An Auction-based Mechanism for Cooperative Sensing in Cognitive Networks [*]

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ABSTRACT

In this paper, we propose an auction based cooperative sensing protocol for secondary users in cognitive networks. The proposed auction mechanism is based on a novel modified Vickrey auction with a three dimensional bidding, that accounts for detection gains as well as for virtual currency gains. We combine the cooperative auction with a prioritized access scheme to increase detection efficiency and decrease response time for the coalition formation procedure. Experimental results show that cooperation is incentivized by the proposed algorithm and leads to significant detection gains, with a more efficient energy expenditure.

Categories and Subject Descriptors

I.6 [**Computing Methodologies**]: Simulation and Modeling

General Terms

Theory

Keywords

Spectrum sensing, Prioritized access, Cognitive networks

1. INTRODUCTION

The problem of coexistence between primary and secondary users in a cognitive radio (CR) network, has been extensively studied in the literature. Secondary users (SUs) aim to utilize unused spectrum holes efficiently with guarantee for the quality of service (QoS) for the primary network. To achieve this goal, the secondary network needs intelligent spectrum management algorithms including spectrum sensing, spectrum selection, spectrum sharing and spectrum mobility ([1]). In this paper, we focus on the cooperative spectrum sensing for detecting the presence of a primary user (PU) in the context of incentivizing SUs' cooperation for efficient energy management.

Cooperative sensing has been shown to be successful in alleviating the hidden PU problem, by exploiting the multiuser diversity gains ([2, 3]), and in improving the detection of a weak signal with a low SNR ([2]). In the literature, many papers have addressed various aspects related to cooperative sensing for cognitive radio networks, for example, maximizing the CR network throughput ([4, 5]), proposing novel fusion and combining rules ([2, 6]), and proposing algorithms for wideband sensing ([5, 7]). Different from these previous works, we do not implicitly assume that SUs are willing to cooperate for spectrum sensing if they do not have packets to send, because spectrum sensing would consume their energy. Instead, we provide a framework incentivizing cooperation for these users.

To the best of our knowledge, the only paper that considers the users' incentive to cooperate is [8], in which the authors analyze the users' mutual benefit of forming coalitions and propose a merge-split algorithm for a more efficient coalition performance. However, the paper [8] only considers the detection performance, and not the energy requirements for individual users. In order to incentivize these users' cooperation, we propose a virtual currency exchange in an auction-based strategy for coalition formation.

This paper is organized as follows. The system model and assumptions are given in Section 2, and our proposed auction-based cooperative sensing protocol is presented in Section 3. Section 4 provides detailed description on the prioritized bidding access control. Simulation results together with analysis discussions are given in Section 5, and conclusions are presented in Section 6.

2. SYSTEM MODEL

We consider a CR network sharing a known spectrum with a primary network which has a single base station in the CR-deployed region. The access paradigm of CR users (i.e., SUs) is the interweave mode, defined in [9] as a mode where SUs are only allowed to access the spectrum holes where PUs are absent. The information on transmission powers and location of the primary base station and SUs is assumed to be known. In addition, we assume a synchronous sensing and data transmission schedule among all SUs and a dedicated control channel for coordinating SUs ([5, 10]).

A similar detection model is considered as in [8], i.e., energy detectors for SUs and several SUs forming a cooperative group/coalition with a head SU who initiates the coopera-

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tion request, collects reports from others via reporting links with BPSK modulation and determines the presence of PU by using the OR rule. For reader's convenience, we give here the detection probability and the false alarm probability for SU i using an energy detector in a Rayleigh fading environment.

$$\begin{aligned} p_{d,i} =& e^{-\frac{\lambda}{2}} \sum_{k=0}^{\theta-2} \frac{1}{k!} \left(\frac{\lambda}{2}\right)^k + \left(\frac{1+\bar{\gamma}_{i,PU}}{\bar{\gamma}_{i,PU}}\right)^{\theta-1} \\ & \times \left(e^{-\frac{\lambda}{2(1+\bar{\gamma}_{i,PU})}} - e^{-\frac{\lambda}{2}} \sum_{k=0}^{\theta-2} \frac{1}{k!} \left(\frac{\lambda \bar{\gamma}_{i,PU}}{2(1+\bar{\gamma}_{i,PU})} \right)^k \right), \end{aligned} \tag{1}$$

