Cognitive Radio as Solution for Ground-Aerial Surveillance through WSN and UAV Infrastructure

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Abstract— **Intelligent collaborative environments, where heterogenous entities operate together in achieving common mission objectives have been increasingly adopted for monitoring and surveillance of interest areas and physical infrastructures. They can be assembled from multiple existing technologies ranging from wireless sensor networks (WSN), terrestrial remote operated vehicles (ROV) and unmanned aerial vehicles (UAV). In this context, we first introduce a multi-level system framework for multi-sensory robotic surveillance of critical infrastructure protection through communication, data acquisition and processing - MUROS. Leveraging a cognitive radio (CR) scheme is discussed as key point of the paper, arguing that by exploiting in an opportunistic fashion the time, frequency and spatial stream of the wireless environment, increased communication reliability can be achieved with positive impact on the availability and service level at each hierarchical level. The application of CR, given the heterogeneous nature of the application across multiple radio interfaces and protocols, stand outs as a novel and feasible research direction. We underline the advantages of this scheme within the constraints of a working scenario and define a simulation-based approach in order to validate our solution.**

I. Introduction

Dense instrumentation of the physical world, mainly through networks of cooperating objects [1] has lead to the emergence of the new intelligent environments paradigm [2]. In these types of scenarios, various autonomous fixed or mobile entities collaborate in order to assure achieving specific objectives, enhancing the human factor for dependable, safe and secure systems. One example of a relevant application has been BorderSense [18], leveraging multiple types of wireless sensor networks, including: multimedia and underground to build a full system for real-time border surveillance. At the top layer of the proposed system, lay unmanned autonomous aerial vehicles which act as high level sensory platforms for complex imaging and high data link communication capacity. This showcases the growing body of research at the interface between WSN and UAV [19]. It is argued that by exploiting the advantages of each platform, the individual drawbacks can be mitigated in achieving superior performance from the system as a whole. Not only critical applications can be enhanced through such approaches but rather the field can be extended towards other types of monitoring and surveillance scenarios in civil [20], commercial and industrial applications.

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Approaching such complex issues from a communication stand point, there is an increasing interest in the use of relatively small, flexible unmanned aerial vehicles (UAVs) that fly at lower altitude for providing relay services for mobile ad hoc networks with ground-based communication nodes. The UAV acts as a decode-and-forward relay, sending the messages from the co-channel users on the ground to some remote base station.

A number of different approaches have been proposed in the literature to address the performance of UAV-assisted communication networks. For example, in [3], a throughput maximization protocol for non-real time applications was proposed for a network with UAV relays in which the UAV first loads data from the source node and then flies to the destination node to deliver it. The authors in [4] investigated different metrics for ad hoc network connectivity and propose several approaches for improving the connectivity through deployment of a UAV. In [5], the authors considered a scenario in which multiple UAVs are deployed to relay data from isolated ground sensors to a base station, and an algorithm was proposed to maintain the connectivity of the links between the sensors and base station.

The work described above assumes that the ground nodes are static and that the UAV is configured with only a single communication channel, but given the benefits of employing multiple channels for communications, other authors have considered the advantages they offer for UAV-based platforms. A swarm of single antenna UAVs was used as a virtual antenna array to relay data from a fixed ad hoc network on the ground in [6]. A relay system with multi-antenna UAVs and multi-antenna mobile ground terminals was investigated in [7].

The system of air-ground communication is one of the most fundamental elements of the surveillance system proposed in this paper. In the last years, due to the increasing of the number of data applications for such communication, the demand to effectively use the limited frequency spectrum has increased. Given the limitations of the natural frequency spectrum, it is obvious that the current static frequency allocation schemes cannot meet the requirements of the air-to-ground bidirectional communication [8]. There are several proposed approaches to solve the drawbacks of static spectrum allocation, which is the major bottleneck for effective use of the limited spectrum, but the inefficiency in the spectrum usage is the new communication paradigm of

Dynamic Spectrum Access (DSA) [9], able to exploit wireless spectrum opportunities.

