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

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Abstract—Intelligent collaborative environments, where heterogeneous 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.

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:

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

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.
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 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.

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) $CR_i$ ($i=1,\ldots,N$) 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]:

$$H_0: y_i(t) = n_i(t), \text{ if PU is absent}$$
$$H_1: y_i(t) = h_i s(t) + n_i(t), \text{ if PU is present}$$

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 $\sigma_s^2$, $n_i(t)$ is the additive white Gaussian noise (AWGN) with zero mean and variance $\sigma_n^2$, 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.
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Among the notable advantages on such approach, one can list

for autonomous robotic platforms have to be provided.

platforms for WSN e.g. the Contiki/COOJA environment, or

scenario, appropriate bidirectional interfaces towards relevant

customizing the system for the particular WSN -UAV

are identified as: PC-based simulation environment and

and algorithms. A . The main components of such a system

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network of cooperating objects composed of WSN nodes,

configurable RF front-ends and digital switches [22]. In

receiver that the PU signal is not transmitted or transmitted.

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

\[
Z = \sum_{i=1}^{N} D_i \left\{ \begin{array}{ll}
\geq n, & H_1 \\
< n, & H_0
\end{array} \right.
\]

(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
(CCSSW) [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-
airial 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


