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# Integrating cognitive radio with unmanned aerial vehicles

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Dissertação de Mestrado do Programa Pós-Graduação em Ciências de Computação e Matemática Computacional (PPG-CCMC)

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**Guilherme Marcel Dias Santana**

# Integrando rádio cognitivo a veículos aéreos não tripulados

Dissertação apresentada ao Instituto de Ciências Matemáticas e de Computação – ICMC-USP, como parte dos requisitos para obtenção do título de Mestre em Ciências – Ciências de Computação e Matemática Computacional. *VERSÃO REVISADA*

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*In memory of my brother,*
*Donizzeti Dias Santana Júnior,*
*and my grandparents,*
*Antônio Carmelito Santana and Conceição Maria de Jesus,*
*João Dias Santana and Maria Gonçalves Santana.*

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*"The essence of knowledge is, having it, to apply it."*
*(Confucius)*

# RESUMO

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Um Veículo Aéreo Não Tripulado (VANT) é uma aeronave que opera sem um humano a bordo, podendo voar de forma autônoma ou sendo pilotada remotamente. Devido à ausência de um piloto, os VANTs necessitam de tecnologias não só para que possam voar de forma autônoma, mas também de tecnologias de comunicação robustas que permitam a eles se comunicarem, seja com estações de base, controladores de tráfego aéreo, computadores, dispositivos, ou até mesmo com outros VANTs. Tradicionalmente, os VANTs operam em bandas de espectro não licenciadas, concorrendo com o crescente número de dispositivos móveis e com outras redes sem fio. Esse uso pode levar a interferências que afetam a comunicação dos VANTs e, além disso, pode levá-los a enfrentar o problema da superlotação de espectro. Rádio Cognitivo (RC) apresenta-se como uma tecnologia promissora para a solução desses problemas. RC permite uma comunicação sem fio inteligente que, em vez de usar uma frequência de transmissão definida no hardware, utiliza software para esta definição. Isto possibilita ao RC adaptar de forma inteligente sua frequência de transmissão, utilizando canais de transmissão livres e/ou escolhendo-os de acordo com os requisitos da aplicação. A integração de VANTs e RC pode ser empregada em missões nas quais VANTs convencionais enfrentam limitações devido a problemas de comunicação. Além disso, RC é considerado um facilitador chave para a implantação satisfatória de paradigmas de comunicação que demandam alta conectividade, tais como Cidades Inteligentes, 5G, Internet das Coisas (IoT) e, consequentemente, Internet das Coisas Voadoras (IoFT). Apesar de RC e VANTs serem áreas de pesquisa bem estabelecidas, a integração dos dois é pouco explorada na literatura. Portanto, este trabalho contribui nos avanços da integração de RC a um VANT. Neste trabalho foram identificadas as lacunas e oportundiades, bem como os desafios na área. Além disso, foram definidas as tecnologias de RC, bem como a integração do mesmo em uma missão real de coleta de dados, obtendo resultados marcantes em relação aos da literatura, como no caso de algoritmos de Aprendizagem de Máquina, tradicionalmente empregados com dados simulados, mas que demonstraram limitação quando utilizados com dados reais coletados neste trabalho.

**Palavras-chave:** Rádio cognitivo, Veículos aéreos não tripulados, Rádio definido por software, 5G, Internet das coisas voadoras.

# ABSTRACT

SANTANA, G. M. D. **Integrating cognitive radio with unmanned aerial vehicles**. 2021. 89 p. Dissertação (Mestrado em Ciências – Ciências de Computação e Matemática Computacional) – Instituto de Ciências Matemáticas e de Computação, Universidade de São Paulo, São Carlos – SP, 2021.

An Unmanned Aerial Vehicle (UAV) is an aircraft that operates without a human on-board and can be flown autonomously or controlled remotely. Due to its unmanned operation, UAVs need technologies so they can not only fly autonomously, but also communicate with base stations, flight controllers, computers, devices or even other UAVs. Traditionally, UAVs operate within unlicensed spectrum bands, competing against the increasing number of mobile devices and other wireless networks. This use could lead to interference that affect UAV's communication and problems with overcrowded spectrum. Cognitive Radio (CR) presents itself as a promising technology to solve these problems. CR provides a smart wireless communication which, instead of using a transmission frequency defined in the hardware, uses software defined radio. This allows CR to adapt its transmission frequency in a smart way, using free transmission channels and/or choosing them accordingly with the application's requirements. The combination of UAVs and CR can be used in missions where the conventional UAVs face limitations due to communication problems. Moreover, CR is considered a key enabler for adequately deploying communication paradigms that require high connectivity, such as Smart Cities, 5G, Internet of Things (IoT) and, thus, Internet of Flying Things (IoFT). Though both CR and UAVs are well-established fields of research, the combination of these two elements is little explored in literature. Therefore, this work identifies gaps and opportunities, as well as challenges on the field. Furthermore, this work contributes to the progress regarding the integration of CR and UAVs. To do so, this work presents the definition of CR technologies, as well as their integration on a real mission of data collection. This work's results differ to the others on the literature in terms of, for example, highlighting the limitation in real scenario of traditionally deployed Machine Learning algorithms using simulated data on the field.

**Keywords:** Cognitive radio, Unmanned aerial vehicles, Software defined radio, 5G, Internet of flying things.

# LIST OF FIGURES

# LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ACM | *Association for Computing Machinery* |
| AR | *Amateur Radio* |
| C4ISR | Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance |
| CR | *Cognitive Radio* |
| DSA | *Dynamic Spectrum Access* |
| ED | *Energy Detector* |
| FANETs | *Flying Ad-hoc Networks* |
| FPGA | Field Programmable Gate Array |
| HMM | *Hidden Markov Model* |
| IEEE | *Institute of Electrical and Electronics Engineers* |
| IoFT | *Internet of Flying Things* |
| IoT | *Internet of Things* |
| ISM | *industrial, scientific and medical* |
| ISR | Intelligence, Surveillance and Reconnaissance |
| LTE | *Long-Term Evolution* |
| MANETs | *Mobile Ad-hoc Networks* |
| MP | *Mobile Phone* |
| PU | *Primary User* |
| SDN | *Software Defined Networking* |
| SDR | *Software Defined Radio* |
| TAG | *Trajectory Aware Geographical* |
| TRB | *Transportation Research Board* |
| UAS | *Unmanned Aircraft System* |
| UAV | *Unmanned Aerial Vehicle* |
| USRP | *Universal Software Radio Peripheral* |
| VANETs | *Vehicular Ad-hoc Networks* |
| WARP | *Wireless Open-Access Research Platform* |

# CONTENTS

CHAPTER

1

# INTRODUCTION

## 1.1 Contextualisation

An *Unmanned Aerial Vehicle* (UAV), also known as drone, is an aircraft without the concept of passengers or passengers on board. Thus, the term "unmanned" implies a total absence of humans within the aircraft (VALAVANIS; VACHTSEVANOS, 2015). A set of hardware and software allows the flight to be pre-programmed before take-off, and that is automatic and stable (AUSTIN, 2010).