The key enabling technology of DSA is the Cognitive Radio (CR) technology that is built on a software-defined radio (SDR). SDR technology allows multimode, multi-band and/or multi-functional wireless devices that can be enhanced using software upgrades. Simply SDR is defined as "Radio in which some or all the physical layer functions are software defined" [10]. As component of SDR, CR is a part of the Adaptive Radio, radio in which communications systems have a means of monitoring their own performance and modifying their operating parameters to improve performance, and at its turn has as inner core the Intelligent Radio technology, which allows the cognitive radio to improve the ways in which it adapts to changes in performance and environment [11].

Therefore, CR is defined as an intelligent wireless communication system that is aware of its environment and uses this methodology to learn from the environment and adapt to statistical variations in the input stimuli. It provides the opportunity to address the static allocation of spectrum issue and offer a more flexible transition approach for the control of an air-ground radio system.

In this paper, a cognitive radio (CR) scheme is discussed as key point in exploiting in optimal way the time, frequency and spatial stream of the wireless environment, with positive impact on the communication performance in a multi-level monitoring and surveillance framework. The rest of the paper is structured as follows. Section 2 describes a new framework and system architecture for heterogeneous multi-level monitoring based on WSN and UAV, focusing on the communication as background for cognitive radio implementation and leveraging its advantages. Cooperative spectrum sensing methods for CR within this scenario are discussed in Section 3. As a means to evaluate and test the proposed approach, methods for implementation of a CR testbed with this goal, are given in Section 4. Final remarks and outlook on future work are handled in Section 5.

II. System Architecture

A. MUROS Framework

We first introduce the MUROS framework [21] with the purpose to develop a surveillance and monitoring system with unmanned aerial platforms for monitoring, preventing and mitigating incidents which have an impact on critical infrastructure such as transport routes for oil products, railways, power lines, highways etc. The main components of system with unmanned aerial vehicles are illustrated in Figure 1:

- GCS (ground control station): data and control management;
- GDT (ground data transmission): communication node between GCS and UAV;
- Launcher: launching mechanism for the UAV;
- Sensors: components of the deployable multisensory network;
- UAV: aerial platform which gathers data from sensors and payload.

The originality and innovative character of the UAV implementation within the framework are given by the following elements:

- Automatic launch and landing of the aerial vehicle;
- Solutions for collecting and transmitting high resolution video images to long distances;
- Correlate information collected by the aerial vehicle with the ground sensors network;
- Command center with a flexible architecture which shall allow the possibility to coordinate land and aerial sensors systems;
- Ensure the security of the aerial vehicle by implementing specific recovery algorithms in case of damage.

The main idea is to design a flexible multisensory robotic system capable of monitoring critical infrastructure in a semi-autonomous manner. As it can be seen, the system is composed from:

- a fixed part:
  - ground station;
  - multisensory network.
- a mobile part (the unmanned aerial vehicle – UAV).

The UAV monitors a surveillance area, collects and process data through on-board sensors and from the ground-based sensorial network communicates to and receives instructions from the ground control station. Depending on the particular module, novel developments include control algorithms for trajectory/path tracking, obstacle avoidance/anti-grounding and anti-stall constraints, terrain mapping and coverage, fault tolerant control. Also, acquisition algorithms from UAV and sensorial network, communication algorithms, data processing algorithms such as feature extraction and image analysis are developed.

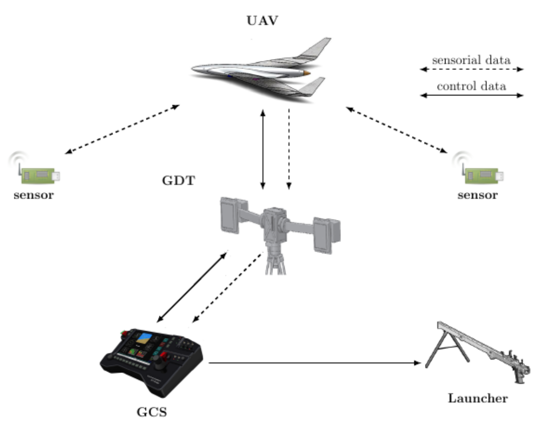

Figure 1. System Components at the UAV Level

Figure 2 showcases the conceptual system architecture on a broader scale for WSN-UAV collaboration in common monitoring and surveillance.

