Broker Based Secondary Spectrum Trading

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***Abstract*—Radio spectrum license is multi-dimensional in nature. This suggests that matching a bid to buy and an offer to sell has to be done across the multiple dimensions to maximize spectrum usage in terms of economic efficiency. In addition, creating a functioning secondary market for trading spectrum requires an intermediary for both pooling the resources and matching the supply and demand sides of the equation. This paper proposes a multiple-dimension auctioning mechanism through a broker to facilitate an efficient secondary spectrum market. A broker for orchestrating the market is proposed describing its basic functionalities. Two trading negotiation protocols, i.e., merchant and auction, are discussed. Focusing on the auction mode, the multiple-winner determination problem (mWDP) is defined and cast into a multidimensional multiple-choice knapsack problem (MMKP). Since the MMKP is NP-complete, two heuristic algorithms to solve the mWDP namely (1) *area-by-area* (ABA), and (2) *maximum-utility-first* (MUFA) are presented. Numerical studies illustrating the potential of the algorithms are presented. The numerical studies indicate that MUFA is better in addressing the exposure problem.**

I. Introduction

The exploitation of the TV white spaces, although conducive to more decentralized methods of spectrum usage, presents risks and challenges which necessitate the introduction of centralized coordination or enabling intermediaries [1] [2] [3]. Such centralized co-ordination through intermediaries, like a broker, could have a positive impact on the development of regulatory policies, business models and enabling technologies in the following ways:

- For regulatory policies, it would ensure conformance to policies, hence helping to achieve an economically efficient usage of spectrum.
- For businesses models, it would provide a mechanism (or platform) for the interaction between TV white space supply and demand sides, hence lowering transaction costs by centralizing the access to information on the availability of spectrum.
- For enabling technologies, it would reduce the complexity of cognitive devices by eliminating the need for sensing modules required in opportunistic spectrum acquisition [4], which in turn would boost investors confidence in developing cognitive technology based services.

Therefore, research in effective brokering mechanisms for supporting secondary spectrum usage is a prerequisite for achieving these goals. This paper presents a broker based approach for the usage of the TV white spaces.

Initial spectrum assignment mechanisms could affect incentives to spectrum trading due to windfall gains in secondary spectrum trading market [5]. However, the TV white spaces present a different scenario where the bands have to be reused while the incumbents are still operational. In this work, we assume that the TV white spaces are acquired from a secondary spectrum market which is orchestrated by the broker. Furthermore, through the broker, dynamic spectrum access will allow the TV white spaces to be traded to allow wireless service providers (WSPs), such as WiFi, LTE, WiMAX, etc., to acquire or lease chunks of spectrum on a short-term basis. In this case the broker both pools the white spaces and provides a platform for trading them. This suggests that matching a bid to buy and an offer to sell has to be done across the multiple dimensions defining the temporary secondary spectrum rights namely frequency band, bandwidth, maximum emission power, geographic region, availability duration, benchmark price, etc. This means that choosing multiple-winners to maximize the economic efficiency of the bands is the main challenge.

The auction winner determination problem in secondary spectrum trading has been studied in [3], where the solution is determined through game theoretic means. However, the exposure problem has not been addressed. This work proposes a holistic approach for secondary spectrum trading based on the broker. Focusing on the auction of spectrum bands, the multiple-winner determination problem (mWDP) is defined and cast into a multidimensional multiple-choice knapsack problem (MMKP). Since the MMKP is NP-complete, two heuristic algorithms to solve the mWDP are proposed. Numerical studies illustrate the potential of the algorithms in terms of their ability to address the exposure problem.

The rest of this work is presented in the following order. Section II presents the multi-dimensional scenario for exploiting the white spaces highlighting the challenges and requirements involved. Section III proposes a broker for facilitating secondary spectrum trading. The auction mWDP is defined at the end of this section. The problem is NP-complete, hence Section IV gives two heuristics for solving the problem by considering its nature. To illustrate the proposed algorithms, Section V presents the numerical studies. Section VI concludes the paper giving a glimpse of future work.