Although UAVs were initially designed for military action, strong technological advances have made them suitable for different applications. These applications include cinema, amateur photography and filming, people and environment monitoring, traffic control, and disaster recovery (PIRES *et al.*, 2016; ARNOSTI; PIRES; BRANCO, 2017).

Due to the absence of a pilot, the UAVs need not only stability and navigation control technologies, but also robust, effective, and secure communication technologies that enable them to communicate with base stations, air traffic controllers, other UAVs, or other devices and computers (VALAVANIS; VACHTSEVANOS, 2015).

Also, while performing their missions, the UAVs may work within an *Internet of Things* (IoT) (GERSHENFELD; KRIKORIAN; COHEN, 2004) context when equipped with IoT devices. Herewith, the UAVs will form an innovative IoT platform operating in the skies, thus being part of a new concept known as the *Internet of Flying Things* (IoFT) (PIGATTO *et al.*, 2018). To perform this role satisfactorily, the UAVs need high data-rate transmission and low latency. They need to support instantaneous and real-time communication, and offer access to high resolution files (e.g., videos and high definition images), even if they are in an overcrowded area. Hence, 5G networks are considered a key enabler for the IoT and the IoFT. 5G networks would not only provide the UAVs with the necessary IoT requirements, but also supply coverage at high altitudes. 5G networks may also support remote change and planning of flight routes, thus helping them avoid collisions with other UAVs (MOTLAGH; BAGAA; TALEB, 2017).

Despite the need for more robust and secure communication, the UAVs traditionally operate within unlicensed spectrum bands (i.e., open/free spectrum), such as IEEE S-Band, IEEE L-Band, and *industrial, scientific and medical* (ISM) radio bands, fixedly defined in their hardware. Hence, the UAVs increasingly face competition from the growing number of mobile devices (e.g., smartphones and tablets), operating within other wireless networks (e.g., WiFi and bluetooth) that use the same spectrum bands. Besides interfering the UAVs communications, this competition may lead to the problem of spectrum scarcity and security-related problems (SALEEM; REHMANI; ZEADALLY, 2015). In this context, *Cognitive Radio* (CR) emerges as a promising technology to solve these issues by enabling *Dynamic Spectrum Access* (DSA) (REYES; GELLERMAN; KAABOUCH, 2015).

Proposed by Mitola (MITOLA, 2000), CR is a smart wireless communication implemented in a *Software Defined Radio* (SDR). An SDR sets its transmission frequency in software rather than in hardware, this allows the CR to intelligently switch to different channels. To switch channels, CR senses the radio spectrum environment around it and adapts accordingly to increase reliability and efficient spectrum use (REYES; GELLERMAN; KAABOUCH, 2015). Furthermore, CR is considered a key network enabler for 5G in emerging IoT applications (AKPAKWU *et al.*, 2018).

Some features would allow CR based UAVs to perform in situations where traditional UAVs face limitations or are often subject to being hacked.

1. **Reduced energy consumption and delay:** The overcrowding of unlicensed radio spectrum bands results in higher packet loss due to interference. Because of the need to retransmit these packets, the UAVs consume more energy and present a longer communication delay. With CR, the UAV could switch to a free channel when it detects that it is in an overcrowded channel. Thus, packet loss is reduced, therefore retransmissions are also reduced, causing the UAVs to increase energy efficiency and decrease communication delay.

2. **Opportunistic spectrum use based on application requirements:** Multimedia applications demand higher data rate for data delivery, but tolerate packet loss. On the other hand, file transmission tolerates delay, but not packet loss. CR based UAVs may opportunistically use spectrum bands based on the application requirements, switching channels according to what is being transmitted.

3. **Multiple UAVs in the same area:** With CR, multiple UAVs may be deployed in the same area using different spectrum bands, thus reducing the interference among them and increasing overall network performance.

4. **Security:** CR does not suffer the effects of some conventional attacks. For example, in the case of a jamming attack, CR senses the current channel as being overcrowded and switches to an available channel.

Examples of such applications are forest fire monitoring (BARRADO *et al.*, 2010), disaster management (QUARITSCH *et al.*, 2010; GHAFOOR *et al.*, 2014), crop monitoring (VALENTE *et al.*, 2011; HERWITZ *et al.*, 2004; ZARCO-TEJADA *et al.*, 2008), commercial drones (The Institute, 2018), traffic surveillance (KANISTRAS *et al.*, 2013), and border patrolling (SUN *et al.*, 2011).

Moreover, CR alongside 5G would permit UAVs to work in an IoFT role within an IoT context. This would fulfil the increasingly growth of applications requiring highly connected devices, such as Smart Cities (CHOURABI *et al.*, 2012).

However, although UAVs and CR are well established research fields, the integration between the two is fairly unexplored (SALEEM; REHMANI; ZEADALLY, 2015), with only one CR-based UAV real experiment in the literature (SKLIVANITIS *et al.*, 2018). Many issues remain open, such as the impact of the UAVs mobility on CR and the definition of hardware compatible with both. These open issues allow new research opportunities and advances in the state-of-the-art.

## 1.2 Motivation

The motivation for CR-based UAVs is detailed in the following sections.

### *1.2.1 Spectrum scarcity*

Although there is a massive growth of wireless connected devices, most of the radio spectrum is under-utilised. Because of the fixed spectrum allocation policy, a big portion of the radio spectrum is reserved to sporadic PUs, while other spectrum portions are overloaded, such as Wi-Fi and mobile bands. Moreover, the UAVs traditionally operate within unlicensed spectrum bands (i.e., open/free spectrum), such as IEEE S-Band, IEEE L-Band, and ISM, fixedly defined in their hardware, under the same fixed spectrum allocation policy (THOMAS; MENON, 2017).

In this context, CR emerges as a promising technology to solve these issues by enabling DSA (REYES; GELLERMAN; KAABOUCH, 2015). CR-based UAVs are able to select idle spectrum bands for communicating. Thus, the UAV overall communication quality increases when using CR, especially in overcrowded areas.

### 1.2.2 Application requirements

UAVs may often be deployed in missions where they are expected to broadcast live video and to send high definition pictures to the base station. However, live stream broadcast tolerate packet loss, but require a high date rate for the timely data delivery. Sending high definition pictures is the opposite operation, as the UAV may need a low data rate with no packet loss tolerance, but with delay tolerance (SALEEM; REHMANI; ZEADALLY, 2015).

