?
- *Market evolution*: How would the information market dynamically evolve along the WSDs' purchasing behaviors? With what type of network image (i.e., positive or negative) will the market appear?
- *Market optimization*: How does the database make the best pricing decision for the information that it sells?

All of the above issues are critical for the formulation and analysis of an information market. Specifically, addressing the first two issues helps us define an information market explicitly; addressing the third issue helps us understand the market evolution; and addressing the last issue helps us design the proper mechanism such that the database can draw desirable profit from the information market.

***The Non-Competitive Information Market*** — In [14], we proposed and studied a non-competitive information market where a single geolocation database sells information to a set of unlicensed WSDs. In the proposed model, the database provides two different kinds of information services:

- *Basic information*: According to the regulator's ruling (e.g., FCC [1]), a geolocation database is mandatory to provide the following basic information for WSDs:
  –The list of available unlicensed TV channels
  –The transmission constraints (e.g., maximum transmission power) on each available channel
  Such basic information service provided by the database is free of charge. With this basic information, a WSD can either randomly choose an unlicensed TV channel from the available channel list, or sense all available TV channels in the list (with some sensing cost) in order to figure out the best one.
- *Advanced information*: Beyond basic service, the database can also provide certain advanced information (called advanced service) to make a profit, as long as doing so does not conflict with the mandatory basic service. In [14], we explicitly define the advanced information as *the interference level on each available channel for each WSD*.[8] With this advanced information, a WSD is able to operate on the best

[8] The framework in [14] is rather general, and can apply to other types of advanced information.

available channel (i.e., that with the lowest interference level). Accordingly, the database can charge a subscription fee to every WSD subscribing to its advanced service.

We propose a general framework for evaluating the value of interference information to WSDs. Notice that the interference on a channel (to a particular WSD) may come from nearby TV stations operating on that channel or from nearby WSDs using that channel. The database can (relatively) precisely predict the interference from TV stations, as it maintains a repository of TV licensees. However, it may not be able to predict the precise interference from WSDs, as some WSDs may not inform the database of their choices of channels. Therefore, the overall interference information provided by the database may not be accurate. This will affect the value of information for WSD users, which in turn will affect how the database may price the information.

After characterizing the value of information to WSDs, we can derive the stable market share (i.e., the percentage of WSDs who purchase advanced information from the database operator), called the *market equilibrium*. In contrast to traditional spectrum markets, which are usually congestion-oriented (i.e., the more users purchasing and using spectrum, the lower the value of spectrum for each user), we show that the information market has the appealing property of *positive externality*. That is, the more users purchasing information from the database, the higher the value of the information for each buyer. This is because when more users purchase the information and reveal their channel selections to the database implicitly, the database can predict the interference more accurately.

Due to the positive network externality, the market equilibrium increases with the initial market share. Interestingly, there are several critical points (called *tipping points*) of the initial market share around which a slight change will result in a significant change on the emerging market equilibrium. Finally, based on the market equilibrium analysis, we derive the optimal information pricing plan that maximizes the database profit or revenue.

Figure 7 presents the database's maximum expected profit from the information market, which shows that the database's profit increases with the level of licensee interference (as a high level of licensed interference implies a potentially high value of the database's information for WSDs) and with the WSD sensing cost α (as a WSD with a higher sensing cost has more interest in purchasing the database's information).

