OPPORTUNISTIC SPECTRUM ACCESS IN MULTI-USER MULTI-CHANNEL COGNITIVE RADIO NETWORKS

Sachin Shetty, Kodzo Agbedanu, Ravi Ramachandran

Department of Electrical and Computer Engineering,Tennessee State University
3500 John A. Merritt Blvd, Nashville, TN 37221
email: sshetty@tnstate.edu, kagbedan@mytsu.tnstate.edu

Department of Electrical and Computer Engineering, Rowan University
201 Mullica Hill Road, Glassboro, NJ 08028
ravi@rowan.edu

ABSTRACT

With the advent of cognitive radio technology, opportunistic spectrum access has the potential to mitigate spectrum scarcity by letting users sense and utilize unused portions of licensed spectrum opportunistically without adverse impact on the primary licensees (licensed spectrum owner). We consider the problem of how multiple secondary users should maximize their total throughput in a multi-channel sensing-based opportunistic spectrum access network under various traffic conditions. We developed two dynamic spectrum access algorithms (Hungarian and Greedy) which allow secondary users (unlicensed opportunistic users) to access spectrum based on non-cooperative independent decisions. Both algorithms allow the secondary users to seek independent spectrum opportunities without cooperation with the objective of minimizing collisions among secondary users and maximizing the spectrum utility. Simulations comparing the performance of the two algorithms yield interesting findings.

1. INTRODUCTION

The proliferation of a wide range of wireless devices has resulted in an overly crowded radio spectrum. In contrast to this scarcity in spectrum availability is the pervasive existence of spectrum opportunities. Real measurements show that, at any given time and location, a large portion of licensed spectrum lies unused [1]. To exploit the abundant spectrum opportunities, cognitive radio networks have been proposed as a novel approach to improve spectrum utilization. Opportunistic spectrum access (OSA) is one of the approaches envisioned for dynamic spectrum management in cognitive radio networks [2]. The basic idea of OSA is to allow secondary users(unlicensed opportunistic users) to identify and exploit spectrum opportunities under the constraint that they do not cause harmful interference to primary users(licensed spectrum owners).

Most of the existing works on OSA strategies have not been evaluated for multi-user, multi-channel environments under varying traffic conditions [2–9]. These OSA strategies maximize the throughput of an individual secondary user in a multi-channel slotted primary network. In presence of multiple channels, a key decision for every secondary user is to determine which channel to sense. With multiple secondary users contending for spectrum opportunities, the sensing decision must take into account the possibility that the good channels may be desired by other users. At the beginning of every slot, every secondary user senses an idle primary channel to potentially transmit over. Based on the sensing decision in the beginning of the slot, secondary users decide if the channel will be idle for the remaining duration of the slot. This leads to potential collisions with the primary users or missed opportunities in spite of perfect sensing during the sensing period. The secondary users need to make a decision to transmit based on its sensing decision. The secondary users should minimize missed opportunities due to inaccurate detection outcomes and limit collisions with the primary users.

The main objective of this paper is to investigate how secondary users maximize the network throughput in a multi-user multi-channel system under various traffic conditions. In this paper, we design and compare two algorithms (Hungarian and Greedy) that all secondary users can adopt to make decisions at each step on which channel they should sense and access. The sensing decision not only provides information on which channel to choose to maximize the throughput providing immediate rewards, but also provides information regarding the primary user's channel occupancy and the presence of other active secondary users, which aids future decisions. Both algorithms do not involve any message exchange between the secondary users. So a cooperative multi-user policy wherein users exchange their belief vectors after every time slot is not employed. This strategy is only applicable in network settings with high bandwidth and control overhead of communicating beliefs is small compared to the data size.

The rest of the paper is organized as follows. We review some related work in Section 2. The network model is given in Section 3. We present the two dynamic spectrum access algorithms in Section 4. We present the simulation results in section 5. Finally in Section 6, we conclude the paper and provide future work.

2. RELATED WORK

Research on OSA strategies have primarily been conducted in the following two scenarios: single-user setting and multi-user setting. In [3, 5], the strategy for a single secondary user to maximize total throughput in a slotted primary network is proposed. However, in real OSA networks, multiple secondary users opportunistically seek spectrum access from primary users. In [4, 6], multiple secondary users reserve channels by sending control messages on coordination channels. The presence of a common control channel is only advantageous in networks where there is high availability of unused channels. In this paper, we propose two algorithms which do not require cooperation or coordination to assign channels to multiple secondary users.