While traditional UAVs may face this problem, CR-based UAVs may easily deal with it. CR-based UAVs may change their communication frequency accordingly to application requirements. Thus, an UAV equipped with CR technology may be live streaming video and switch to a low bandwidth to send a large file when required. This feature not only optimises the overall network performance of CR-based UAVs, but it also opens new application opportunities for these aircraft.

### 1.2.3 Security

Communication security is critically important for UAVs. These aircraft are also considered critical systems, a security issue, which can be used to manage confidential information, thus in a UAV may often represent a serious safety issue. Some conventional attacks, such as jamming and location spoofing (sometimes referred to as GPS spoofing or GNSS spoofing), could lead the base station to lose the UAV. This problem is particularly evident in overcrowded or hostile areas.

Jamming is an attack in the physical layer which causes a high interference to a spectrum band by overloading it. It may provoke the attacked devices to present an excessive energy consumption due to package retransmission, or even interrupt its communication channel (PIGATTO *et al.*, 2018). When a CR is under a jamming attack, it simply understand that spectrum band as being busy or overcrowded, and then it switches its transmission to a new channel, thus avoiding the attack.

Location spoofing attacks also happen in the physical layer and they have become more frequent. It happens when an attacker uses a signal that is stronger than and mimics the attributes of a genuine location satellite signal to spoof the receiver (PIGATTO *et al.*, 2018). By using a location spoofing attack, attackers may capture UAVs and/or take control of their flight path. Such attacks have become easy to launch (HOSSEINI; MATOLAK, 2017). However, location spoofing attacks are much more complex to be executed to CR devices. In (ZENG; RAMESH; YANG, 2014), the authors provide some strategies for spoofing attack detection and countermeasure solutions in CR networks.

Hence, UAVs may benefit from CR technology security. Conventional jamming and location spoofing strategies may be easily avoided by CR. These attacks are only possible to CR when the attacker is also using a CR with different and specific strategies, therefore attacking a

CR device is a more complex problem than attacking conventional wireless devices.

### 1.2.4 Energy efficiency

Although CR devices may represent a computational overload to UAVs, they may be capable of actually reducing energy consumption to these aircraft. Because the UAVs operate in overcrowded spectrum bands, they are susceptible to a high number of loss, thus increasing packet retransmission. The energy consumed for packet retransmission may be greatly reduced when a UAV is equipped with a CR.

In (LI *et al.*, 2010), the authors proposed a method to maximise energy efficiency based on a joint optimisation with both medium access control (MAC) and physical layers, considering CR networks. In their scenario, a CR user senses different channels simultaneously and uses some idle ones for data transmission. The authors showed that, the more channels the CR device is able to use, more efficient is its bits/joule ratio throughput. The data rate also increased with the number of channels used.

So, this work contributes by identifying, characterising, developing and implementing a low-cost CR-based UAV testbed ready for experimentation in the field. This work will also point out gaps that may be explored for a optimum integration between CR and UAVs.

## 1.3 Objectives

This work has a different focus related to the works involving UAVs and CR. Typically, those works present theoretical analysis or computational simulations, with a paucity of real missions with CR-based UAVs.

Therefore, the main objective of this one is to integrate a UAV to the CR technology. This aircraft is able to choose autonomously the spectrum band for communication. It serves as a platform for the development of real experiments involving CR-based UAVs.

In addition, part of the objective of this work is the analysis of transmission methods, spectrum sharing and spectrum mobility in CR in the literature. This evaluation was carried out with a focus on validating which methods fulfil the energy and physical space constraints of UAVs. It also aims at improving the overall communication performance and security of UAVs.

## 1.4 Text Organisation

This paper is organised as follows: In Chapter 2 some background information about CR and UAVs is given, and a systematic review of the field is presented in Chapter 3. The experiments performed, including its details on the methods that were used and results are given in Chapter 4. Finally, conclusions are discussed in Chapter 5.

CHAPTER

2

# BACKGROUND

## 2.1 Chapter Overview

This section presents some background information needed to understand this work. First, it gives a brief description of the concepts related to CR and its operation. Second, it gives an overview of UAVs. Finally, it discusses the main aspects regarding CR-based UAVs.

## 2.2 Cognitive Radio

The European Telecommunications Standards Institute (ETSI) defines CR as "radio, which has the following capabilities: to obtain the knowledge of radio operational environment and established policies and to monitor usage patterns and users' needs; to dynamically and autonomously adjust its operational parameters and protocols according to this knowledge in order to achieve predefined objectives, e.g. more efficient utilisation of spectrum; and to learn from the results of its actions in order to further improve its performance" (European Telecommunications Standards Institute, 2018).

CR is also able to operate as a secondary user (SU) within a spectrum band of a licensed user or primary user (PU). A secondary user may be defined as a user who has lower priority in a given spectrum band. In (BALDINI *et al.*, 2012) and (AKPAKWU *et al.*, 2018), CR is described as an intelligent SDR with the following components:

1. spectrum sensing: identifies available spectrum and detects PUs when operating in a licensed band;

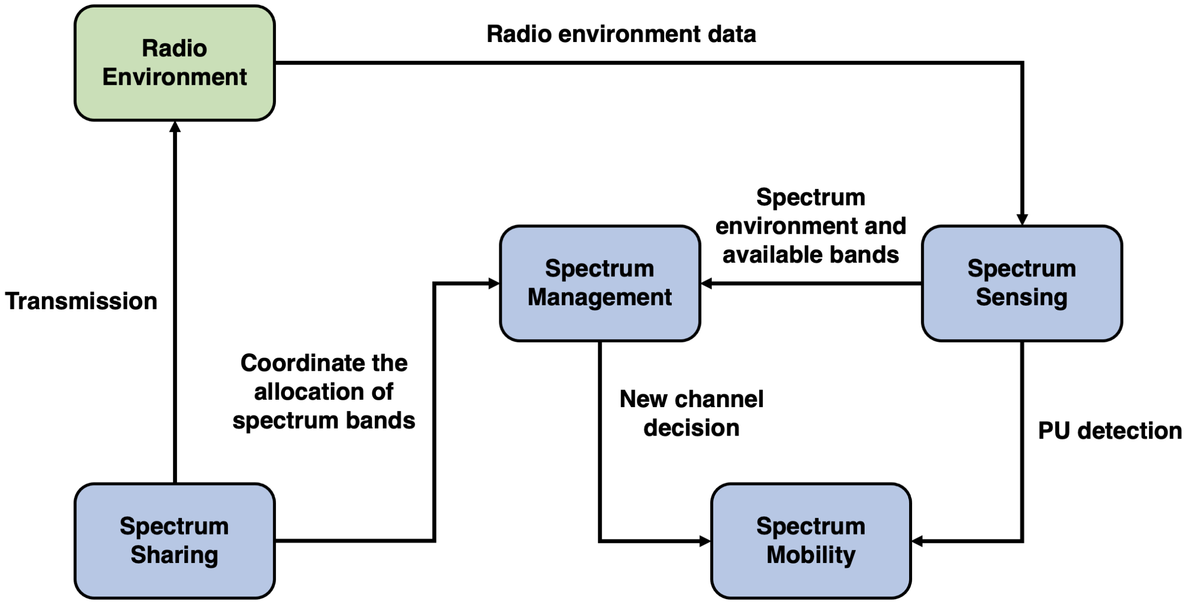
2. spectrum management: selects the best available channel;