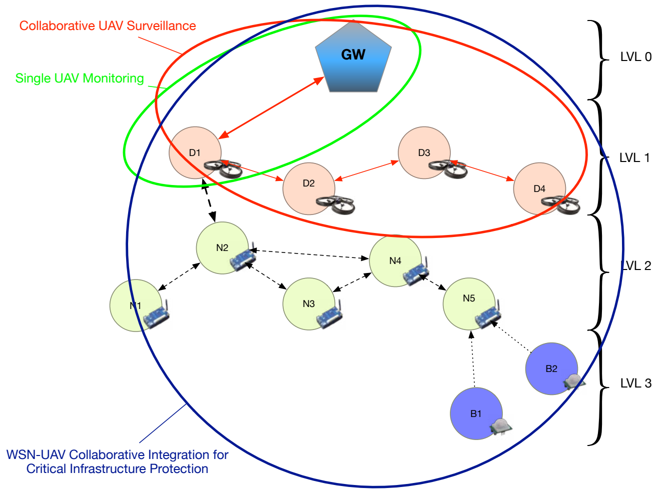

Figure 2. Heterogenous Multi-level Architecture for Communication, Data Acquisition and Processing – MUROS

The first design option was to employ a multi-level architecture which is modular, scalable and adaptable to the constraints of each particular application. At level 0 we include the central gateway (GW) as the ultimate data collection and control entity and the main point for human operator actions. Level 1 is represented by mobile airborne platforms with advanced communication and sensing e.g. photo/video. These can be either operator-controlled or function autonomously given a mission plan and objectives, support for multiple cooperative operation with other UAVs is included. Level 2 covers the ground deployed WSN with scalar sensors e.g. temperature, humidity, magnetic, luminosity, etc., operating in a low power radio mesh network in an energy efficient manner. At the lowest level, level 3, low-cost binary detectors have been included for specific use cases like intrusion detection and target tracking. Based on this four level architecture, three operation modes have been defined, in increasing order of complexity. First, we define the conventional single UAV monitoring of a target area through levels 0 and 1. This extends to multiple UAV collaborative surveillance, when a larger area has to be covered effectively or with different types of airborne sensors and communication links. Finally the most advanced use case encompasses all level from 0 to 3 in a unified platform for WSN-UAV integration.

Elaborating on the ground sensor network, with mesh capabilities and low power operation, we define three functional modes:

- normal/low rate data acquisition with low duty cycle 1-2% of the sensor nodes; data reaches the sensor network sink or they are periodically collected by the UAV and/or mobile terrestrial robotic platforms in the case of partitioned networks; the UAV is operated on demand, given high mission cost and communication link in non-critical scenarios;

- alert level, where certain predefined events are detected through the significant variation of a monitored parameter or by correlation among the reported values of the various on-board sensors; the data acquisition rate grows for a limited timeframe in the interest area, until the system is reset from a superior decision level;

- alarm level, the event is confirmed and continuous monitoring is initiated; this case maximizes the probability of communication channel congestion given the high number of nodes transmitting simultaneously and represents a solid argument in favor of a CR scheme at the communication layer.

B. Communication structure description as basis for CR scheme

Ground stations assure both data collection and event detection. In the basic set-up, their placement is fixed and are linked through a mesh network for both configuration and collaborative information processing towards critical event detection/alerting. The events are reported under real-time constraints. The UAV enhances system functionality by implementing relaying and a communication backchannel.

Around each ground station, considered as Primary User (PU) in the CR scheme, an ad-hoc CR network is formed with mobile platforms, implemented as ROVs, having the role of transmitting data from the PU towards the UAV. The UAV follows a known route and thus the mobile platforms place themselves as to maximize coverage in the interest area. Even if there is a way to establish a direct PU-UAV link, its role is only to send and receive calibration messages, confirming the degree of confidence for the data transmitted by the intermediary CR stations.

Figures 3 and 4 highlight the fundamental approach for CR communication in the multi-level monitoring framework. First an use case is suggested based on a network of CR-equipped ground stations, relaying messages to an aerial UAV platform, following a predefined route for data collection. CR is essential for allowing the implementation of real-time constrains on event detection and/or target tracking, as it leads to efficient usage of the communication channel. The distributed nature of the communication in the CR scheme is shown next.