3. NETWORK MODEL

We consider a slotted primary network with $m = 1,2,..,M$ secondary users. Each secondary user can sense $n = 1,2,..,N$ primary channels, each with bandwidth B_j $(j = 1,2,...,N)$. The occupancy of the N channels by primary users are modeled as independent continuous-time Markov processes [7]. The availability of channel j for secondary user i is modeled as a two-state continuous time Markov chain with a state of $S^i_j(t)$, where $S^i_j(t) = 1$ indicates that there is an opportunity for secondary user i in channel j, and $S^i_j(t) = 0$ otherwise. The idle and busy periods for channel j are exponentially distributed with parameters λ_j and μ_j, respectively. This leads to an unslotted primary network, where the primary users can access the channel at any time. Secondary users, adopt a slotted transmission structure with a slot length of τ. At each slot, a secondary user chooses one of the N channels to sense and decide whether to transmit over the chosen channel based on the sensing outcome. The operations in a secondary slot are shown in Fig. 1.

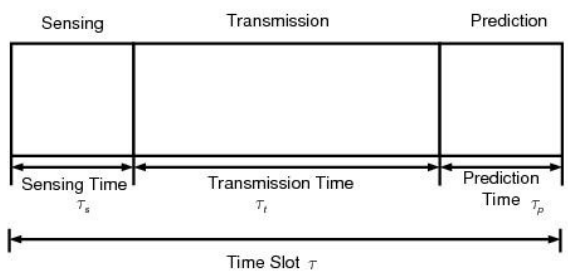

Figure 1: Operations in a secondary slot.

Consider the transmission slot of length τ starts at time t. The beginning of the slot is used for sensing one of the N channels which takes τ_s seconds. We assume that a secondary user can distinguish primary user traffic from other secondary users. Based on the current sensing decision and past sensing results, the secondary user can choose to either transmit on one of the N channels or not transmit at all. The channel access takes place during the access period $[t+\tau_s, t+\tau_s+\tau_t]$ of the slot. If the channel remains idle for the entire duration of $[t+\tau_s, t+\tau_s+\tau_t]$, the transmission is successful; otherwise, a collision occurs. At the end of each time slot, a secondary user predicts the states of the channels in the next time slot with the latest sensing outcome. Notice that even if a secondary user has sensed the channel to be idle during the sensing period τ_s, the primary user may become busy during the time duration $[t+\tau_s, t+\tau_s+\tau_t]$.

3.1 Problem Formulation

We formulate the channel access problem as a constrained POMDP(Partial Observable Markov Decision Process) represented by the tuple (S,A,R,W) given below.

- S represents the state of the underlying system at the beginning of each slot for every secondary user. For secondary user i, the state in channel j is given by $S^i_j(k) \triangleq S^i_j(t)|_{t=(k-1)\tau}$, where $k = 1,...,T$ is the slot index. The system state in slot k for all secondary users is thus $S(k) = [S^1_1(k), S^1_2(k), ..., S^1_N(k), S^2_1(k), ..., S^M_N(k)] \in \{0,1\}^{M,N}$. Recall that $S^i_j(k)$ is a discrete-time Markov chain for secondary user i and channel j. The state transition probabilities of the Markov chain are as follows,

$$\begin{aligned} p^{ij}_{00}(k) &= 1 - \frac{\mu_j}{\lambda_j+\mu_j}(1-exp(-(\lambda_j+\mu_j)k)) \\ p^{ij}_{01}(k) &= \frac{\mu_j}{\lambda_j+\mu_j}(1-exp(-(\lambda_j+\mu_j)k)) \\ p^{ij}_{10}(k) &= \frac{\lambda_j}{\lambda_j+\mu_j}(1-exp(-(\lambda_j+\mu_j)k)) \\ p^{ij}_{11}(k) &= 1 - \frac{\lambda_j}{\lambda_j+\mu_j}(1-exp(-(\lambda_j+\mu_j)k)) \end{aligned} \quad (1)$$