3. spectrum sharing: coordinates accessibility to the available channel with other users;

4. spectrum mobility: vacates the channel when a PU arrives.

Figure 1 shows the interaction among the CR components. First, the spectrum sensing component collects data from the radio environment and keeps sending the sensed radio data to spectrum management component. Also, it informs spectrum mobility component when a PU is detected and a spectrum handover has to be executed. Spectrum management component sends the best available channel to spectrum mobility component, so a new channel is used when the current channel has to be vacated. Finally, the spectrum sharing component communicates with the radio environment to coo-handover coordinate the allocation of spectrum bands.

Figure 1 – The interaction among CR components.



Source: the author (SANTANA; CRISTO; BRANCO, 2021).

In practice, CR consists of a hardware associated with an intelligent software. Usually, the hardware consists of a radio platform, generally an SDR, and a computational platform. Most computational platforms used for CR applications are single-board computers, such as the ODROID (Hardkernel Co., Ltd., 2018), the Raspberry Pi (Raspberry Pi Foundation, 2018), and the BeagleBoard (Texas Instruments, 2018). The *Universal Software Radio Peripheral* (USRP) from Ettus Research (RESEARCH, 2018) and the *Wireless Open-Access Research Platform* (WARP) from Rice University are both SDRs and the most common radio platforms used in CR (UNIVERSITY, 2018; YOUNG; BOSTIAN, 2013).

Figure 2 shows one of the latest available SDR hardware: the USRP X310 by Ettus Research. It has a technology able to provide a simulation of full-duplex wireless communication within a frequency range starting from 50 MHz varying up to 6 GHz. Its architecture offers compatibility with a variety of softwares and frameworks, such as C++, Python, GNU Radio, Amarisoft LTE 100, OpenBTS, etc.

Figure 2 – USRP X310 by Ettus Research. Its price is currently U$5,290.00.

Source: (RESEARCH, 2018)

## 2.3 Unmanned Aerial Vehicles

The term UAV usually refers to a different types of aircraft, such as fixed-wing aircraft, rotary-wing aircraft, quadcopters, and even airships (TRINDADE *et al.*, 2010; AUSTIN, 2010). Moreover, UAVs are described with different terms, such as drones. These terms vary according to the research field, often describing the same thing though (VALAVANIS; VACHTSEVANOS, 2015). For the purpose of this work, UAV is defined as an aerial vehicle, with an embedded computer platform, capable of flying with no human pilot onboard.

UAVs are composed by fuselage and physical parts, and by a communication unity, which is a key component of a UAV. They also have various essential systems, including navigation, flight control, propulsion, collision avoidance, and electric systems. UAVs can be remotely controlled and/or autonomous, and they can perform a variety of tasks. Although initially purposed for military tasks, there has been an increasing growth in civilian, commercial and scientific applications (e.g., traffic surveillance, communication relays, disaster management, data and image acquisition, etc.) (BENTO, 2008). The main features used to evaluate a UAV suitability for a given mission are its range, speed and energy consumption. Its range depends on its endurance, speed, battery life or fuel capacity, as well as its energy efficiency. While its speed is related to other specifications, such as fixed or rotary wings.

As shown in Table 1, UAVs can be classified according to their weight, altitude and endurance (SALEEM; REHMANI; ZEADALLY, 2015). Figure 3 shows an example of a mini UAV, the Inspire 2, by DJI, as categorised by Table 1 (Dà-Jiāng Innovations Science and Technology Co. Ltd., 2018). This UAV weighs around 3.3 kg and its flight reaches up to 27 minutes.

Table 1 – UAVs classification. Adapted from (SALEEM; REHMANI; ZEADALLY, 2015).

| UAV | Weight (kg) | Altitude (km) | Endurance (hours) |
|---|---|---|---|
| Micro | 0.1 | 0.25 | 1 |
| Mini | <30 | 0.15-0.3 | <2 |
| Short range | 200 | 3 | 2-4 |
| Medium range | 150-500 | 3-5 | 30-70 |
| Long range | - | 5 | 6-13 |
| Endurance | 500-1500 | 5-8 | 12-24 |
| Medium altitude, long endurance | 1000-1500 | 5-8 | 24-48 |
| High altitude, long endurance | 2500-12500 | 15-50 | 24-48 |

Figure 3 – DJI Inspire 2, a mini UAV weighing around 3.3kg and capable of a flight time up to 27 minutes.

Source: (Dà-Jiāng Innovations Science and Technology Co. Ltd., 2018)

For mini and micro UAVs, battery represents an important portion of their weight. The DJI Inspire 2, for example, typically works with a pair of 4280 mAh batteries, weighing 515g each. Although over 30% of this UAV weight is assigned to batteries, its is only able to fly 27 minutes per charge.

UAVs may be deployed as a part of a *Unmanned Aircraft System* (UAS). UASs are usually composed by multiple UAVs, ground control stations, and data communication links. They typically also include support systems (e.g., systems for the aircraft maintenance, take-off, landing, and transport), and additional equipment needed to perform a given mission.

The ground control station (or base station) is a computer or device designed to operate missions and UAVs. It is responsible for executing different controls in a UAS, such as the take-off and flight operation. It is, therefore, the UAS operational control centre. It may also execute tasks other than control, from processing sensors data to play the role of an interface between the UAS and external devices.

