Impact of Spatio-Temporal Correlation in Cooperative Spectrum Sensing for Mobile Cognitive Radio Networks

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***Abstract*—Cooperative Spectrum Sensing (CSS) has been proposed as a solution to increase accuracy of spectrum sensing in a Cognitive Radio Network (CRN), but with a few exceptions the design and performance evaluation of CSS schemes has focused so far on static networks, neglecting the role and potential impact of terminals mobility, in conjunction with channel spatio-temporal correlation. This work addresses such issues by proposing a CSS scheme with a correlation-based nodes selection and by evaluating its performance in a realistic simulation environment using accurate models for signal propagation, degree of correlation among sensing measurements and mobility behaviour.**

The proposed scheme adopts the well known Moran's I statistical index, defined in 1950 by P.A.P. Moran, as the metric for determining the degree of correlation between Secondary Users (SUs), and selects a subset of SUs characterized by low correlation and high expected sensing performance in order to achieve satisfactory network sensing performance while reducing the overhead related to sensing in terms of bandwidth utilization and energy consumption. The proposed scheme is compared with an alternative solution, where all SUs participate in the sensing process, by means of computer simulations considering both static and mobile SUs under accurate models for channel correlation and mobility. Simulation results, while confirming that the proposed scheme achieves a reduction in the number of devices involved in sensing without significant performance loss, hint that the advantage guaranteed by SU mobility might be lower than what estimated by previous studies under simpler assumptions.

I. Introduction

Spectrum Sensing (SS) is traditionally one of the most important and distinguishing functions of Cognitive Radio (CR) devices. Several studies pointed out however the potential limitations and drawbacks when SS is adopted to identify spectrum opportunities within opportunistic secondary spectrum application scenarios [1][2][3][4].

Cooperative Spectrum Sensing (CSS) schemes, relying on cooperation between Secondary Users belonging to the CRN (SUs), have been proposed to partially address the above issues [5]. However, in [5] and [6], it was also demonstrated that the performance increase over Local SS (LSS) achievable by CSS depends on localized shadowing and fading characteristics of channels between Primary Users (PUs) and different SUs and specifically on the degree of correlation between measurements and sensing decisions of SUs. The authors of [6] show that, in a given area, a direct proportionality between the number of SUs and the correlation between the SUs' themselves measurements and an inverse proportionality between degree of correlation and CSS performance can be observed. As a result, the positive effect of cooperation between sensors increases as the number of SUs increases as well, until no further performance increase can be obtained by further increasing the number of SUs involved in the sensing process, because of correlation between measurements. As pointed out in [7] and [8], this means that efficient CSS schemes must rely in most cases on the selection of a subset of SUs on the basis of clustering algorithms grouping nodes according to specific, sensing-related, performance metrics. As a result, several works exist in the literature focusing on analysis and definition of correlation-based metrics for nodes selection in CSS scenarios [9][10].

Mobility is a second phenomenon that can influence performance of both CSS and LSS. Mobility of SUs can in fact increase the spatial diversity in the collection of signal samples for sensing purposes. This observation is supported by results in [11] and [12], obtained however under several simplifying assumptions, including same speed and constant direction of movement for all SUs, as well as total uncorrelation of measurements taken by different SUs, irrespectively of their positions; in addition, changes in connectivity between SUs induced by mobility were not taken into account.