$$p_{f,i} = \frac{\Gamma(\theta, \lambda/2)}{\Gamma(\theta)}, \tag{2}$$

where θ is the time bandwidth product, λ is the energy detection threshold and $\bar{\gamma}_{i,PU} = \frac{P_{PU} h_{i,PU}}{\sigma^2}$ is the average SNR of the received signal from the PU to SU i given that P_{PU} is the transmission power of the PU, σ^2 is the Gaussian noise variance and $h_{i,PU} = \frac{\varphi}{d_{i,PU}^{\nu}}$ is the path loss between the PU and SU i, where φ is the path loss constant, ν is the path loss exponent and $d_{i,PU}$ is the distance between the PU and SU i. $\Gamma(\cdot,\cdot)$ is the incomplete gamma function and $\Gamma(\cdot)$ is the gamma function. So the miss detection probability of the SU i is $p_{md,i} = 1 - p_{d,i}$. In our work, the energy detection threshold λ is conditioned by an imposed false alarm probability p_f.

The cooperative detection probability and the cooperative false alarm probability for a cooperative group (G) using the OR rule are given as follows. In this group, the SU k is the head node and all the other SUs report to it. A cooperative false alarm is reported if at least one member reports a false alarm.

$$P_{d,G} = \prod_{i \in G} \left[p_{d,i} \left(1 - p_{e,i,k}\right) + p_{md,i} p_{e,i,k} \right], \tag{3}$$

$$P_{f,G} = 1 - \prod_{i \in G} \left[p_f \cdot p_{e,i,k} + \left(1 - p_f\right)\left(1 - p_{e,i,k}\right) \right], \tag{4}$$

$$p_{e,i,k} = \frac{1}{2} \left(1 - \sqrt{\frac{\bar{\gamma}_{i,k}}{1+\bar{\gamma}_{i,k}}} \right), \tag{5}$$

where $p_{e,i,k}$ is the probability of errors due to the fading over the reporting channel between the SU i and the SU k. The cooperative miss detection probability for the group is given as $P_{md,G} = 1 - P_{d,G}$.

3. PROPOSED COOPERATIVE SENSING

A cooperative sensing mechanism relies on users' participating in sensing and reporting for improved detection accuracy. However, sensing will drain batteries for cooperating users. Thus, rational users have no reason to help others sense the spectrum if they do not desire to access the spectrum.

In our model, the CR network is lightly loaded, so there are many CR users in the neighborhood that are not interested in accessing the spectrum to transmit packets at the moment. In order to incentivize these users to cooperate, we introduce a virtual currency that can be used to reward spectrum sensing cooperation. Users that accumulate enough currency may benefit by forming sensing coalitions to improve their spectrum sensing detection accuracy. Based on this virtual currency, users can initiate requests, and form sensing coalitions based on a bidding algorithm reminiscent of auctions.

Therefore, we propose a three dimensional modified Vickrey auctioning mechanism for spectrum sensing coalition formation, and this auctioning mechanism preserves the desirable truthfulness property of the classic Vickrey auction ([11]).

3.1 Utility Functions

The players in the auction game (potential cooperative SUs and the SU initiating the cooperation request) will choose their actions that will maximize their individual utilities.

We define the utility for the head SU node (the node initiating the request for cooperation) as a tradeoff among the detection probability, the false alarm probability [8], as well as the virtual currency cost for setting up the coalition:

$$u_h = P_{d,G} - C(P_{f,G}) - \sum_{i=1}^{n_m} b_i, \tag{6}$$

where $P_{d,G}$ and $P_{f,G}$ are respectively the cooperative detection probability and the cooperative false alarm probability, b_i is the price asked by the responding/member SU i and n_m is the number of the member nodes. The $C(P_{f,G})$ function is a logarithmic barrier penalty function given by:

$$C(P_{f,G}) = \left\{ \begin{array}{ll} -\alpha^2 \cdot ln \left(1 - (\frac{P_{f,G}}{\alpha})^2\right), & if \quad P_{f,G} < \alpha \\ +\infty, & if \quad P_{f,G} \geq \alpha \end{array} \right. , \tag{7}$$

where α is the false alarm constraint for the cooperative group.