The data communication links are communication components within the UAS, which main purpose is to ensure continuous communication between the UAV and the base station. Recently, Multi-UAV systems have been employed as *Flying Ad-hoc Networks* (FANETs) to collaboratively complete missions more efficiently when compared to single UAV systems. However, much of the work carried out for other ad-hoc networks, such as *Mobile Ad-hoc Networks* (MANETs) and *Vehicular Ad-hoc Networks* (VANETs), does not consider special issues in FANETs. FANETs demand studies addressing the variety of their unique features. These characteristics involve, for example: the high mobility of UAVs and different mobility levels among them; intermittent links and fluid topology; routing protocols considering energy constraints and changing link quality. Hereof, *Software Defined Networking* (SDN) is a key enabler for flexible and efficient deployment, while increasing both security and availability in these networks (GUPTA; JAIN; VASZKUN, 2016).

## 2.4 CR-Based UAVs

A CR-based UAV may be seen as a UAV with SDR platform embedded to it. It should also contain a computational unity that will interact with the SDR platform in order to autonomously take decisions regarding the radio spectrum usage. In this section, we first discuss the need for CR-based UAVs, potential applications, and hardware/software characteristics.

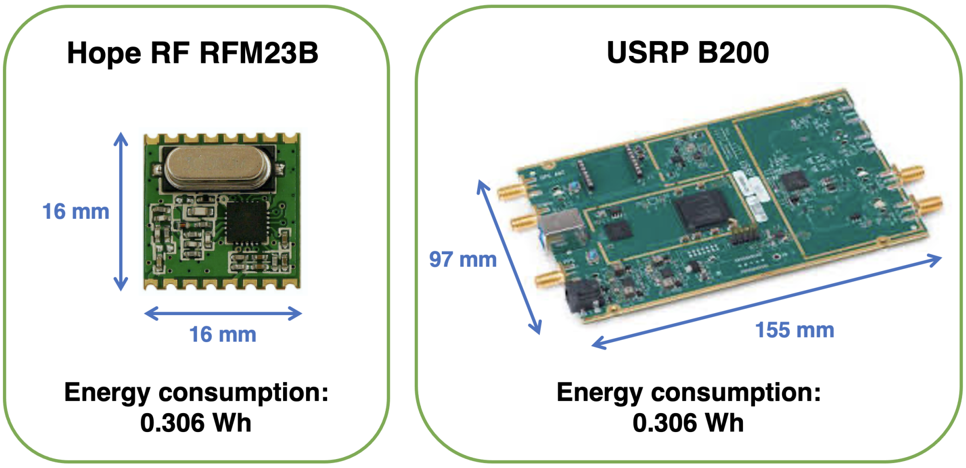
### *2.4.1 Hardware Characteristics*

Usually, CR hardware consists of a radio platform, typically an SDR, and a computer platform. The Wireless Open-Access Research Platform (WARP) from Rice University (UNIVERSITY, 2018), and the USRP, from Ettus Research(RESEARCH, 2018) are the most commonly deployed radio platforms for CR (YOUNG; BOSTIAN, 2013).

A recent implementation of SDR, however, has been carried out using various methods rather than considering the integration with UAVs. As a consequence, for UAVs, overhead, energy consumption and time delays associated with conventional SDR are constraints. Alternatively, (YOUNG; BOSTIAN, 2013) built the SKIRL, a simple and low-cost RFIC-based RF CR platform suitable for the experimentation of small radio-controlled UAVs. The Hope RF RFM22B (MICROELECTRONICS, 2018) was used as the radio platform, whereas the BeagleBoard-xM (Texas Instruments, 2018) single board was deployed as the computer unit. This was done to reduce resource consumption and simplify CR design.

Figure 4 shows the physical dimensions of the USRP B200, 97x155 millimetres, and the Hope RF RFM23B, 16x16 millimetres. For UAVs, particularly for micro UAVs, where physical space is limited, so if a large board is inserted to it, series of changes may be triggered in the aircraft system, configuration, and scale. Thus, this difference in size is critical. Moreover, the energy consumption of the Hope RF RFM22B is just 0,306 Wh in the worst case scenario. The USRP B200, on the other hand, may have up to 4,092 Wh of energy consumption. Because the energy capacity of a LiFe SourceHCAM6426 UAV lithium battery, a typical UAV battery, is just 12 Wh, so energy consumption is a key aspect to take into account in this context.

Figure 4 – Physical aspects of the Hope RF RFM23B on the left and the USRP B200 on the right. The boards are shown in different size scales.



Source: the author (SANTANA; CRISTO; BRANCO, 2021).

### 2.4.2 Software Characteristics

The CR software design and applications can be divided into multiple categories, from MAC protocols and routing algorithms to machine learning approaches used to predict channel occupancy. In this work we summarise three of those categories: (*i*) spectrum sensing algorithms, focusing mainly on transmitter detection and identification of spectrum holes (MALIK *et al.*, 2010; PERERA; HERATH, 2011); (*ii*) methods to perform the spectrum handover (CHRISTIAN *et al.*, 2012); (*iii*) and simulation software (NIR; SCHEERS, 2015).

#### 2.4.2.1 Spectrum sensing

The literature commonly refers to spectrum sensing as the procedure of gathering and analysing radio data to establish the spectrum occupancy (HOSSAIN; NIYATO; KIM, 2015). In order to detect transmitters, some well-known methods can be employed, i.e., Energy detector, Matched-filter and Cyclostationary feature detection. These algorithms are connected with two hypotheses formally defined as follows (ZHENG *et al.*, 2009; ABDELRASSOUL; FATHY;

ZAGHLOUL, 2016):

$$x(t) = \begin{cases} n(t), & H_0 \\ s(t) + n(t), & H_1 \end{cases} \tag{2.1}$$

where $H_1$ indicates the presence of a licensed user, whereas $H_0$ represents the null hypothesis. $x$ represents the received signal, $t$ is the time sample, $s$ and $n$ denote the PU signal and the additive noise, respectively.

In cases where the signal receiver has no prior information about the PU signal, the energy detector algorithm may be deployed at a low computational cost. It functions by comparing a signal sample from the data to a pre-defined threshold, where a value higher than the threshold suggests the presence of a primary user, whereas a value smaller than the threshold implies the lack of band utilisation. The main downside of this approach is the fixed threshold value, as noise power can differ over time possibly assuming unknown behaviour. In this case, the threshold could be surpassed by the noise power, indicating an invalid PU presence in a given spectrum band (KIM; SHIN, 2008; AKYILDIZ *et al.*, 2008).

The matched-filter contrasts the current signal with previous collected samples from the same transmitter, in comparison to the energy method. It appears to be more precise, has a shorter sensing time and maximises the ratio of signal to noise (SNR). However, the need for prior knowledge of the form of the transmitter signal restricts its feasibility only to the point where licensed users cooperate.(KAPOOR; RAO; SINGH, 2011).