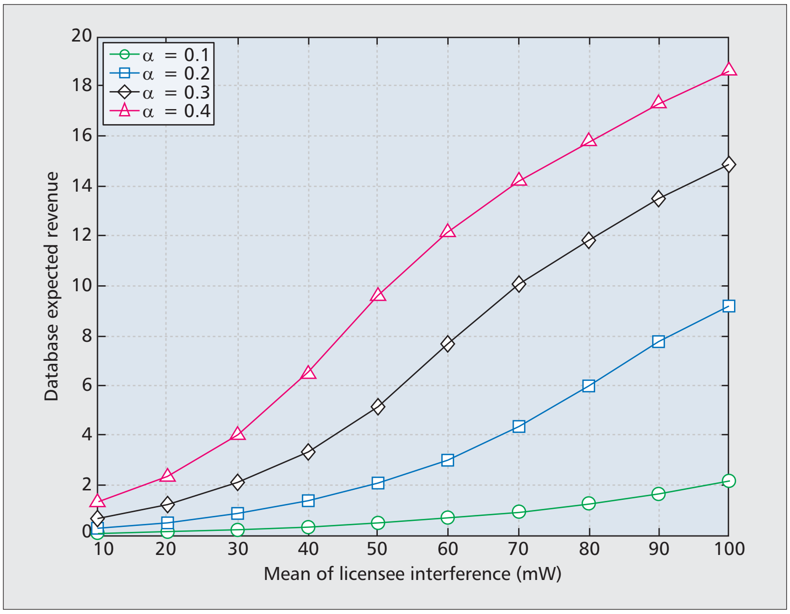


**Figure 7.** Database profit in a non-competitive information market.

***The Competitive Information Market*** — In [15], we proposed and studied an oligopoly competitive information market, where two databases compete for selling information to WSDs. Comparing with the non-competitive market, the analysis in a competitive market becomes more challenging due to the following reasons:

- The information possessed by different databases may be different, because of either the different knowledge of databases or the different market shares of databases.[9] Hence, WSDs need to jointly consider the quality and price of information before choosing with which database to interact.
- The positive externality of the information market provides a large incentive for each data operator to increase its market share, and hence makes the competition between database operators more intense than a market without positive network externality.

We study the oligopoly price competition in such an information market systematically and characterize the equilibrium analytically in [15]. Our analysis indicates that given the prices of databases, there may be multiple market equilibria, and which one will actually emerge depends on the initial market shares of both databases. We also quantify the impact of the databases' initial market shares and information prices on the market equilibrium. Our results show that

- When the prices of two databases are very different, there is a unique stable market equilibrium independent of the databases' initial market shares, where the lower price database achieves a large market share and the higher price database does not have any subscribers;
- When the prices of two databases are similar, there are two stable market equilibria depending on the databases' initial market shares, where the database with the higher initial market share achieves a large market share at the equilibrium, and the database with the lower initial market share achieves a small market share. Based on this market equilibrium analysis, we further derive the equilibrium of the databases' price competition game.

Our numerical simulations show that the database with a larger initial market share has a significant advantage in the competition, and can achieve most of the market share under the equilibrium.

[9] As mentioned previously, a database's information accuracy increases with its market share.

Our analysis not only shows how different network entities interact with each other in both markets, but also shows how the markets dynamically evolve under different circumstances and what the market equilibria are. These results can serve as an important first step toward the study of the general and large-scale TVWS market.

## Future Challenges and Open Issues

In spite of recent efforts from industry and academia, there are still many future challenges and open issues in the business modeling of database-assisted TVWS networks.

### Spectrum Market and Information Market: Conflicting or Complementing?

As mentioned previously, the spectrum market mainly targets licensed (and underutilized) TV channels, and the information market mainly targets unlicensed TV channels. In practice, licensed and unlicensed TV channels coexist in most cases. Some WSDs may prefer to lease licensed TV channels from licensees for exclusive use, while other WSDs may prefer to share free unlicensed TV channels with others. Hence, a joint formulation and optimization of both the spectrum and information markets is highly desirable.

### An Ad-Sponsored Business Model

An ad-sponsored business model may be another possible choice for a database operator. In an ad-sponsored model, it is important to understand how the database operators, advertisers, and WSDs interact with each other, and the unique feature of an ad-sponsored TVWS network. Generally, as in many ad-sponsored models, more WSDs making inquiries of the database may provide more business opportunities and incentives for advertisers, but too much advertising may annoy WSDs and drive them away to other databases. It is hence a delicate balance to achieve so as to coordinate the behavior of all involved parties to achieve a win-win situation.

## Conclusions

Business modeling is critical for the practical commercialization of database-assisted TVWS networks. In this article, we outline and analyze two promising business models: spectrum market and information market. These models allow the geolocation databases to exploit the unique characteristics of licensed and unlicensed TV channels. Our analysis not only shows how different network entities interact with each other in both markets, but also shows how the markets dynamically evolve under different circumstances and what the market equilibria are. These results can serve as an important first step toward the study of the general and large-scale TVWS market.

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## Biographies


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