- A is the combined action space for all secondary users. Specifically, after every sensing operation, every secondary user can either choose to transmit in one of the N channels or, alternatively, not transmit at all. We use $a^i(k)$ to denote the action taken by user i in time slot k. An acknowledgement (ACK) is piggybacked to indicate whether the transmission by secondary user i on channel j is successful or not; $ACK^i_j(k) \in \{0(\text{no success}), 1(\text{success})\}$.
- R represents the reward accrued by a successful transmission. The reward is defined as the number of bits delivered when a secondary user senses and transmits on the channel chosen by action $a^i(k)$ in the current time slot. We use $R^i_j(k)$ to denote the award accrued by secondary user i on channel j during time slot k.
- W represents the belief vector. Each secondary user cannot directly observe the entire system state due to limited sensing. However, a secondary user can infer the system state from its decision and observation history. The statistical information on the system state provided by the entire decision and observation history can be encapsulated in a belief vector. A belief vector for user i at time slot k, namely $W^i(k)$, is a N-dimensional vector $(w^i_1(k), w^i_2(k), ..., w^i_N(k))$, where $w^i_j(k)$ denotes the conditional probability for secondary user i to access channel j in time slot k given $S^i_j(k) = 1$.

We propose the Hungarian and Greedy algorithm based OSA approach. The goal of our OSA approach is to achieve maximal throughput for secondary users. Here, we measure the throughput as the total number of bits that can be delivered by secondary users in T slots, which can be computed by summing the expected reward for all secondary users. Thus, the problem can be formulated as follows,

$$\begin{aligned} &max(\sum_{k=1}^{T}\sum_{i=1}^{M} R^i_j(k)) \\ &s.t.\ P^{pu}_j(k) = Pr\{\Theta_j(k) = 1 | \Psi_j(k) = 0\} = 0, \forall j,k \end{aligned} \quad (2)$$

where $\Theta_j(k) \in 0(noaccess), 1(access)$ denotes the decision taken by the secondary users to access channel j during the access time period. The collision constraint defined in the above equation indicates that the probability of collision

$P_j^{pu}(k)$ perceived by the primary users in any channel j and slot k is equal to zero. $\Psi_j(k)$ is defined as the availability of an idle channel j :

$$\Psi_j(k) = \begin{cases} 1, & S_j(t) = 1 \ \forall t \in [(k-1)\tau + \tau_s, k\tau] \\ 0, & \text{otherwise} \end{cases}$$

In each time slot, our proposed algorithms allow each secondary user to implement the three main operations from Fig. 1 in following four phases: i) channel sensing phase, ii) channel access phase, iii) reward phase, and iv)prediction phase. Next, we will present the details of the two algorithms.

4. HUNGARIAN AND GREEDY BASED OSA ALGORITHMS

The proposed Hungarian and Greedy based OSA algorithms reduce the problem of channel assignment to a revenue assignment problem. Given K users and N channels, and nonnegative edges W_k, which represent the revenue of assigning user k to channel n, the revenue maximizing assignment needs to be found. With such representation, the channel selection becomes a revenue assignment problem which can be solved by the classical Hungarian and Greedy algorithms[10]. The optimal channel assignment is the assignment with the minimal cost summation of all channels assigned to users with respect to the number of users, channels and cost matrix. The cost represents the amount of bandwidth used by the user for a given channel.

Both algorithms follow the metaheuristic problem solving of making the locally optimal choice at each stage with the hope of finding the global optimum. Both algorithms will be used by selecting the best channel. The channel with a best bandwidth will be selected to perform the allocation to achieve a significant throughput for the secondary users.

4.1 Hungarian Algorithm Implementation

Let L subcarriers be assigned to K active users (connections) at the downlink. An active user is defined as one with nonempty buffer at the moment of channel assignment, with each having a queue length of q_i, $i = 1, ..., K$. The original assignment matrix is K by L with the element C_{ij}, which is the instantaneous subcarrier capacity. The channel assignment is done by the station allowing the secondary users to access the channel. The secondary user will be assigned to a spectrum hole to transmit its buffer contents. If the size of the user buffer is less than the channel capacity, the user will be able to transmit the entire information. However, if the user buffer is more than the channel capacity, then the user can only transmit at the channel capacity. For each round, one channel is assigned to one secondary user based on the channel matching result by the Hungarian algorithm. After each round, when a channel is assigned and the user's queue becomes empty, the cost matrix is updated by the station in updating the user buffer (reducing the user buffer) and therefore, allocating a reward to that user. This procedure continues until all the channels within the total time slot T have been assigned. Initially, the reward per user is equal to zero since none of the secondary users have access to the spectrum or can send some bits within the channel. Then the channel occupancy probabilities are obtained. The channel occupancy follows a bursty traffic model. The bandwidth of all channels is defined per number of users and number of channels. The initial belief which actually determines the availability of the channel is defined based on the probability of the channel being busy and idle. Due to the fact that each secondary user has a buffer which determines the user state (active or non- active), a buffer state needs to be initialized (empty buffer), and the size needs to be defined based on the number of users. In order to perform the allocation of users to channels, the Hungarian algorithm requires a cost matrix, involving active users and active channels.