II. Scenario and Challenges in Using the TVWS

A. Scenario

Figure 1 illustrates an example of a scenario where white spaces are used to provide wireless access services. Lets assume that there are N frequency bands indexed as $\{1, \ldots, n, \ldots, N\}$; and M stations or geographic regions indexed as $\{1, \ldots, m, \ldots, M\}$. In the figure, two broadcast

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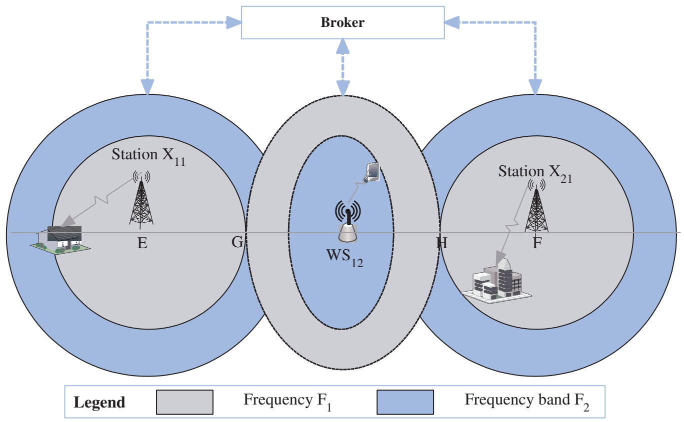

Fig. 1. Field intensity condition for enabling shared use of the same channel

channels marked by F_1 and F_2 are used. Incumbent broadcast stations are marked as X_{mn}, meaning the m^{th} station operates in the n^{th} band. Similarly, white space access points are marked as WS_{mn}. Each incumbent broadcast station X_{mn} uses frequency band F_n to transmit in a given areas as shown in the figure.

In this work, we assume a centralized TV white spaces acquisition mechanism. The broker stores the information about DTV stations, including respective geo-location information, maximum transmission power, etc. This information is processed to a quality that the broker trades the bands for profit.

Reliable information is vital for successful deployment of wireless services with varying QoS guarantee. For convenience, the broker characterizes this piece of information of a spectrum *good* as a temporary exclusive right represented by the following generic tuple:

$$\mathcal{L} = \{F, P_{max}, (x, y), T, \ldots\},$$

where P_{max} is the allowed maximum power in a given band; (x, y) the geo-location coordinates of the region of operation; and T is the time frame that the band can be used.

This information of TV white spaces will be stored, managed and distributed by the broker based on dynamic resource allocation algorithms. The broker may earn revenue in the following ways:

1) *Auction* mechanism where the white space systems bid for the TV white spaces and the winner(s) is(are) chosen such that the broker's revenue is maximized or the spectrum usage efficiency is maximized.
2) *Merchant* mechanism where the broker directly charge secondary spectrum users based on fixed or negotiated fees derived from market-driven rules.

In this work we consider the first revenue model, i.e., the broker earns revenue through auctioning the TV white spaces to participants. Specifically, we consider reducing the exposure problem that bidders of multiple-bids encounter in acquiring spectrum, assuming that the broker runs profitably.

B. Challenges and requirements

We consider a secondary spectrum market environment having a broker as a supplier and several master-slaves communication systems forming the demand side. The market allows the master devices to buy or lease temporary exclusive rights from the broker.

The setting poses an enormous number of challenges especially when conflicting goals come into the picture. These include maximizing the broker's revenue while lowering management overhead; increasing spectrum acquisition flexibility while ensuring reliability; maximizing spectrum efficiency while minimizing interference; and the list goes on. These challenges emanates from the following aspects:

A.1 *Multi-bands:* The TVWS management complexity increases with the increase of the number of bands in the broker's portfolio.

A.2 *Multi-bids:* On the demand sides, different masters systems are posed to request for different bands.

A.3 *Multiple locations:* The broker manages bands across a wide geographic area. Therefore, band reuse has to be considered in order to maximize spectrum usage.

The above setting implies that the broker has to simultaneously satisfy conflicting needs in the most efficient and cost effective way. Different goals will lead to different strategies. In this work, while ensuring reasonable revenue for the broker, we aim at maximizing spectrum usage while lowering management overhead. To this end, simple heuristic algorithms to generate the multiple 'winners' of the TVWS bands will be investigated.

III. Broker Architecture and the Auction Multi-Winner Determination Problem

In this section, a centralized broker platform to support the trading of the TVWS is introduced. The spectrum users include cellular operators, WiFi providers, etc. The spectrum broker controls the amount of bandwidth and power assigned to each user in order to keep the desired QoS and interference below the interference limits. Further, the mWDP is formalized.