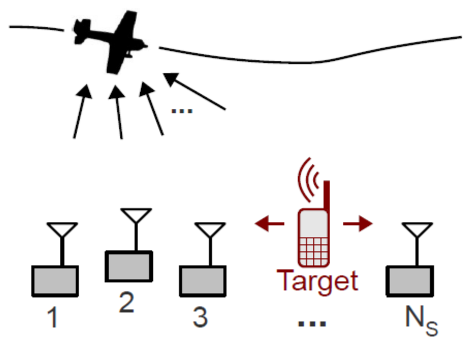

Figure 3. Use Case for CR Operation for WSN-UAV Monitoring

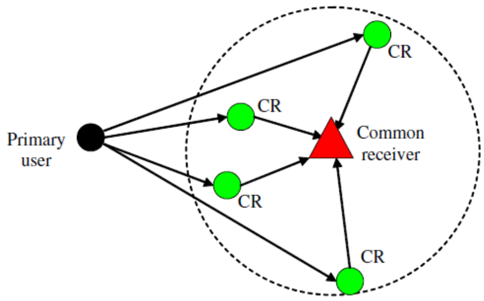

Figure 4. Communication Subsystem Schematic

We applied the CR based collaborative spectrum sensing in a UAV scenario, where the UAV serves as a natural collection point for the distributed measurements. The ground nodes in our scheme sense the spectrum in parallel. Each sensor node transmits measurements when the UAV is in the air in a certain zone around the ground station.

An additional function of the UAV is to assure the decoding of the received data sets. By means of the proposed weighted CR scheme, frequencies associated with higher power signals receive processing priority. Moreover, information detected from such a priority signal is used to enhance the precision for the decoding of the information stemming from other sensors.

The proposed scenario assumes the improvement the performance of the communication system. The UAV has sufficient on-board computing resources to carry out additional processing, such as filtering out invalid results or assigning weights on the decoded data.

Following the approach from [12], the two main directions for application of the collaborative decoding have been identified, namely sensor-diversity and measurement-delivery variation. The former is useful whenever the is a significant difference between signal strengths coming from two or more ground stations at a common receiver. In this way the decoding carried out for the stronger signal(s) can be effectively be applied to improve the outcome of the decoding procedure for the weaker classified stations. The latter case account for the situation in which, at the UAV level, batches of different measurements are received. As these sets might have different sizes, dependant on the individual link characteristics at any given time and emitter-receiver pair, we can use the results from decoding the more significant larger sets upon the smaller ones, with the goal of increased accuracy.

III. Cooperative Spectrum Sensing Scheme for CR

The ultimate objective of the cognitive radio is to obtain the best available spectrum through cognitive capability and reconfigurability. Tasks required for adaptive operation are: Spectrum sensing, spectrum analysis, spectrum decision [13]. Once the operating spectrum band is determined, the communication can be performed over this spectrum band. However, since the radio environment changes over time, space, and frequency, the cognitive radio device should keep track of the changes of the radio environment. If the current spectrum band in use becomes unavailable, the spectrum mobility function is performed to provide a seamless transmission. Any environmental change during the transmission, such as primary user appearance, user movement, or traffic variation, can trigger this adjustment. The main tasks of CR in cognitive cycle are summarized in Figure 5.

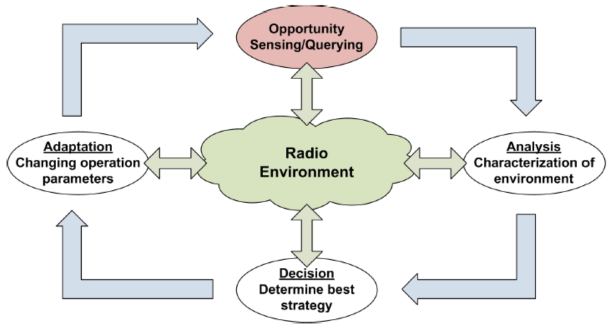

Figure 5. Simplified cognitive cycle (after [14])

In this paper we mainly focus on the spectrum sensing since it is the most crucial part of the cognitive cycle. One of the great challenges of implementing spectrum sensing is the hidden terminal problem, which occurs when the cognitive radio is shadowed, while a primary user (PU) is operating in the vicinity. In order to deal with this problem, multiple cognitive users can cooperate to conduct spectrum sensing.