We simplify the expression in (6) to reduce the overhead on payment information exchange and complexity [12] by implementing a more generous payment policy in which all member SUs are equally paid with r_m, which is defined as the maximum of all the prices asked by the member SUs in the current cooperative group (G), i.e., $r_m = \max_{i \in G} b_i$. Thus, the utility for the head SU is simplified as,

$$u_h = P_{d,G} - C(P_{f,G}) - n_m r_m. \tag{8}$$

The utility of an arbitrary SU i is defined as

$$u_{m,i} = \left\{ \begin{array}{ll} b_i - C_{e,m}, & if \quad b_i - C_{e,m} > 0 \\ -\infty, & if \quad b_i - C_{e,m} \geq 0 \end{array} \right. , \tag{9}$$

where $C_{e,m} = \epsilon \cdot c_{e,m}$ is the energy cost for cooperation assuming a price ϵ per unit energy and an energy expenditure $c_{e,m}$. This utility definition characterizes a SU's payoff when it chooses to cooperate, reflecting the difference between its profit and cost.

3.2 Modified Vickrey Auction Mechanism

In the traditional Vickrey auction, the bidder with the highest bidding wins and it pays the second highest bidding. For our cooperative sensing scenario, the head SU selects its members such that the selection maximizes its utility, and thus the bidding price alone may not be used to determine the winner. Further, multiple winners for the auction are possible. It becomes clear that the classic Vickrey auction mechanism needs to be modified in order to accommodate these new constraints ([13]), but the requirement is to preserve the desired truthfulness characteristic.

In our proposed auctioning mechanism, the proposed payment is defined as the highest price in the winning group, denoted as G_w, plus the difference between the maximal utility ($u_{max} = P_{d,G} - C(P_{f,G}) - n_m r_m$ according to (8)) and the second maximal utility ($u'_{max} = P'_{d,G} - C(P'_{f,G}) - n'_m r'_m$), divided by the number of the member SUs in the winning group. Thus, the payment ρ_m is given by:

$$\rho_m = \max_{i \in G_w} b_i + \frac{u_{max} - u'_{max}}{n_m} \equiv \max_{i \in G_w} b_i + x, \qquad (10)$$

with $x = \frac{u_{max} - u'_{max}}{n_m} > 0$.

Note that as $r_m = \max_{i \in G_w} b_i$, the payment expression is simplified as

$$\rho_m = \frac{[P_{d,G} - C(P_{f,G})] - u'_{max}}{n_m}. \qquad (11)$$

3.2.1 Truthfulness property

Theorem 1. ***Truthfulness property for the proposed Auction Scheme*** *The above proposed payment mechanism for our modified Vickrey auction ensures that all users have a dominant strategy of bidding their true valuation of resources.*

The motivation behind the above proposed payment mechanism is that the actual payment should be unrelated to the SU's own bidding, but should benefit the SU, which guarantees the truthfulness. In the above formula, a higher payment than the winning SU's own bidding benefits the SU because $x > 0$, and the benefit is equally distributed among the member SUs. From (11), we can tell the actual payment does not depend on the SU's own bidding. The detailed proof steps for the theorem are similar to the proof in [13] and are omitted due to page limitation.

3.2.2 Bidding

We propose a three-dimensional bidding structure, $B_i = (p_{d,i}, p_{e,i,k}, b_i)$, where $p_{d,i}$ is the local detection probability of node i, node k is the requesting node, $p_{e,i,k}$ is the error probability over the link between node i and node k, and b_i is the price asked by node i. This 3D bidding mechanism allows the auctioneer to evaluate the gains in terms of detection probability that a new cooperating user may bring to the coalition, as well as the costs in terms of both false alarm probability and virtual payments.

The detection probability and the error probability can be calculated using (1) and (5) given the known/estimated power and distance information.

The bidding price asked by SU i is defined as a function of its residual energy and its current virtual currency balance. The price should increase when the SU has less residual energy. The SUs energy valuation is modulated by their current residual battery energy levels. Additionally, the valuation of the same payment is different based on the current virtual currency balance of SUs (a "rich SU" would be less interested in accumulating more currency).

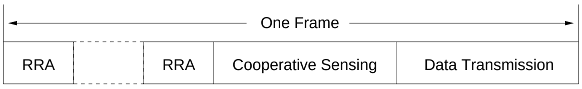

Figure 1: Illustration of the frame structure

Based on these observations, we propose a virtual currency based bid $b_i = \beta \frac{c_i}{e_{r,i}}$ where β is a scaling parameter, c_i is the money balance of SU i and $e_{r,i}$ is its residual energy.