This work provides a more realistic evaluation of the impact of mobility and spatio-temporal correlation on CSS performance by relaxing and removing some of the above assumptions. To this aim, a set of simulation scenarios that takes into account realistic conditions for channel correlation and SUs mobility is defined. Results confirm the need for the definition of CSS schemes that rely on a (eventually) correlation-based metric to select the optimal set of SUs to be involved in the sensing process. The work addresses the problem of CSS in presence of correlation between measurements by defining a novel node selection metric based on the statistical index known as Moran's I, widely used to test for the presence of spatial dependence in observations taken on a lattice and, given its simplicity, also frequently used in exploratory analyses of spatially referenced data [13]. In the proposed framework the Moran's I is used to determine the degree of correlation between decisions taken by different SUs in different locations of the defined environment, and to select a sub-optimal group of *quasi*-uncorrelated SUs to be involved in the CSS procedure. The performance of the proposed node selection scheme is evaluated over a set of simulation scenarios taking into account realistic conditions for channel correlation and SUs mobility. The paper is organized as follows: Section II introduces the theoretical setting for SS for fixed and mobile CRNs; Section III introduces the system model and the framework for the selection of nodes to be involved in the CSS procedure. Section IV presents and discusses simulation results. Finally, Section V concludes the paper.

II. Spectrum Sensing for Static and Mobile CRNs

Energy Detection Spectrum Sensing (ED-SS) is a widely adopted choice for sensing applications, as it does not require any knowledge on the PUs signal. In ED-SS SUs measure the energy of the received waveform in the frequency band of interest W (hertz), over an observation time window of T (seconds), and compare the test statistic Y, approximating the signal energy, with a properly selected threshold λ [15]. Denoting by $\mathcal{H}_0$ and $\mathcal{H}_1$, respectively, the two hypotheses of PUs presence and absence in the frequency band, the SS decision problem is defined as follows:

$$\mathcal{H}_0 \colon Y < \lambda,$$
$$\mathcal{H}_1 \colon Y \geq \lambda.$$

In LSS a SU opportunistically transmits when it does not detect presence of any PUs and its decision is not related to SS results of other SUs. CSS has been proposed in order to improve LSS performance [5]. This work considers a centralized CSS scheme with hard fusion rule, assuming the presence of a Fusion Center (FC). The FC is the device in the CRN that applies the selected fusion rule on the local decisions, evaluating and then broadcasting the cooperative network decision.

Assuming a general *k out of n* fusion rule, if k or more SUs decide the hypotheses $\mathcal{H}_1$, then the FC will decide for $\mathcal{H}_1$. If $k = (n+1)/2$, the rule is referred as Majority rule; special cases are defined for $k = 1$ (OR rule) and $k = n$ (AND rule). Having N collaborating SUs in the CRN, experiencing independent and identically distributed fading/shadowing with same average SNR γ, conditionally independent (*uncorrelated*), employing ED-SS with same threshold λ, then the probabilities of detection and false-alarm for the collaborative scheme (Q_{d} and Q_{fa}, respectively), applying the generic n-out-of-N fusion rule, are:

$$Q_{\mathsf{d}} = \sum_{k=n}^{N} \binom{N}{k} P_{\mathsf{d}}^{k} (1 - P_{\mathsf{d}})^{N-k}, \tag{1}$$

$$Q_{\mathsf{fa}} = \sum_{k=n}^{N} \binom{N}{k} P_{\mathsf{fa}}^{k} (1 - P_{\mathsf{fa}})^{N-k}, \tag{2}$$

where P_{d} and P_{fa} are the local probabilities of detection and false alarm for each SU. Formulas for Majority rule ($\lceil N/2 \rceil$ out of N) becomes:

$$Q_{\mathsf{d}} = \sum_{k=\lceil N/2 \rceil}^{N} \binom{N}{k} P_{\mathsf{d}}^{k} (1 - P_{\mathsf{d}})^{N-k}, \tag{3}$$

$$Q_{\mathsf{fa}} = \sum_{k=\lceil N/2 \rceil}^{N} \binom{N}{k} P_{\mathsf{fa}}^{k} (1 - P_{\mathsf{fa}})^{N-k}. \tag{4}$$