Let consider a cognitive radio network (CRN) composed of a primary user (PU), N cognitive radios (secondary users SU) CR_i (i=1,..,N) and a common receiver.. The common receiver functions as a base station (BS) which manages the cognitive radio network and all associated N cognitive radios. We assume that each CR performs local spectrum sensing independently, by deciding between the following two hypotheses [15]:

H_0: $y_i(t) = n_i(t)$, *if PU is absent*

H_1: $y_i(t) = h_i s(t) + n_i(t)$, *if PU is present* (1)

where $y_i(t)$ is the observed signal at the i^{th} CR, $s(t)$ is the PU signal assumed to be with zero mean and variance σ_s^2, $n_i(t)$ is the additive white Gaussian noise (AWGN) with zero mean and variance σ_n^2, and h_i is the complex channel gain of the sensing channel between the PU and the i^{th} cognitive radio.

In cooperative spectrum sensing (CSS), each cooperative partner makes a binary decision based on its local observation and then forwards one bit of the decision D_i (1 standing for the presence of the PU, 0 for the absence of the PU) to the common receiver through an error-free channel. The structure of centralized cooperative spectrum sensing in CR networks is shown in Figure 6.

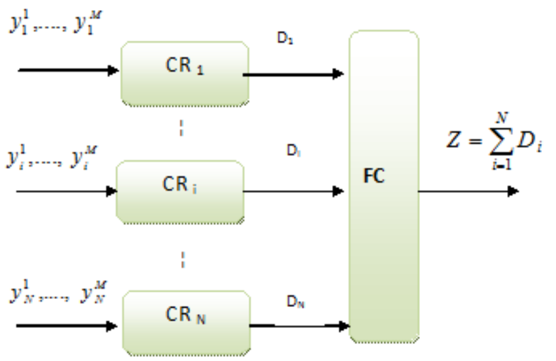

Figure 6. Centralized Cooperative Spectrum Sensing

The general process is as follows: first, every CR user executes local single-node detection independently and gets detection statistic y_i, second, the local dual-decision $D_i \in \{0,1\}$is obtained by comparing y_i with the detection threshold, and then, all CR users sent D_i to FC; the final decision is made according to AND, M rank and OR criteria [16]. At the common receiver, all 1-bit decisions are fused together according to logic rule

$$Z = \sum_{i=1}^{N} D_i \begin{cases} \geq n, H_1 \\ < n, H_0 \end{cases} \quad (2)$$

where H_0 and H_1 denote the inferences drawn by the common receiver that the PU signal is not transmitted or transmitted.

For the same false alarm needs, the detection probability of CSS is higher than single-node detection, i.e. in the ideal environment cooperative sensing is better than single-node detection. On the other hand, in many cases, every CR nodes are placed in different channel environment, so the detection performance of each user is not the same. A solution to avoid this drawback, due to the fact that even the same single node detection method is used, the detection probability of each node is not the same and consequently each CR user's detection results have different influence on the final decision is the cooperative spectrum sensing based on the weighting (CSSW) [17]. CSSW method implies screening nodes firstly from CR networks before all local decisions and weighted factors are sent to FC, and then the final information fusion is making by CR nodes obtained from nodes screening stage.

IV. Cognitive Radio Testbed for WSN-UAV Collaborative Monitoring

Subsequent step in implementing the CR scheme on a network of cooperating objects composed of WSN nodes, terrestrial mobile ROVs and UAVs is a customized testbed enabling research and development on various CR schemes and algorithms. A . The main components of such a system are identified as: PC-based simulation environment and toolchain, emulator hardware for radio frequency network, configurable RF front-ends and digital switches [22]. In customizing the system for the particular WSN-UAV scenario, appropriate bidirectional interfaces towards relevant platforms for WSN e.g. the Contiki/COOJA environment, or UAV, e.g. the USARSim virtual development environment for autonomous robotic platforms have to be provided. Among the notable advantages on such approach, one can list flexibility, ability to perform a vast array of experiments with minimal hardware and software costs due to the reconfigurable nature of the system. Including realistic channel effects, taken from previous real measurement or predefined channel models (Gaussian, Rayleigh, Riccian, etc.). Dynamic role assignment for various topologies can also enable scalable reconfiguration among primary users, cognitive intermediate radios and common receivers. In this way, experiments become repeatable under controlled conditions and provide a first step towards deployment in real world conditions. Hybrid structure among simulated and emulated CR and SDR nodes is controlled by the experiment designer and reflects a trade-off between experiment accuracy and speed. Once the testbed results become satisfactory under dynamic environment conditions, the next step is to deploy the system under realistic conditions outside the lab.