4. PRIORITIZED ACCESS FOR BIDDING

Under the assumption of a densely populated CR network with a light load, we anticipate very few collisions in initiating cooperation requests and substantial collisions for the bidding responses. As such, a simple exponential backoff scheme for requesting SUs' collision resolution may be employed. For the responding bidder SUs, we propose a prioritized backoff access scheme in order to reduce the collision probability, improve the delay in establishing coalitions and prioritize the best choices to respond first.

4.1 Frame Structure

In our proposed auction-based cooperative sensing, a frame consists of a coordination sub-frame, a cooperative sensing sub-frame and a data transmission sub-frame (see Fig. 1). The coordination sub-frame is comprised of several Requesting-Responding-Acknowledge (RRA) phases, which are further divided into the requesting sub-phase, the responding sub-phase and the acknowledgement sub-phase. The number of RRA phases is a parameter which can be designed in order to optimize the network performance taking into account SUs' distribution and traffic characteristics.

In the requesting sub-phase, SUs who need to, and are able to ask for cooperation will send their cooperation requests; In the responding sub-phase, SUs who hear a request and are interested to cooperate respond to the request with their bids. The requesting/head SU then selects SUs to form its cooperative sensing group to maximize its utility. In the acknowledgement sub-phase, the requesting SU pays the selected responding SUs and thus confirms the formation of the cooperative group.

During a RRA phase, there is at most one successful request in the neighborhood, but in the entire network, there could be multiple successful requests without interfering each other. After the coordination sub-frame, it is the cooperative sensing sub-frame, during which the formed cooperative sensing group will sense the spectrum to determine whether it is available, and the data transmission sub-frame, in which the requesting SU will transmit its data if the spectrum is detected as idle.

4.2 Priority level

We define a priority level for responding SUs according to their biddings, i.e., their local detection probability, their error probability of the reporting link and their bidding price. Let us assume without loss of generality that SU k is the requesting SU (head node). Then, the priority level of a bidding SU i can be defined as:

$$l_i = w_1 \frac{p_{d,i}}{p_{e,i,k}} + w_2 \left(-b_i\right), \qquad (12)$$

where $p_{d,i}$ is the local detection probability of SU i, $p_{e,i,k}$

is the error probability of the reporting link between SU i and SU k, b_i is the asked price by SU i, w_1 and w_2 are weights associated with the ratio of $p_{d,i}$ to $p_{e,i,k}$, and b_i respectively. We note that a high local detection probability, a good quality of the reporting link and a low price are preferred in terms of the requesting SU's utility.

The responding SUs' backoff windows are set according to their priority levels. Specifically, a responding SU with a priority level l_i would set its backoff window between t and $t+2^{L/log(l_i)}$, where t is the beginning time of the responding sub-phase and L is used to scale the priority level and to garantee the randomness.

We note that the prioritized response statistically ensures that good bids are received first and thus allows the requesting SU to collect only the first N responses rather than to collect all the responses, without degrading the performance significantly. Further, the complexity of the winners' selection also decreases with the decrease in the number of received bids, as the head SU needs to consider all possible combinations when determining the winning group that achieves a maximum utility.

4.3 Coordination procedure

Fig. 2 illustrates the prioritized access control for coalition formation. At the beginning of a requesting sub-phase, if a SU has a non-empty queue, it will send a request packet if it has not heard any successful request in the previous requesting sub-phase. The SU will quit contending to send requests in the following requesting sub-phases of the current frame if it heard that some other SU has sent a request. If the requests collide, the requesting SUs will not receive any response in the responding sub-phase and then they will reschedule their requests in the next request sub-phase based on the exponential backoff scheme.

In the responding sub-phase, SUs who hear a request and are interested in participating in the sensing coalition will respond to the requesting SU with their biddings by using a random access with a backoff window modulated by their priority levels. Colliding SUs abandon the competition for the current RRA phase. The winners are selected by the head SU, among the successful received bids in this phase. In the acknowledge sub-phase, the head SU acknowledges the winners with the payment.

5. SIMULATION RESULTS

The simulations in this paper are implemented in Matlab. We consider 32 nodes deployed in a square region of 3km-by-3km with a fixed PU base station at the center. The transmission power of the base station is 100mW and the transmission power of SUs is 10mW. The path loss exponent is chosen to be 3. For the local energy detector, the given false alarm probability is set to be 0.01 used to determine an energy level threshold for detection. Another threshold for local detection probability, set to be 0.9, is used by the SUs to determine whether or not to ask for cooperation.