The cost matrix has been defined to be empty initially. In each time slot, the base station performs a buffer update. With the arrival of a new message (geometrically distributed in slot), the base transceiver station assigns each message to each secondary user uniformly and updates the buffer of the secondary users according to the new message assignment. Moreover, the cost matrix needs to be constructed based on the number of available users and available channels as mentioned above. The cost matrix comprises of the following parameters: active user, available channels, user identification, and channel identification. To populate the cost matrix, the station needs to identify the number of active users and available channels. The active users are identified based on the contents of the user buffer. If the secondary user buffer is non-zero, that secondary user will be considered as active, and reciprocally, if the user buffer is zero then that user will be considered idle (no information to transmit). The station will proceed to find the number of available channels. Now that the number of active users and the number of available channels have been determined, the station can construct the cost matrix.

4.2 Greedy Algorithm Implementation

The concept used to set up the channel parameters in the Hungarian algorithm will be similar to the Greedy algorithm with the exception that in the Greedy algorithm, the channel access will use a different concept. The Greedy concept has been used to allow Secondary users, in a cognitive environment, to access spectrum in the presence of multi-user multi- channel environment. This algorithm works in following phases. At each phase, the best option is selected without regard for future consequences. By choosing a local optimum at each step, a global optimum is reached [19]. After creating the buffer state similar to the Hungarian algorithm, the necessity of creating an idle probability is crucial within the Greedy algorithm. That idle probability will be a function of the belief vector, which is described by the channel availability. Similar to the Hungarian algorithm, the average reward per user is set to zero. If the buffer of user is empty, we do not need to perform a sensing action, and therefore the belief vector will be equivalent to the idle probability. On the other, meaning is the user buffer is not empty, and then the immediate reward will be the idle probability multiply by the channel bandwidth. Consequently the reward or throughput will be equivalent to the maximum immediate reward. Thus, in the Greedy algorithm if we have multiple channels with different bandwidth, choose the one with the largest bandwidth and transmit the information, then update the corresponding channel availability or belief vector and the user buffer.

5. SIMULATION ANALYSIS AND RESULTS

In this section we present comprehensive simulations in MATLAB to evaluate the performance of our proposed Hungarian and Greedy based OSA approaches. We will compare the performance of the proposed approaches for varying users and channels in various traffic conditions. In our simulations, the values for primary traffic parameters λ and μ are motivated by practical experiments conducted in [9]. The number of primary users in the network is equal to the total number of channels N. The idle-times show heavy-tailed behavior and are approximated b an exponential distribution with parameter $1/\lambda = 4.2ms$. The channel busy period is assumed to be $1/\mu = 1ms$. We assume that the bandwidth $B = 1$ and the length of the time slot $\tau = 1ms$.

5.1 Performance of the proposed approaches in presence of multiple secondary users

Message arrivals at the secondary users form a Poisson process. The message length is geometrically distributed with an average length of 50 packets. In each slot, secondary users do not participate in the channel sensing and access activities if they do not have packets to transmit. The total number of time slots used in simulations are 1000.Fig. 2 and Fig. 3 depict the throughput performance for the secondary users.