Furthermore, using the OR rule (1 out of N), (1) and (2) become, respectively:

$$Q_{\mathsf{d}} = 1 - (1 - P_{\mathsf{d}})^{N}, \tag{5}$$

$$Q_{\mathsf{fa}} = 1 - (1 - P_{\mathsf{fa}})^{N}, \tag{6}$$

and, for the AND rule (N out of N):

$$Q_{\mathsf{d}} = P_{\mathsf{d}}^{N}, \tag{7}$$

$$Q_{\mathsf{fa}} = P_{\mathsf{fa}}^{N}. \tag{8}$$

For large values of the Time-Bandwidth product m, the Gaussian Approximation can be applied to the test statistic Y under either $\mathcal{H}_0$ or $\mathcal{H}_1$ [14]. In this case one has:

$$P_{\mathsf{fa}} = \frac{1}{2} \mathrm{erfc}\Big(\frac{\lambda - 2m}{2\sqrt{2m}} \Big), \tag{9}$$

$$P_{\mathsf{d}} = \frac{1}{2} \mathrm{erfc}\Big(\frac{\lambda - 2m - 2\gamma}{2\sqrt{2}\sqrt{m + 2\gamma}} \Big). \tag{10}$$

In the following we assume to use the so-called CFAR operating mode for CSS. In this mode the overall CRN fixes a target probability of false alarm $\bar{Q}_{\mathsf{fa}}$, selected so to optimize the usage of spectrum opportunities when the licensed channel is free. Given $\bar{Q}_{\mathsf{fa}}$, the corresponding $\bar{P}_{\mathsf{fa}}$ can be obtained inverting the chosen fusion rule formula. This leads to the evaluation of the threshold λ, inverting (9), and the consequent evaluations of achievable P_{d} and Q_{d}, for a given value of γ. In this case, the generic formulation of the ED threshold λ is:

$$\lambda^{\mathrm{CFAR}} = \mathrm{erfc}^{-1}(2\bar{P}_{\mathsf{fa}})[2\sqrt{2m}] + 2m. \tag{11}$$

In this general scenario regarding spectrum sensing, the hypothesis of mobility of SUs beloging to the CRN still appears quite under-investigated, except for few notable works, as pointed out in [15], [16]. As mentioned in the Introduction, results in [11] and [12], even if under several simplifying assumptions, suggest the conclusion that mobility of SUs can increase the spatial diversity in the collection of signal samples for sensing purposes, providing a general improvement of the performance (in particular for LSS). In this paper the analysis of CSS performance under the hypothesis of a complete mobility model for SUs is addressed and results are shown in Section IV-B.

III. System Model

A. Propagation Channel Model

An accurate modeling of the wireless propagation channel is critical in the design and performance evaluation of algorithms and protocols for CRNs, and it has thus been suggested as an important research topic [17]. Aspects that are highly dependent on how the physical transmission channels PUs-SUs and SUs-SUs are modeled include the analysis of interference to PUs from SUs, sensing performance, and the design of a dedicated control channel between SUs. In particular, path loss models help to predict the median interference powers at PU receivers; shadowing models, thanks to spatial variability, relate power measurements on SU-SU paths to interference levels over SU-PU paths; finally, fading models are instrumental in reasonably predicting the statistical variability of SU-PU interference. In this work the following simple yet accurate model is adopted for both PUs-SUs channels and SUs-SUs channels power attenuation:

$$\alpha_{\mathsf{channel,dB}} = \alpha_{\mathsf{PL,dB}} + \alpha_{\mathsf{f,dB}} + \alpha_{\mathsf{s,dB}} \tag{12}$$

where $\alpha_{\mathsf{PL,dB}}$ is the attenuation factor for the path loss model, depending on carrier frequency of the working frequency band and distance between devices; $\alpha_{\mathsf{f,dB}}$ is the fast fading coefficient, modelled using the Jakes approximation of the Rayleigh fading model [18]; lastly $\alpha_{\mathsf{s,dB}}$ is the coefficient due to shadowing (slow fading) effect, modelled with a log-normal distribution.