For the initial testing scenarios, the approach described in [23] is used. This begins with a basic two user scenario in which a UAV covers a target area and communicates with the ground stations, tasked at uploading raw or aggregated data toward the mobile aerial platform. Under fundamental assumption of constant UAV altitude, h_u, constant UAV speed, v_u, and where D is the distance among nodes, three possible scenarios have been highlighted for modeling communication performance [23]:

- $D \gg h_u$
- $D \ll h_u$
- $D = O(h_u)$

Among these three case, the first one leads to low SNR values given variable path loss and leading to an alternative behaviour of the UAV above each of the users. The second scenario concludes with the UAV following a tight pattern directly above the users, minimizing path loss given similar angle-of-arrival (AoA) of the ground stations. For equalizing uplink rates the third case assumes a symmetric trajectory centered around the midpoint of the two users. By means of the CR testbed these scenarios can be further investigated and extended to the desired multi-user ground-aerial environments.

V. Conclusion

Summarizing the paper, we have introduced a new framework and system architecture for multi-level heterogeneous monitoring and surveillance based on ground-aerial intelligent systems taking the form of wireless sensor networks (WSN) and unmanned aerial vehicles (UAVs). In order to increase the communication efficiency, a solution based on Cognitive Radio (CR) was proposed which shows promise given the specific requirements of the applications. Among their potential benefits, one can list: improving of the overall communication structure for increased availability and service level across the heterogeneous communication interfaces, reducing the effect of interferences and other link losses, better utilization of the existing spectrum and exploitation of the existing spectrum in a flexible way, increased security by mitigating for example denial of service (DoS) attacks and other forms of attacks.

The most prominent commercial application of a system implementation is linked to the automatic ground-aerial surveillance of pipeline infrastructures. Thus, by combining ground intrusion detection in a protected area along with event detection e.g. pipeline breach, with aerial monitoring by image collection and processing. At a higher decision level, data from all sources is fused for threat detection and implementing a decision support system for human operators which ultimately classify the situation and are able to dispatch intervention teams effectively in the concerned area.

Prospective work covers a pilot system implementation in a mixed simulated, emulated and real environment for subsystem level validation of the approached highlighted by this paper.

REFERENCES

[1] Marron, P.J., "Keynote: Are we ready to go large-scale? Challenges in the deployment and maintenance of heterogeneous networks of Cooperating Objects," Pervasive Computing and Communications Workshops (PERCOM Workshops), 2012 IEEE International Conference on , vol., no., pp.50,50, 19-23 March 2012.

[2] Augusto, J.C., Callaghan, V., Cook, D., Karneas, A., Satoh, I., "Intelligent Environments: a manifesto", Human-centric Computing and Information Sciences, 3:12, June 2013.

[3] C. Cheng, P. Hsiao, H. Kung, and D. Vlah, "Maximizing throughtput of UAV-relaying networks with the load-carry-anddeliver paradigm," in *Proc. IEEE WCNC 2007*, Mar. 2007, pp. 4417–4424.

[4] Z. Han, A. L. Swindlehurst, and K. J. R. Liu, "Optimization of MANET connectivity via smart deployment/movement of unmanned air vehicles," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3533–3546, Sep. 2009.

[5] E. P. de Freitas, T. Heimfarth, I. F. Netto, C. E. Lino, C. E. Pereira, A. M. Ferreira, F. R. Wagner, and T. Larsson, "UAV relay network to support WSN connectivity," in *Proc. IEEE ICUMT 2010*, Oct. 2010, pp. 309–314.