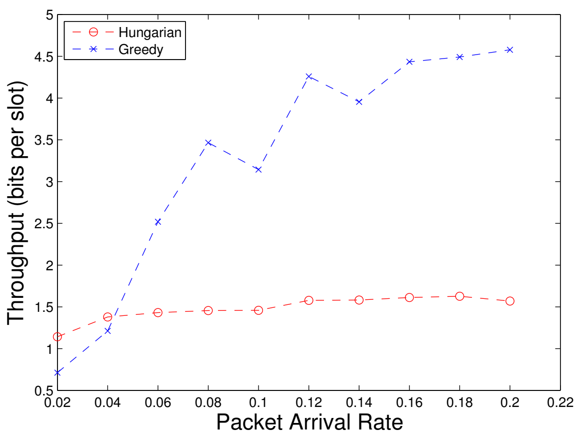

Figure 2: Performance of OSA approaches in presence of constant channels and large number of uses (5 channels and 70 users)

In presence of constant channels and varying number of users, the Greedy algorithm outperforms the Hungarian algorithm in terms of the throughput per Secondary user. The Greedy algorithm allows a secondary user to achieve an average throughput of 1.7 bits per slot and maximum throughput of 1.8 bits per slot. In contrast, the Hungarian algorithm provides a secondary user a maximum throughput of 0.8 bits per slot and an average throughput of 0.7 bits per slot. Based on the above results, in an environment comprising of fewer channels, the secondary users achieve better throughput using the Greedy algorithm.

In presence of constant channels and varying number of users, the Greedy algorithms provides secondary users more throughput than the Hungarian algorithm when the number of channels are few. However, as the number of channels increases, the Hungarian algorithm outperforms the Greedy algorithm.

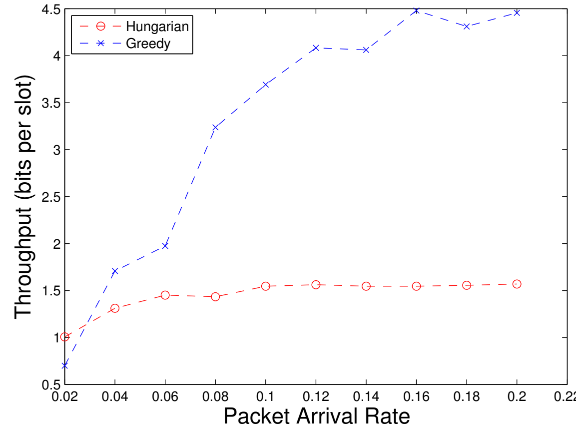

Figure 3: Performance of OSA approaches in presence of constant channels and medium number of uses (5 channels and 30 users)

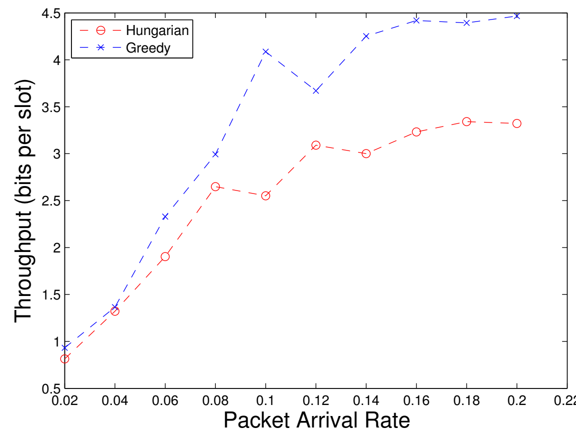

Figure 4: Performance of OSA approaches in presence of constant users and fewer channels (15 channels and 5 users

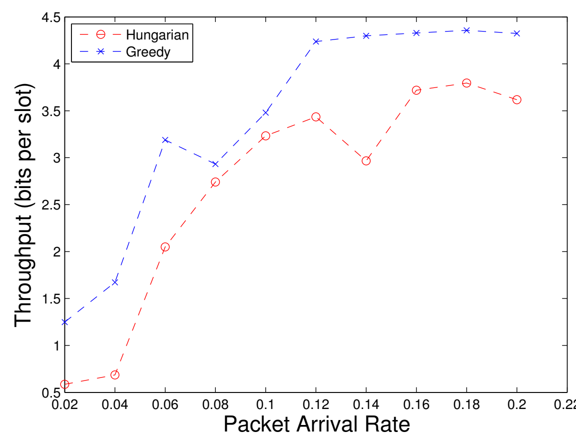

Figure 5: Performance of OSA approaches in presence of constant users and large number of channels (15 channels and 70 users)

In presence of varying channel idle/busy probabilities, the throughput of the Secondary users under the Hungarian algorithm is higher in presence of increasing probability of