B. Moran's I-based Nodes Selection Framework for CSS

In the CSS scheme proposed in this paper, the Moran's I statistic is evaluated and used by the FC in order to determine the degree of correlation between decisions by different SUs. The main goal is to discard from the next CSS phases the SUs that appear to be *highly* correlated with other SUs and that, for this reason, do not provide additional useful information for CSS. To do so, the working environment is divided by n squared cells. The assumption is that the SUs are able to provide to the FC information about their position in the environment. For each SS phase the collaborating SUs will transmit to the FC the decisions and the location in which they have taken them. When the FC receives two or more decisions from the a given cell, it evaluates Moran's I for that cell, defined as in [13]:

$$I \triangleq \frac{N}{\sum_k \sum_j w_{ij}} \frac{\sum_k \sum_j w_{ij}(X_i - \bar{X})(X_j - \bar{X})}{\sum_i (X_i - \bar{X})^2} \tag{13}$$

where N is the number of spatial units indexed by i and j (in our scheme N is the number of SUs taking a decision in the cell under test); X is the variable of interest (the sensed energy by each SU pair (i, j)); $\bar{X}$ is the mean of X and w_{ij} is an element of a matrix of spatial weights (in the proposed scheme, the shorter the distance between two SUs, the higher the assigned spatial weight).

From its definition, Moran's I is defined in the interval $[-1 \quad 1]$; for our purposes, we basically state that if $I \approx 0$, it means that the data (decisions) used to evaluate I are ultimately uncorrelated. For this reason, the proposed scheme defines an interval of uncorrelation $\mathcal{C} : I \in [-0.25, 0.25]$. If $I \notin \mathcal{C}$, the FC will conclude that the measurements are correlated. Following this decision, the FC will determine the average value of the decision variable in the cell and inform the SUs in the cell with a value of the decision variable lower than such average value that they are excluded from the next phase of SS. This is done iteratively during each sensing phase. No discarding process occurs when the evaluated statistic $I \in \mathcal{C}$. On the contrary, the FC will allow all the SUs within the cell to cooperate again when only one SU in the cell is left to sense in the next CSS, making impossible a further Moran's I evaluation.

IV. Results and Discussions

A. Simulation Environment and Settings

The simulation environment foresees the presence of a DVB-T Transmitter (Primary User) and a set of devices forming a CRN (Secondary Users). The PU is located in the top left corner of a square area of 10×10 km^2, and it uses a fixed transmitter power (200 kW) and a single DVB-T 8 MHz channel in the UHF band for its own licensed transmission. The CRN is located at the lower right area of the playground, within a 700×700 m^2 area, centered on the position of the FC. The SUs communicate among them and with the FC using a maximum transmission power of 110 mW. The SUs forming the CRN can be static or mobile; when mobility is present, the SUs are allowed to move within the working area using a Gauss-Markov mobility model [19] with an average speed $v = [5 \quad 10 \quad 15 \quad 20]$ m/s. To the purpose of the proposed Moran's I-based CSS scheme, the CRN playground is divided by 16 175×175 m^2 squared cells. Moreover, the SUs are equipped with two different radio interfaces working on different frequency bands: a data interface used to sense the PU channel and transmit data packets when the sensing decision is that the PU is absent, and a control interface working on a common channel (modeled as 20 MHz 802.11 channel) always available to SUs, used to exchange control packets required for the organization and the management of the network, and in particular for the execution of the procedures related to the CSS algorithm.

The implementation of the environment was carried out within the OMNeT++ simulation environment, taking advantage of the MiXiM framework [20]. Each run covers 1 hour of simulated time, during which each collaborating SU takes a local decision exploiting a sensing phase of $T = 50\mu$s and then transmits its decision to the FC during the subsequent exchange phase of 1 second. Finally, a global decision is taken by the FC each 5 seconds. The proposed scheme is compared with a scheme where each SU belonging to the CRN cooperates in the CSS, sending its own local decision to the FC. The FC will apply then a fusion rule, obtaining a global decision.