In order to check whether or not the transmitted signal has periodicity, the cyclostationary feature detection adopts a spectral correlation function (SCF) (ONER; JONDRAL, 2007). Unlike the previous approaches, it helps the CR user to distinguish between noise and user signal, improving the efficiency of the algorithm in channels where there is greater noise (CABRIC; MISHRA; BRODERSEN, 2004). Because of its computational complexity, perhaps the most serious drawback of this approach is the need for long processing time, an undesired characteristic for small energy consumption systems such as UAVs.

Finally, machine learning approaches have been adopted in the literature to enhance the detection of transmitters. The authors in (POPOOLA; OLST, 2011) achieved an overall success rate of over 99.50% in predicting PU presence by using an Artificial Neural Network (ANN) at different SNR frequencies. Similarly, (ZHANG; WU; LIU, 2012) proposed a cooperative detection device combining the energy detector with ANNs, adding a basic ANN for each SU and a base station responsible for final decision-making, referred to as the Fusion Centre. (MATINMIKKO *et al.*, 2013) proposed a new Fuzzy logic system to adapt each spectrum scenario to the most suitable transmitter detection algorithm. The reader may refer to (ARJOUNE; KAABOUCH, 2019; Tavares *et al.*, 2020) for further information concerning spectrum sensing techniques.

#### 2.4.2.2 Spectrum handover

The channel occupied by an unlicensed should ideally be vacant when a PU arrives. This is desirable in order to generate minimal interference to the primary user transmission. The literature generally refers to the process of hoping to another channels as spectrum handover. It involves distinct strategies with regards to its integration with spectrum sensing, such as non-handover, pure proactive, pure reactive, hybrid, and ML approaches, which incorporates the preceding (CHRISTIAN *et al.*, 2012).

In the non-handover strategy, the SU remains idle until the PU leaves the channel, resuming the transmission of data later. Although spectrum sensing is limited solely to current channel monitoring, the drawback of this concept is unveiled during a long PU transmission, which significantly restricts the transmission time available to the SU, in terms of detection of PU arrivals and departures.

Unlike non-handover, before and after the arrival of the PU, both pure proactive and reactive strategies concentrate on handover to an idle channel respectively. The pure proactive algorithm tries to predict the arrival of the PU while perceiving the atmosphere to locate a spectrum hole based on the traffic pattern of the channel. On the contrary, after the identification of the PU, the pure reactive approach only senses and switches to an unused channel. A potential disadvantage in the pure proactive method may be created by a poor prediction of traffic, leading to an unnecessary handover, whereas the pure reactive approach may have a greater handover delay just after a PU arrival due to the execution of the spectrum sensing stage.

The hybrid handover strategy, taking advantage of the advantages of both methods, incorporates proactive spectrum sensing phase, perceiving the spectrum holes before the arrival of the PU, and reactive handover action. Therefore, due to the proactive process, the handover delay is reduced, and not every PU arrival needs to be predicted by the algorithm. However the backup channel can become obsolete before use, as in the proactive method, thus driving the algorithm to perform a supplementary spectrum sensing phase.

The literature has stressed the utility of ML algorithms to overcome the complexities of spectrum handover. (TRIGUI; ESSEGHIR; MERGHEM-BOULAHIA, 2012) developed a method of negotiating multi-agent systems that enables SUs to migrate opportunistically to the most adequate spectrum band provided its characteristics, achieving around 97% of spectrum utilisation. An investigation on the Hidden Markov Model (HMM) application for spectrum handover and simulated data showed that in detecting transmission opportunities, this technique can give SUs greater accuracy (PHAM *et al.*, 2014a). Finally, in order to achieve dynamic handover management, (ANANDAKUMAR; UMAMAHESWARI, 2017) suggested a supervised Machine Learning (ML) approach referred to as Spectrum Particle Swarm Optimisation (SpecPSO), using Visitor Location Register and Home Location Register databases to train the algorithm.

#### 2.4.2.3 Simulation tools

All levels of abstraction, from the physical layer to protocols and routing, should be associated with a full CR simulation program. We have not found a method in the literature that embodies all these characteristics. The only way to do this, to the best of our knowledge, is to combine open source resources, such as radio simulators (e.g. GNU Radio (GNU Radio, 2018), CogWave (NIR, 2018)) and general network simulators (e.g. Omnet++ (OpenSim Ltd., 2018b) and ns-3 (GeorgiaTech, 2018)).

GNU Radio is free and open source software designed to use its graphical user interface flow graphs to simulate radio transmissions and signal processing (GNU Radio Companion). It could be compared to LabView (INSTRUMENTS, 2018) and Simulink (MathWorks, 2018). Standard flow graph blocks encompass waveform generators, modulators, instrumentation sinks, math operators, filters, and Fourier Analysis. It also facilitates the development of new blocks using the programming language C++, as well as the design of the flow graph using Python. In addition, GNU Radio can be connected to SDR hardware, thus allowing simulations from the testbed to be used.

Another open-source program suggested for designing CR waveforms is CogWave. It involves many modulation systems, including multichannel DAA-OFDM, Fathers, and others from GNU Radio, such as (e.g. OFDM, BPSK, QPSK). During run-time, CogWave is able to reconfigure the modulation scheme and can communicate with SDR hardware, as well as GNU Radio, to provide real-time transmission between USRP devices.

Omnet++ and INET (OpenSim Ltd., 2018a) have been widely used in the literature to simulate CR networks for general network simulators (PATHAK *et al.*, 2016; NOOR *et al.*, 2016; ABEYWARDANA; SOWERBY; BERBER, 2017). Omnet++ offers a C++ component-based architecture where modules and components can be assembled using a graphical user interface or a high-level network description language, similar to flow graphs in GNU Radio (NED). Its modular architecture therefore eases the reusability of the built models. Furthermore, INET offers protocols, templates, routing and mobility simulation as an open-source model library for Omnet++.

Another well-established tool is the ns-3. It is an open discrete-event simulation environment for network research that provides C++ libraries of models for wired protocols, IP and non-IP, wireless, dynamic routing protocols, and so forth. For instance, the ns-3 has been applied in the simulation of CR networks regarding spectrum handover (GKIONIS *et al.*, 2017), data collection (WU; CARDEI, 2016), and channel sharing (BANSAL; LI; SINHA, 2014).

It is necessary to note that many programming languages can be used to build a custom simulator, as they provide access to several network and scientific libraries (e.g. Java, C++, Python and Julia). However, most simulation scenarios encountered in literature are complex enough to require thousands of lines of code, turning this option impractical for most of the problems.

### 2.4.3 Spectrum Mobility

When a PU resumes transmission through the same channel as the SU, the latter has to vacate the channel by suspending its transmission and restart communication through a vacant channel. This CR feature is called Spectrum Mobility (CHRISTIAN *et al.*, 2012).