A. The White Space Broker Model

The white space broker is a centralized intermediary that orchestrates the exploitation of the TVWS. As Fig. 2 shows, the broker has the following sub-systems: *(*1) Spectrum context database; *(*2) WS allocation server; *(*3) WS trading server; and *(*4) Registration and validation. In more details, the subsystems perform the following respective tasks.

1) Spectrum context database: The spectrum context database obtains TVWS information from the national database. The broker then enhances the radio environment map by analyzing availability usage patterns. The database must also contain regulatory policies for the specification of secondary spectrum usage rights and obligations and prioritization of TVWS access.

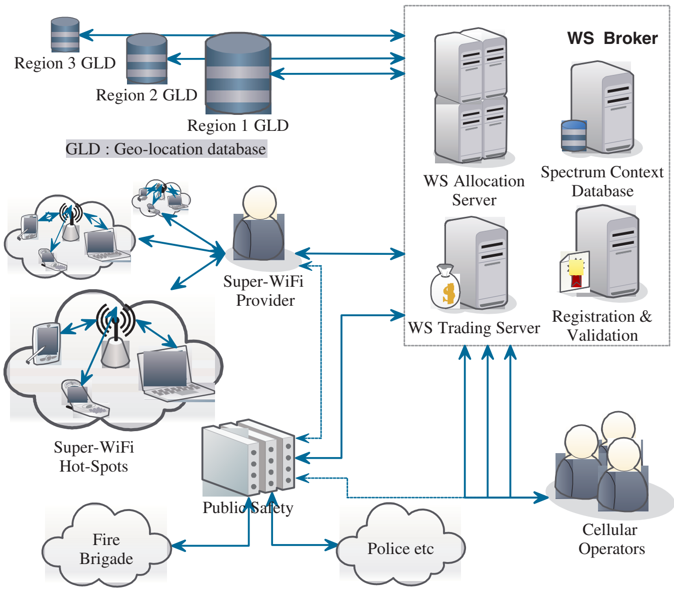

Fig. 2. The White Space Broker Model

2) WS allocation server: The broker, through its trading and price discovery mechanisms, matches the player's requirement with available resources and thus allocates the TVWS based on preset rules. The TVWS allocation mechanism implements an algorithm that uses information from the database to determine the TVWS bands and power at which a secondary user (player) should be allowed to operate to avoid spectrum fragmentation, optimize QoS and guarantee fairness in TVWS access.

3) WS trading server: The main function of the trading mechanism is to determine the revenue maximizing set of buyers or bidders. The broker aims at selling the temporary exclusive rights to the most valuable user(s). The best way to achieve this is through auctioning. Besides discovering the willingness-to-pay price of the buyer, the broker needs to determine a benchmark price to start the auctioning. This ensures profitability, and limits the chances of collusion to lower the spectrum prices. Dealing with collusion is not in the scope of this work.

4) Registration and validation: To support secure spectrum trading, a security framework is required to prevent unauthorized spectrum access. Therefore, tracing users of the broker's service is achieved through a registration and validation mechanism. Tracing users is also important in case of conflict resolution.

B. The Auction Multiple-Winner Determination Problem

A provider of wireless service access may wish to buy temporary exclusive rights in a geographic area of a country. This could be for WiFi, LTE, etc. The provider will incur less roaming cost of using a competitor's network if wider coverage is achieved [6]. On the other hand, limited coverage may result into loss of a wider customer base leading to decreased profit. Therefore, when bidding for TV white spaces, the provider may prefer (or has incentives) to bid for a combination of white spaces over several geographical regions. Depending on the need, the provider may opt for "all-or-nothing" bids or prioritize regions according to potential revenue. Therefore, an appropriate auction mechanism has to be designed in order to achieve a viable white space secondary spectrum market.