[6] R. Palat, A. Annamalau, and J. Reed, "Cooperative relaying for ad-hoc ground networks using swarm UAVs," in *Proc. IEEE MILCOM 2005*, Oct. 2005, pp. 1588–1594.

[7] P. Zhan, and A. L. Swindlehurst, "Optimization of UAV Heading for the Ground-to-Air Uplink" *IEEE Journal on Selected Areas in Communications, Vol.:30 , Iss.5*, 2012, pp. 993 – 1005

[8] G. Conte, M. Hempel, P. Rudol, D. Lundstrom, S. Duranti, M. Wzorek, and P. Doherty. High Accuracy Ground Target Geolocation Using Autonomous Micro Aerial Vehicle Platforms. In Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit, 2008.

[9] Chen, Zi Li; Wei, Nai Qi, Cognitive Radio as Enabling Technology for Dynamic Spectrum Access, Applied Mechanics and Materials — 2013, Volume 2560, Issue 347-350, pp. 1716-1719

[10] SDR forum page, Available on-line at - http://www.sdrforum.org/pages/documentLibrary/documents/SDRF-06-R-0011-V1_0_0.pdf

[11] J. Mitola III, Cognitive Radio Architecture: The Engineering Foundations of Radio XML, John Wiley & Sons, 2006

[12] H-C. Chen, H. T. Kung, D. Vlah, D.Hague, M. Muccio and B. Poland - Collaborative Compressive Spectrum Sensing in a UAV Environment, Paper 5.1, MILCOM, 2011

[13] Patil, K., R. Prasad and K. Skouby, "A Survey ofWorldwide Spectrum Occupancy Measurement Campaigns for Cognitive Radio", Proceeding of the International Conference on Devices and Communications (ICDeCom), pp. 1–5, February 2011

[14] H. B. Yilmaz. Cooperative spectrum sensing and radio environment map construction in cognitive radio networks, PhD thesis. Bogazici University, 2012

[15] I. F. Akyildiz, B. F. Lo, and R. Balakrishnan, "Cooperative spectrum sensing in cognitive radio networks: A survey", Physical Communication, 4, pp. 40–62, 2011

[16] Y. Li, S. Shen, and Q. Wang, "Study and Optimization of Cooperative Spectrum Sensing in OFDM Cognitive Radio Networks", International Journal of Computer Science Issues, Vol. 9, Issue 6, No 3, pp.172-176, 2012

[17] Y. Li, H. Huang, and F. Ye, "An Improved Cooperative Spectrum Sensing in Cognitive Radio", Journal of Computational Information Systems 8: 4, pp. 1399-1406, 2012

[18] Sun, Z., Wang, P., Vuran, M., Al-Rodhaan, M., Al-Dhelaan A., and Akyildiz, I. 2011. "BorderSense: Border patrol through advanced wireless sensor networks.", Ad Hoc Netw. 9, 3 (May 2011), 468-477.

[19] Dorling, K.; Messier, G.G.; Magierowski, S.; Valentin, S., "Improving aerially deployed sensor networks using cooperative communications," Communications (ICC), 2012 IEEE International Conference on , vol., no., pp.376,380, 10-15 June 2012

[20] Stamatescu, G.; Sgarciu, V., "Evaluation of wireless sensor network monitoring for indoor spaces," Instrumentation & Measurement, Sensor Network and Automation (IMSNA), 2012 International Symposium on , vol.1, no., pp.107,111, 25-28 Aug. 2012

[21] MUROS Project, Romanian Space Agency Competition C2, 2013-2016, Available on-line: http://imtt.pub.ro/MUROS3/muros

[22] Ding, L., Sagduyu, Y., Yackoscki, J., Azimi-Sadjadi, B., Li, J., Levy, R., Melodia, T., "High Fidelity Wireless Network Evaluation for Heterogenous Cognitive Radio Networks", Proc. SPIE 8385, Sensors and Systems for Space Applications V, 83850R, May 2012.

[23] Feng Jiang; Swindlehurst, AL., "Optimization of UAV Heading for the Ground-to-Air Uplink," Selected Areas in Communications, IEEE Journal on , vol.30, no.5, pp.993,1005, June 2012.