It is considered a daunting problem due to the erratic behaviour of the wireless medium in combination with the high mobility of UAVs. Thus, network protocols for ground-based networks could not perform as expected for UAVs, and their high mobility should be taken into account when designing CR-based UAV transport protocols (SALEEM; REHMANI; ZEADALLY, 2015; XIE *et al.*, 2014).

One of the forms in which an SU does not trigger disruption in a PU-licensed band is to perform a spectrum handover as soon as the SU detects the existence of the PU. In general, UAVs take their places in a CR network as SUs, and they are likely to conduct a high number of spectrum handovers, as they will be on a mission throughout their route in the presence of various PUs. Therefore, spectrum handover is a key element in CR-based UAVs.

A general spectrum handover process is shown in Figure 5. A SU keeps monitoring the spectrum environment during the evaluation phase by sensing it. The link maintenance process begins when a handover signal is identified, then the SU pauses its transmission and performs a channel handover to a backup channel and resumes its transmission, returning to the evaluation phase.

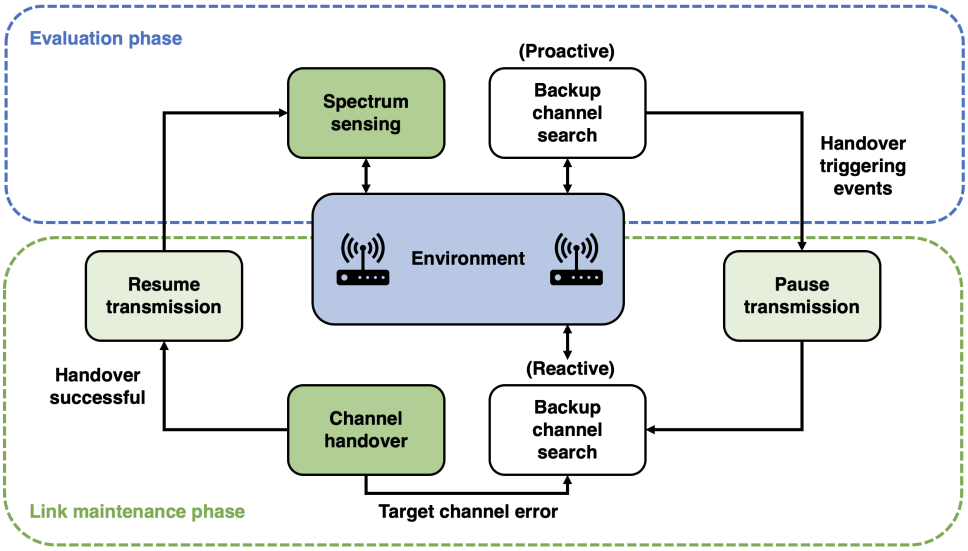
A handover trigger could be provided by a PU or by the SU itself, depending on the application purposes and signal quality. Depending on the spectrum handover strategy, a backup channel could be searched proactively during the assessment process, and a channel handover could also be performed proactively.

On the other hand, both backup channel scanning and channel handover are performed reactively in a reactive technique. A new backup channel has to be checked and another channel handover attempt is made if a channel handover is not successful due to any incident affecting the target channel (e.g., a PU started a transmission through the target channel) (CHRISTIAN *et al.*, 2012).

On the one hand, proactive strategies usually benefit from lower delay rates. On the other hand, reactive strategies may require less spectrum handover executions. Since little to none interference in PUs is allowed, proactive strategies are actually hybrid strategies, i.e., they will also sense the environment for reactive handovers in case they fail to predict a PU presence.

Considerable energy consumption is required in a spectrum handover. Furthermore, some communication problems, such as packet loss and delay, may increase during the spectrum

Figure 5 – Spectrum handover process.

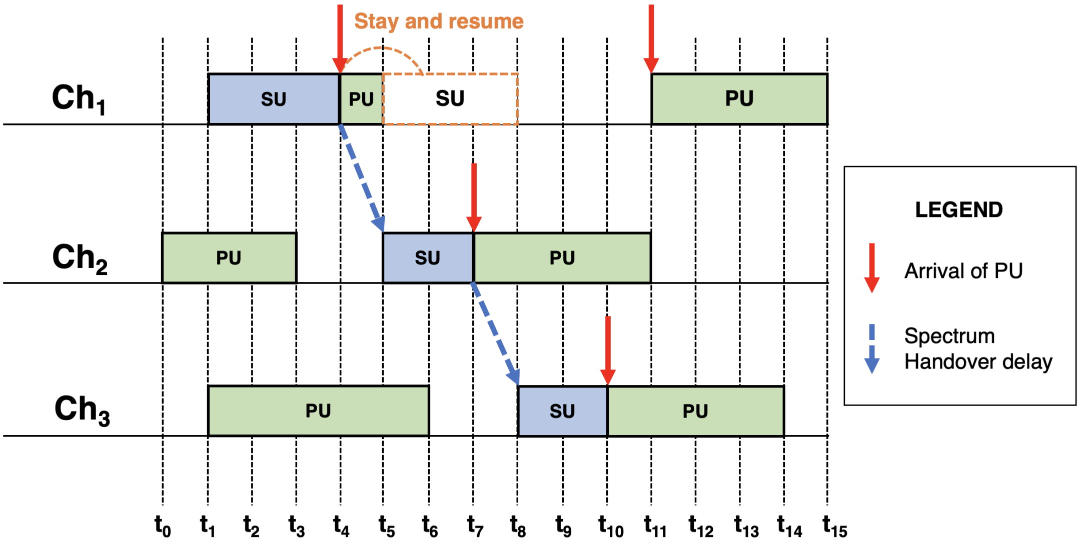


Source: the author (SANTANA; CRISTO; BRANCO, 2021).

handover process. In a spectrum handover, delay is also a significant performance factor (HANIF; ZEESHAN; AHMED, 2016).

Figure 6 demonstrates the effect of the spectrum handover delay over a SU after many PU channel reclaims. In that case, an SU establishes a connection whose operation requires the completion of 7 time slots. However, due to successive PU arrivals, the process needs 9 time slots. Nevertheless, as the existence of a PU on channel Ch1 is quite short, the first SU channel handover was unnecessarily executed, which means that the SU was submitted to excessive channel handover costs (LERTSINSRUBTAVEE; MALOUCH; FDIDA, 2012). Regardless of the spectrum handover strategy being reactive or proactive, there will be some amount of delay associated with it.

Figure 6 – Spectrum handover delay caused to an SU.



Source: the author (SANTANA; CRISTO; BRANCO, 2021).