B. Simulation Results

Figure 1 presents the impact on nodes selection in the proposed correlation-based scheme, in terms of the average number of SUs collaborating in the CSS during the simulation, for both static and mobile cases and for different values of SUs in the CRN.

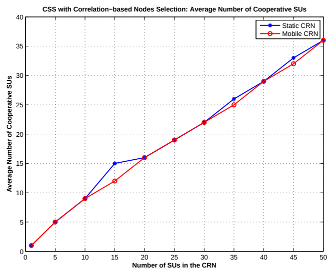

Fig. 1. Average Number of cooperative SUs for CSS with proposed 'Node Selection' scheme.

Three main results are shown: 1) the chosen individual mobility model impacts, slightly downward, the nodes selection and 2) until the number of SUs is lower than the number of cells, practically no nodes selection occurs. These results are mainly due to the hypotheses of randomly chosen SUs positions in the static scenario and *quasi*-random feature of the mobility model that, on average, led to a low degree of correlation when a low number of SUs is in the network (on average, the SUs are spatially dispersed in the playground). Finally, when the number of SUs is higher that the number of cells, 3) the higher the number of SUs in the network, the higher the number of discarded SUs. This is actually related to the obvious direct proportionality between the number of SUs and the degree of correlation of the SUs' decisions.

Figures 2 and 3 show, respectively, the measured Q_{d} for CSS with Majority rule, as a function of the CFAR target $\bar{Q}_{\mathsf{fa}}$ and the number of SUs ($N = [1 \quad 5 \quad 15 \quad 25 \quad 35 \quad 45]$), for schemes without and with nodes selection. Similar results in Figures 4 and 5 for, respectively, AND and OR rules with $N = [1 \quad 5 \quad 50]$. For the evaluation of the single user P_{d} an average $\gamma = 5\mathsf{dB}$ is assumed.

The plots for Majority rule show that, after a significant improvement given by cooperation of SUs, the performance does not improve significantly with the number of SUs to similar values, making the use of more SUs less and less useful. Therefore, from this point of view, the scheme with nodes selection achieves comparable perfomance with respect to the previous scheme even if with a lower number of cooperative SUs. Similar results were obtained for AND and OR rules where, in addition, a lower improvement given by cooperation can be observed.

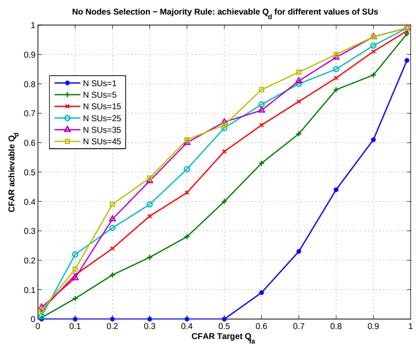

Fig. 2. ROC for CSS + Majority with 'No Nodes Selection' scheme.

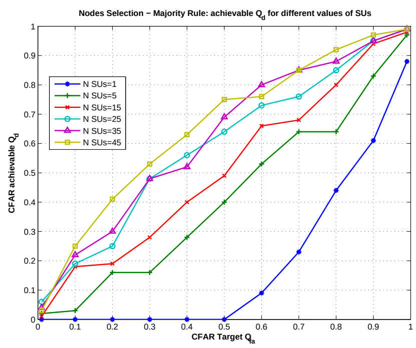

Fig. 3. ROC for CSS + Majority with proposed 'Nodes Selection' scheme.

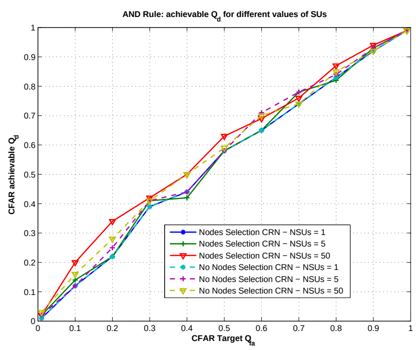

Fig. 4. ROC for CSS + AND for proposed 'Node Selection' scheme vs. 'No Node Selection' scheme.