To formalize this problem, let the amount of white space 'items' that the broker simultaneously trades be given by a matrix $\mathbf{Q} = \{q_{mn}\}$, where the subscripts represents the frequency band index and corresponding geographic regions respectively. The number of master nodes (bidders) is I. As pointed out in [7], auction of spectrum resources differs from other goods in that the former is interference-constrained while the latter is quantity-constrained. Therefore, the auctioning of spectrum goods has to consider interference in its definition. In this work, we consider interference in terms of geo-location and maximum emission power. The combination of these parameters qualifies the boundaries of a *spectrum good offer*. This has two connotations based on **A.1**, **A.2** and **A.3**:

- *One-offering multiple-winners* [7]: Since spectrum-bands are interference-limited, then one band offering for auction can receive bids from multiple participants, denoted by set $\mathcal{I}$.
- *Multi-bids:* One participant can request for one band in multiple locations forming a multi-bid's problem. Similarly, one participant can bid for multiple bands in the same location.

For the bidder, we define a bid as a tuple $b_i = \{q^i_{mn}, p^i_{mn}, w^i_{mn}\}$, where b_i is the bid from participant $i \in \mathcal{I}$; q^i_{mn} is the spectrum band requested; p^i_{mn} is the corresponding payment; and w^i_{mn} is the weight allocated for the respective band for the given region. This information is part of the broker's bidding language for the participants to encode their preferences. In this particular case, it is used to address the exposure problem. A participant may multi-bid by submitting several requests for a band in different locations or different bands in the same location with constraints on its utility.

Assuming the bidder is determined to provide services in several areas $\mathcal{M}_i \subseteq \mathcal{M}$; when bidder i is in need of spectrum, it submits a set of $\mathcal{M}_i$ two dimensional bids $b_i = \{b^1_i, \dots, b^{\mathcal{M}_i}_i\}$. The exposure problem can be modeled by considering that the bidder i allocates a weight w^i_{mn} for each band in each region such that $\sum w^i_{mn} = 1$. Therefore, a bidder's utility can be defined as

$$\mathcal{U}_i = \sum_{n=1}^{N} \sum_{m=1}^{M_i} w^i_{mn} q^i_{mn} p^i_{mn}, \tag{1}$$

Considering that the TV white spaces have similar RF properties, n may be dropped. Let us define the social utility of the broker as

$$\mathcal{U}_{\text{broker}} = \sum_{n=1}^{N} \sum_{m=1}^{M} q^*_{mn} p^*_{mn}, \tag{2}$$

where p^*_{mn} is the price offered by (determined for) the bid winner, and q^*_{mn} is the corresponding amount of spectrum frequency. Therefore, the broker's objective is to maximize its utility (revenue), that is:

$$\text{Maximize } \mathcal{U}_{\text{broker}} \tag{3}$$

In order to do that, the broker has to determine the $k-$best winners such that its revenue is maximized (and the signaling overhead is minimized), subject to conditions that the total spectrum allocated does not exceed $\mathbf{Q}$. Moreover, in case the bidder bids for "all-or-nothing", then the broker must address the exposure problem, that is, ensure that the bidder wins bands in all chosen areas or risk to lose revenue.

Hence, for the exposure problem of each bidder, one of the constraints that the broker has to consider is,

$$\begin{aligned} \sum_{n=1}^{N}\sum_{m=1}^{M_i} w_m^i p_{mn}^i \leq \mathcal{U}_i \ \ \forall i \ \in \ \mathcal{I}; \\ \sum_{m=1}^{M_i} w_{nm}^i = 1 \ \ \forall m. \end{aligned} \tag{4}$$

The revenue maximization problem solved by the broker, i.e., the multiple-winners determining problem (mWDP) of the auction is equivalent to a multi-dimensional multiple-choice knapsack problem (MMKP). A multiple-dimensional knapsack problem is one kind of knapsack where the resources are multi-dimensional, i.e., there are multiple resource constraints for the knapsack. The mWDP problem is MMKP. Every instance of the MMKP can be formulated as a mWDP; hence mWDP is NP-hard. For this case, an exact solution is not suitable for such a real time problem, so a heuristic based on approximation algorithm to allocate spectrum among multiple bidders is developed.

Moreover, we exploit some characteristics of the problem to find the solution of the mWDP as presented in the next section.