5.1 PU and SU activity models

In our simulation, we use a two state birth-death process with the death rate δ and the birth rate μ to model the PU activity ([10]). The death rate δ and the birth rate μ respectively measure how quickly that the PU's state transits from ON (active) to OFF (silent) and from OFF to ON. We also assume that the duration of the ON state and the OFF state are exponentially distributed ([10]) with the parameters δ and μ, respectively. The death rate is chosen to be $\delta = 4$ and the birth rate $\mu = 1.5$ for the numerical results.

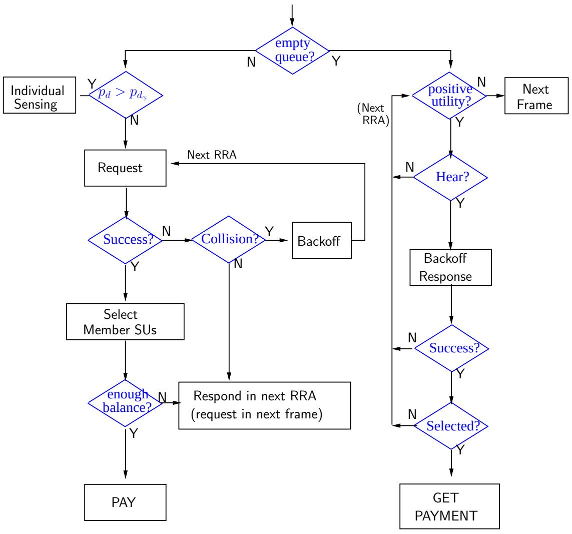

Figure 2: Flow chart of the coordination procedure

For the SU activity, we model SUs' data arrival as a Poisson process with the expected number of arrivals η in one frame equal to 0.5.

5.2 Performance analysis

To illustrate the tradeoffs among different performance measures that the prioritized response access achieves, we consider the following three cases and compare the cooperative miss detection probability, the cooperative false alarm probability, the computational complexity (the number of combinations that need to be computed and compared in the requesting SU to maximize utilities) and the window length of the responding sub-phase. In the following, we denote the qualified neighbors as the neighboring nodes with positive utilities, not members of another cooperative group and not currently waiting to initiate cooperation requests.

- **Case I: Perfect response access.** It is the ideal case involving no collisions by perfect scheduling of all responses.
- **Case II: Complete prioritized response access.** All the qualified neighbors perform prioritized backoff. Some responding neighbors may collide, but the requesting SU needs to wait for all the good responses to be collected.
- **Case III: Truncated prioritized response access.** The requesting SU only collects the first N responses, or only waits for a fixed period of time in the responding sub-phrase. This case is proposed to overcome the possibly undesirable long response sub-phrase, at the cost of degraded detection performance. For the numerical results illustration, only the first response is collected by the requesting SU.

Fig. 3 illustrates the three performance metrics together with all the results being normalized to Case I results. We can see that the detection performance deteriorates in Case

II and Case III compared to Case I, while lower false alarm probabilities are achieved. Furthermore, we see that the processing complexity for the head SU decreases significantly especially for Case III. As expected, Case II has the longest responding window. In practice, Case III is an attractive implementation choice, due to its simple implementation, predictable responding window length and acceptable detection performance.

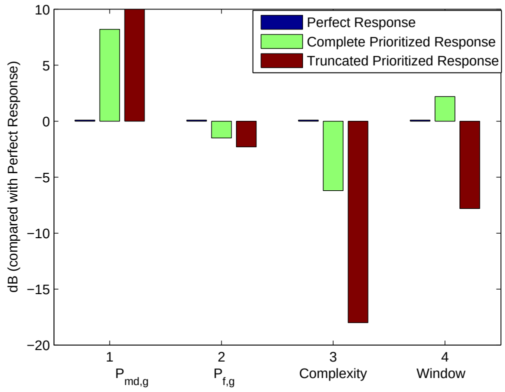

Figure 3: Response performance comparison

5.3 Cooperative detection performance

Fig. 4 shows the cooperative sensing performance for some example SUs in terms of the miss detection probability and the false alarm probability, to compare with the individual non-cooperative sensing. In our simulation we set the desired local false alarm probability for a single SU detection, to be 0.1. The false alarm probability is expected to increase for the cooperative detection scheme, due to the use of an OR rule to aggregate the individual readings. From Fig. 4, we see that the false alarm probability for the cooperative case is kept within a desired range. Furthermore, the detection performance is improved significantly by cooperation.