Finally, Figure 6 presents the performance of CSS with Majority fusion rule, for the scheme without nodes selection and a number of SUs belonging to the network equal to 25. Differently from the previous analysis, in this case a Gauss-Markov mobility model is assumed for each SU. Results for the nodes selection scheme are not reported but also in the mobile case a good match between the two schemes is observed, confirming that node selection based on correlation does not

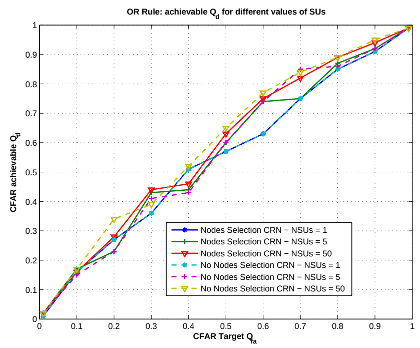

Fig. 5. ROC for CSS + OR for proposed 'Node Selection' scheme vs. 'No Node Selection' scheme.

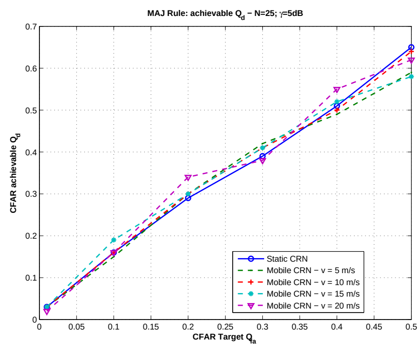

Fig. 6. CSS performance comparison for static and mobile CRNs.

cause significant performance loss. Moving the impact of mobility the results do not show the clear improvement shown in [11] [12] for a single SU, but quite similar performance of the CSS scheme. A possible explanation to this discrepancy is related to the fact that in this work some previous simplifying hypotheses were removed in favor of a more realistic modeling of propagation channel and mobility behaviour. The results call thus for further studies to determine the actual advantage introduced by mobility in real-world scenarios.

V. Conclusions

This work addressed the study of the impact of spatio-temporal correlation and mobility on CSS under the CFAR operating mode. In particular, a novel framework for nodes selection, based on the Moran's I statistical index was proposed, and simulation results show that the proposed scheme achieves sensing performance comparable to CSS relying on all network nodes while only involving a reduced number of SUs. Results confirm thus the idea that when correlation is taken in account, efficient CSS schemes can be defined based on the selection of a subset of SUs. Furthermore, a preliminar assessment of the impact of introducing a *quasi*-realistic mobility model was carried out. Simulation results, show the impact of more realistic mobility models with respect to results presented in previous works relying on simpler mobility and channel modelling, calling for further studies on the role of mobility in cooperative spectrum sensing.

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References

[1] Cabric, D.; Mishra, S.; Brodersen, R.; *Implementation issues in spectrum sensing for cognitive radios* - in Proc. Asilomar Conf. on Signals, Systems and Computers, Vol. 1, pp. 772-776, California, USA, Nov. 2004.

[2] Sahai, A.; Hoven, N.; Tandra, R.; *Some fundamental limits on cognitive radio* - in Proc. 42nd Annu. Allerton Conf. Commununication, Control, and Computing, pp. 1662-1671, Monticello, IL, Oct. 2004,

[3] Tandra, R.; Sahai, A.; *SNR walls for signal detection* - IEEE J. Select. Topics Signal Process., Vol. 2, pp. 4-17, Feb. 2008.

[4] Axell, E.; Leus, G; Larsson, E.G.; Poor, H.V.; *Spectrum Sensing for Cognitive Radio: State-of-the-Art and Recent Advances* - in Signal Processing Magazine, IEEE, (Vol. 29, Issue 3), pp. 101-116, May 2012

[5] Ghasemi, A.; Sousa, E. S.; *Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments* - New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium, pp.131-136, Baltimore, MD, USA, Nov. 2005.