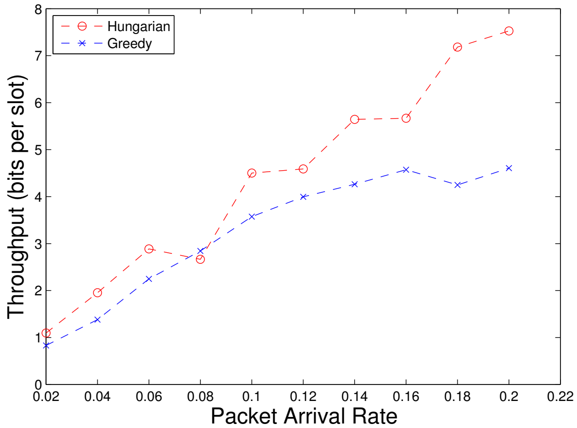

Figure 6: Performance of OSA approaches in presence of varying channel availability probabilities (45 channels and 10 users)

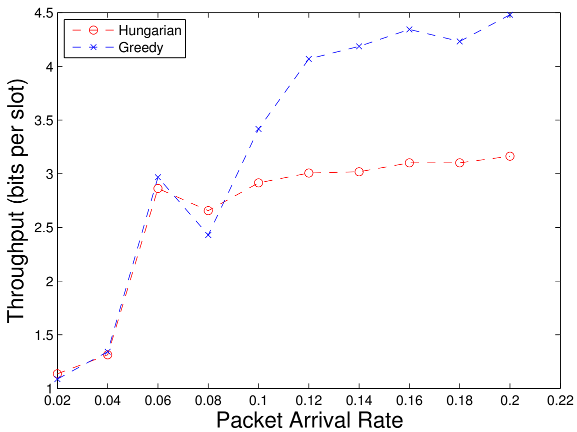

Figure 7: Performance of OSA approaches in presence of varying channel availability probabilities (10 channels and 45 users)

channel availability and number of channels. These results proves that Greedy algorithm is preferable over Hungarian algorithm when the number of channels are fewer in compared to the number of users. But, in presence of large number of channels as compared to users, Hungarian algorithm is preferable.

6. CONCLUSIONS

In this paper, we proposed Hungarian and Greedy based algorithms to allow multiple secondary users to achieve maximal throughput by exploiting idle periods in an unslotted primary network. Our approach is computationally less expensive and has no communication overhead as it does not involve exchange of spectrum maps among other secondary users. The performance of the proposed algorithms are closer to the optimal approaches with no communication overhead.

REFERENCES

[1] M. McHenry, "Spectrum white space measurements," New America Foundation Broadband Forum, 2003.

[2] Q. Zhao and B.M. Sadler, "A survey of dynamic spectrum access," IEEE Signal. Processs. Mag, May 2007.

[3] Q. Zhao and A. Swami, "Structure and Optimality of Myopic Sensing for Opportunistic Spectrum Access," Proc. of the IEEE International Conference on Communications(ICC), 2007.

[4] Y. Yuan, P. Bahl, R. Chandra, P. A. Chou, J. I. Ferrell, T. Moscibroda, S. Narlanka, and Y. Wu, "Knows: Cognitive radio networks over white spaces," in Second IEEE International Symposium on Dynamic Spectrum Access Networks, 2007.

[5] Y. Chen, Q. Zhao, and A. Swami "Joint Design and Separation Principle for Opportunistic Spectrum Access in the Presence of Sensing Errors," IEEE Transactions on Information Theory, May 2008.

[6] D. Raychaudhuri and X. Jing, "A spectrum etiquette protocol for efficient coordination of radio devices in unlicensed bands," in Proc. on Personal, Indoor and Mobile Radio Communications, 2003.

[7] Q. Zhao, S. Geirhofer, L. Tong, and B. M. Sadler, "Opportunistic spectrum access via periodic channel sensing," IEEE Transactions on Signal Processing, Vol. 56, No. 2, Feb. 2008.

[8] Q. Zhao and K. Liu, "Detecting, Tracking, and Exploiting Spectrum Opportunities in Unslotted Primary Systems," In Proc. of IEEE Radio and Wireless Symposium (RWS), 2008.

[9] S. Geirhofer, L. Tong, B.M. Sadler, "Dynamic spectrum access in WLAN channels:Empirical model and its stochastic analysis," Workshop Technol. Policy Accessing Spectrum (TAPAS), 2006.

[10] J. Munkres, "Algorithms for the assignment and transportation problems," Society for Industrial and Applied Mathematics, vol. 5 issue 1, pp. 3238, March 1957.