6. CONCLUSION

In this paper, we propose a novel cooperative sensing framework for CR networks, which incentivizes CR users to cooperate by introducing a virtual currency reward in an auction game. In this game, CR users are guaranteed to bid their true valuation. Together with our proposed prioritized bidding response access, our cooperative sensing framework has control of the group formation delay and has a low implementation complexity. Our numerical results show that our cooperative sensing scheme improves detection performance, while keeping the false alarm probability below an acceptable threshold.

7. REFERENCES

[1] Antonio De Domenico, Emilio Calvanese Strinati and Maria-Gabriella Di Benedetto, *A Survey on MAC Strategies for Cognitive Radio Networks* IEEE Communications Surveys and Tutorials, 2010.

[2] Unnikrishnan J. and Veeravalli V.V., *Cooperative Sensing for Primary Detection in Cognitive Radio* IEEE Journal of Selected Topics in Signal Processing, 2008, **2**(1):18–27.

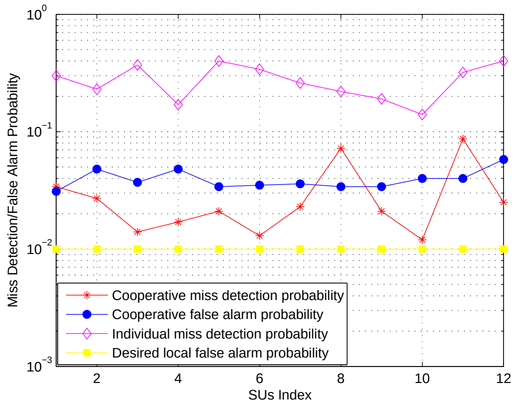

Figure 4: Detection performance comparison

[3] Mishra S.M., Sahai A. and Brodersen R.W., *Cooperative Sensing among Cognitive Radios* IEEE International Conference on Communications, 2006,1658–1663.

[4] Junyang Shen, Tao Jiang, Siyang Liu and Zhongshan Zhang, *Maximum channel throughput via cooperative spectrum sensing in cognitive radio networks* IEEE Transactions on Wireless Communications, 2009, **8**(10):5166–5175.

[5] Rongfei Fan, Hai Jiang, Qiang Guo and Zhou Zhang, *Joint Optimal Cooperative Sensing and Resource Allocation in Multichannel Cognitive Radio Networks* IEEE Transactions on Vehicular Technology, 2011, **60**(2):722–729.

[6] Jun Ma, Guodong Zhao and Ye Li, *Soft Combination and Detection for Cooperative Spectrum Sensing in Cognitive Radio Networks* IEEE Transactions on Wireless Communications, 2008, **7**(11):4502–4507.

[7] Zhi Tian, *Compressed Wideband Sensing in Cooperative Cognitive Radio Networks* IEEE Global Telecommunications Conference, 2008.

[8] Saad W., Zhu Han, Basar T., Debbah M. and Hjorungnes A., *Coalition Formation Games for Collaborative Spectrum Sensing* IEEE Transactions on Vehicular Technology, 2011, **60**(1):4502–4507.

[9] A. Goldsmith, S. A. Jafar, I. Maric and S. Srinivasa, *Breaking Spectrum Gridlock with Cognitive Radios: An Information Theoretic Perspective* IEEE Proceedings, 2009, **97**(5):894–914.

[10] Won-Yeol Lee and Akyildiz I.F., *Optimal spectrum sensing framework for cognitive radio networks* IEEE Transactions on Wireless Communications, 2008, **7**(10):3845–3857.

[11] William Vickrey, *Counterspeculation, auctions and competitive sealed tenders* Journal of Finance, 1961, **16**(1):8–37.

[12] Demir C. and Comaniciu C., *An Auction based AODV Protocol for Mobile Ad Hoc Networks with Selfish Nodes* IEEE ICC 2007.

[13] Cristina Comaniciu, Narayan B. Mandayam, H. Vincent Poor and Jean-Marie Gorce, *An Auctioning Mechanism for Green Radio* Journal of Communications and Networks, 2010, **12**(2):114–121.