[6] Pratas, N.; Marchetti, N.; Rodrigues, A.; Prasad, R.; *Capacity limits introduced by data fusion on cooperative spectrum sensing using correlated environments* - in 8th International Conference on Communications (COMM '10) pp. 497-502, June 2010.

[7] Sun, C.; Zhang, W.; Letaief, K. B.; *Cluster-Based Cooperative Spectrum Sensing in Cognitive Radio Systems* - Communications, 2007. ICC '07. IEEE International Conference on, pp. 2511-2515, June 2007.

[8] De Nardis, L.; Domenicali, D.; Di Benedetto, M.-G.; *Clustered Hybrid Energy-aware cooperative Spectrum Sensing (CHESS)* - IEEE Cognitive Radio Oriented Wireless Networks and Communications 2009 (CROWNCOM '09), June 22-24 2009, pp.1-6, Hannover, Germany.

[9] Wu, Q.; Ding, G.; Wang, J.; Yao, Yu-D.; *Spatial-Temporal Opportunity Detection for Spectrum-Heterogeneous Cognitive Radio Networks: Two-Dimensional Sensing* - in Wireless Communications, IEEE Transactions on (Vol.12, Issue 2), Feb.2013, pp. 516-526.

[10] Selen Y.; Tullberg H.; Kronander J.; *Sensor Selection for Cooperative Spectrum Sensing* - in New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 3rd IEEE Symposium on, 2008.

[11] Min, A. W.; Shin, K. G.; *Impact of mobility on spectrum sensing in cognitive radio networks* - in Proceedings of the 2009 ACM workshop on Cognitive radio networks (CoRoNet '09). pp. 13-18, New York, NY, USA, 2009.

[12] Arshad, K.; Moessner, K.; *Mobility driven energy detection based Spectrum Sensing framework of a Cognitive Radio* - in Proceedings of UKIWCS 2010, Delhi, India, Dec. 2010;

[13] Moran, P. A. P.; *Notes on Continuous Stochastic Phenomena* - in Biometrika 37 (1), pp. 1723, 1950.

[14] Urkowitz, H.; *Energy Detection of unknown deterministic signals* - Proc. IEEE, vol.LV pp. 523-531, Apr. 1967.

[15] De Nardis, L.; Guirao, M.-D.P.; *Mobility-aware design of cognitive radio networks: Challenges and opportunities* - in Cognitive Radio Oriented Wireless Networks & Communications (CROWNCOM), 2010 Proceedings of the Fifth International Conference on, pp. 1-5, Cannes, France, June 2010.

[16] De Nardis, L.; Di Benedetto, M.-G.; Tassetto, D.; Bovelli, S.; Akhtar, A.; Holland, O.; Thobaben, R; *Impact of mobility in cooperative spectrum sensing: Theory vs. simulation* - in Wireless Communication Systems (ISWCS), 2012 International Symposium on, pp. 416-420, 2012.

[17] Molisch, A.F. ; Greenstein, L.J.; Shafi, M.; *Propagation Issues for Cognitive Radio* - in Proceedings of the IEEE (Vol.97, Issue 5), May 2009, pp. 787-804.

[18] Jakes, W.C.; Editor (February 1, 1975), *Microwave Mobile Communications*, New York: John Wiley & Sons Inc.

[19] Camp, T.; Boleng, J.; Davies, V.; *A Survey of Mobility Models for Ad-hoc Networks research* in Wiley Wireless Communications and Mobile Computing, vol. 2, no. 2, pp. 483-502, 2002.

[20] Koepke, A.; Swigulski, M.; Wessel, K.; Willkomm, D.; Klein Haneveld, P.T.; Parker, T.E.V.; Visser, O.W.; Lichte, H.S.; Valentin, S.; *Simulating Wireless and Mobile Networks in OMNeT++: The MiXiM Vision.*