Algorithm 1 Area-by-Area Algorithm (ABA)

1: INPUT: $DTV(X,Y)$, P_{DTV}, Φ, $CR(x,y)$, and p_{max}.
2: Pre-processing
  1) Enhance REM in broker repository and estimate availability index
  2) Estimate TVWS demand and benchmark price p_{bmp}
  3) Prepare WS portfolio $\mathbf{Q}$
3: Advertise bands for sale (auction)
4: Receive WS bids from interested parties

$$B = \{b_1, \ldots, b_M\}$$

  where $b_i = \{q_i, p_i, (x_i, y_i), t_i\}$.
5: **for all** Bids **do**
6:   Sort b_i in descending order based on price p_i.
7: **end for**
8: **for all** $\mathbf{Q} \neq \{\}$ **do**
9:   Allocate requested temporary exclusive rights following the sorted order for each bid

$$q_i^* \leftarrow q_i \text{ and } b_i \leftarrow \{q_i^*\}$$

10:   Update allocated bands as

$$Q^* \leftarrow Q^* \cup \{q_i^*\}$$

11:   Update available bands as

$$Q \leftarrow Q \cap Q^{*c}$$

12: **end for**
13: Inform winning bidders $B^* = b_i^*$
14: Update WS occupancy repository

IV. Heuristics for Spectrum Allocation

Two heuristics to address the mWDP problem are presented in this section. The heuristics are namely (1) *area-by-area* (ABA), and (2) *maximum-utility-first* (MUFA). The first algorithm simply collects the bids, and groups them in area by area basis. The algorithm then sorts the bids from highest price to lowest for the bands in a given area and matches them to the value of the bands in the portfolio for that locality until there are no more bands remaining in the broker's portfolio. Here we assume that the demand exceeds supply. This heuristic is summarized in Algorithm 1.

The second heuristics considers the aggregate utilities for the bidders in all regions of interest. The algorithm sorts the bids from the highest aggregate utility to the lowest. The bands are then allocated following the sorted order across the broker's portfolio. This heuristics is summarized in Algorithm 2.

Algorithm 2 Maximum-Utility-First Algorithm (MUFA)

1: INPUT: $DTV(X,Y)$, P_{DTV}, Φ, $CR(x,y)$, and p_{max}.
2: Pre-processing
  1) Enhance REM in broker repository and allocate availability index
  2) Estimate TVWS demand and benchmark price p_{bmp}
  3) Prepare WS portfolio $\mathbf{Q}$
3: Advertise bands for sale (auction)
4: Receive WS bids from interested parties

$$B = \{b_1, \ldots, b_M\}$$

  where $b_i = \{q_i, p_i, (x_i, y_i), t_i, \mathcal{U}_i\}$.
5: Sort b_i in descending order based on aggregate utility $\mathcal{U}_i$.
6: **for all** $\mathbf{Q} \neq \{\}$ **do**
7:   Allocate temporary exclusive rights as in steps 9 – 11 of Algorithm 1.
8: **end for**
9: Inform winning bidders $B^* = b_i^*$
10: Update WS occupancy repository

The data used in the allocation algorithm are as follows: $DTV(X,Y)$ is the location grid of DTV transmit stations; P_{DTV} is the maximum DTV station transmit power; Φ is the set of operating frequencies; $CR(x,y)$ is the location grid of an operating CR transmitter and p_{max} is the required (maximum) transmit power.

V. Numerical study

This section presents numerical studies to illustrate the potential of the proposed algorithm in solving the multiple winner determination problem. The numerical study emphasizes on the potential for addressing the *exposure* problem prevalent in multi-bid auctions.

The band portfolio studied consists of five bands in seven regions. The bands are graded according to an availability score ranging from 0 to 1. The lower the score, the less the value of the band and the higher the potential for interference - causing interference or being interfered. The higher the score, the higher the value of the band the lower the risk for interference, i.e., being interfered or interfering other systems. For simplicity, we assume that all the bands have the highest score.

In this experiment, there are 20 bidders competing for the available bands. Each bidder intends to provide wireless services in several regions in which the broker auctions its bands. The bidder submits bids, indicating its utility for each region, and the aggregate utility for all the regions of interest. For simplicity, we assume that the aggregate utility of the bidders is the sum of the utilities for each region submitted.

In selecting the highest bidder, this paper proposes two heuristics: *(*1) *area-by-area* (ABA), and *(*2) *maximum-utility-first* (MUFA). Figure 3 shows the utility of winning bidders obtained through the two methods compared to expected utility. If the utility of the winning bidder equals its expected utility, then the bidder is not exposed. From the number of winning bidders achieving the expected utility seen in the figure, it can be said that the MUFA heuristic has less of the exposure problem than ABA.

From the brokers perspective, both algorithms could maximize its utility. However, from the operator's angle, MUFA has the potential of lowering running costs by avoiding roaming costs in other provider's networks. This is true especially for providers of mobile services across different regions. However, for fixed services, ABA algorithm is better, especially if those services are provided by separate providers. In that case, ABA has the potential of enabling start-ups to acquire spectrum bands and compete in their locality, hence spur innovation.

VI. Conclusion and Future Works

This paper has considered the problem of matching multiple-bids to buy, and band portfolio to sell as offered by a spectrum broker. The matching was done across multiple dimensions to maximize spectrum usage in terms of economic efficiency. The scenario was given to illustrate the multiple-dimensional nature of the problem. A simple broker model for orchestrating the market was proposed describing its functional blocks with respective tasks. The multiple-winner determination problem (mWDP) was cast into a multidimensional multiple-choice knapsack problem (MMKP), which is NP-complete. Two heuristic algorithms to solve the MMKP

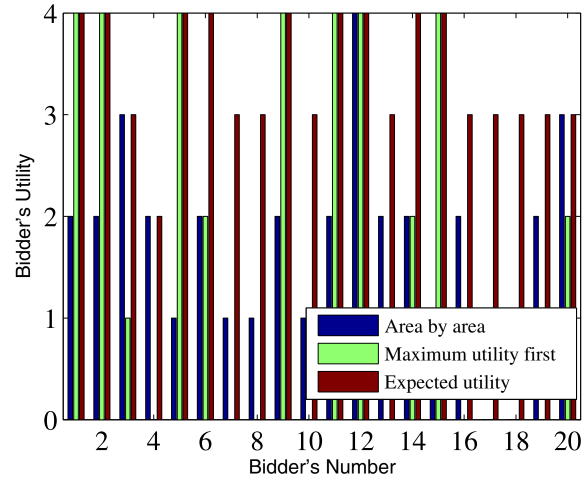

Fig. 3. Illustration of the number of exposed and non-exposed bidders in '*area by area*' and '*maximum utility first*' algorithms.

mWDP namely *(*1) *area-by-area* (ABA), and *(*2) *maximum-utility-first* (MUFA)were presented. The heuristics were based on the nature of the problem. MUFA has shown to be better in addressing the exposure problem compared to ABA.

Further study has to address the various needs of the bidders as well as maximization of the broker's revenue. Also, in case demand is less than supply, pricing mechanism to give incentives for spectrum usage has to be studied. It will also be interesting to compare the social utility of the proposed broker approach with distributed approaches for example. Analysis of other issues such as complexity and latency are also possible future directions.

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References

[1] R. Berry, M. Honig, and R. Vohra, "Spectrum markets: motivation, challenges, and implications," *IEEE Communications Magazine*, vol. 48, no. 11, pp. 146 –155, November 2010.

[2] J. W. Mayo and S. Wallsten, "Enabling efficient wireless communications: The role of secondary spectrum markets," *Information Economics and Policy*, vol. 22, no. 1, pp. 61 – 72, 2010, wireless Technologies.

[3] S. Sengupta and M. Chatterjee, "An economic framework for dynamic spectrum access and service pricing," *IEEE/ACM Transactions on Networking,*, vol. 17, no. 4, pp. 1200 –1213, August 2009.

[4] FCC 10 - 174, "Second memorandum opinion and order," September 2010. [Online]. Available: http://www.fcc.gov/Document_Indexes/Engineering_Technology/2010_index_OET_Order.html

[5] Q. Song, M. You, and T. Lv, "Incentives to spectrum trading," in *IEEE International Conference on Network Infrastructure and Digital Content (IC-NIDC), 2009*, November 2009, pp. 948 –952.

[6] K. Leyton-Brown and Y. Shoham, *A Test Suite for Combinatorial Auctions*. MIT Press, 2006, ch. 18, pp. 451–478.

[7] K. J. R. Liu and B. Wang, "A multi-winner cognitive spectrum auction game," in *Cognitive Radio Networking and Security: A Game-Theoretic View*. Cambridge University Press, 2010.