UAVs designed for real-time multimedia broadcasting could cause unsatisfactory user experience, since spectrum handover latency could have a significant effect on delay-sensitive applications. For optimal transmission, therefore, delay reduction has to be considered (WU *et al.*, 2016).

## 2.5 Final Remarks

This section presented the background information on CR and UAVs needed to achieve proper understanding of this work. It gave an overview on both areas, but it focused on the most important aspects. Although CR may be employed in a wide range of applications, and likewise there is vast range of UAV models, this project focuses on the use of CR to enhance the communication of a single mini UAV, considering its energy, space and weight constraints. Other types of UAVs and scenarios are beyond the scope of this work. Next chapter shows the related work regarding CR for UAV communication.

CHAPTER

3

# LITERATURE REVIEW - THE STATE-OF-THE-ART IN CR FOR UAV COMMUNICATION

## 3.1 Chapter Overview

This section presents a systematic review and some case studies to show the state-of-the-art in CR for UAV communications. It was held in November 2020, seeking works involving UAVs, SDR and CR. The main idea was to find the state-of-the-art of CR-based UAVs. SDR-based UAVs represent a step backwards for CR-based UAVs, they were also included in the review.

## 3.2 Systematic Review

The digital libraries of the *Transportation Research Board* (TRB), the *Association for Computing Machinery* (ACM), Scopus, and the *Institute of Electrical and Electronics Engineers* (IEEE) were all used for this review. The query strings used in each digital library can be found in Appendix D.

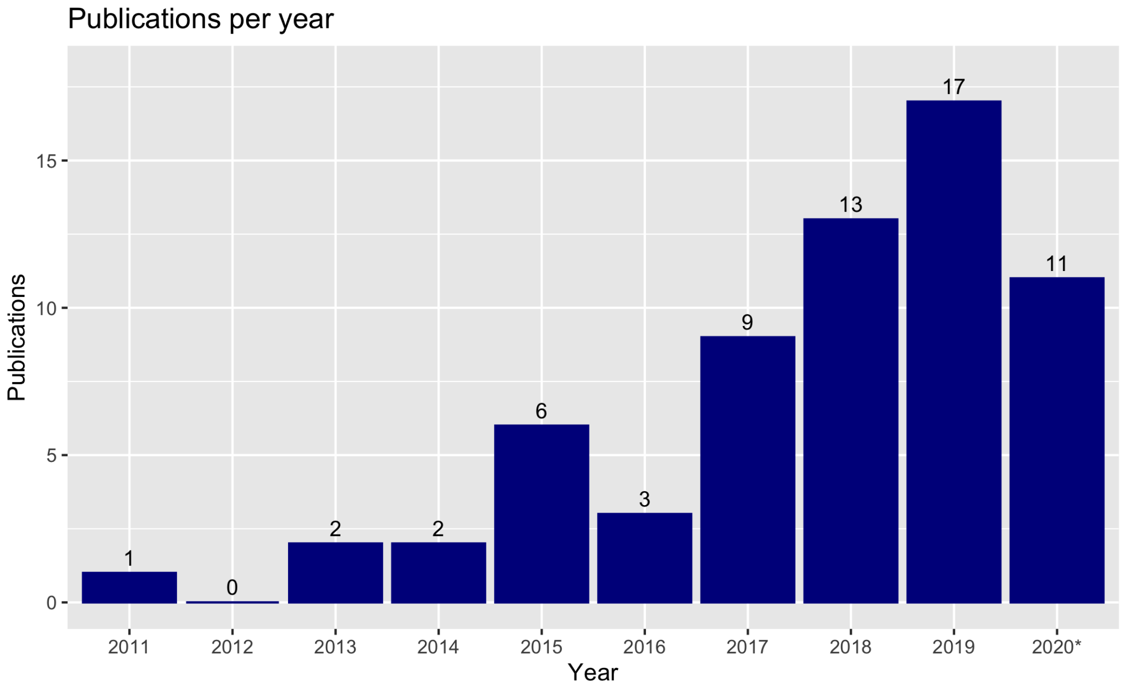
A total of 520 publications from four different digital libraries were evaluated. However, the majority of those articles were identified marginally related to the scope of this work. Thus, the final studies dataset obtained after analysing them regarding the following exclusion criteria consisted of 64 articles:

1. non-English publications. Although I used English language keywords, I found a few publications in other languages. I had to exclude them merely because I would not be able to analyse them in depth;

2. papers not downloadable online;
3. publications not related to CR, SDR or UAVs as defined in this work (other research fields);
4. papers focusing on CR or SDR applications other than UAVs wireless communication.

Figure 7 outlines the number of publications per year, among those selected in this review. It shows an increasing interest over the recent years in this research field. Moreover, more works might have been published after this review but not yet published online. Note that a number of papers may have been published from January 2020 to November 2020, but not yet available online either.

Figure 7 – Publications per year.

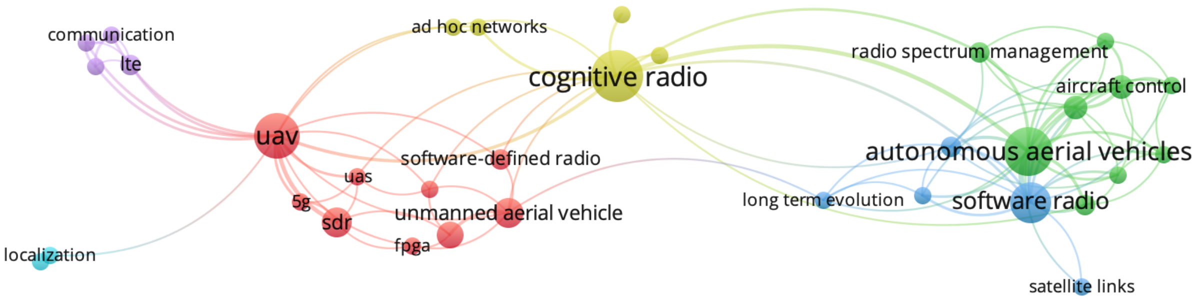


Source: the author (SANTANA; CRISTO; BRANCO, 2021).

Figure 8 presents keywords graph and occurrence mapping for all 64 articles selected on this review. Keywords with at least two occurrences and at least one link to other keywords are considered. Thereby, the keyword mapping consists of 34 keywords in total. On Figure 8, it is possible to note an expressive amount of links correlating UAV-related keywords and SDR-related keywords. However, although CR-related keywords are well present on Figure 8, there are barely links correlating them to UAVs. Thus, Figure 8 outlines the paucity of studies on the integration of CR and UAVs.

In order to measure how fit each selected publication is to CR-based UAVs research field, each paper was analysed regarding the following aspects:

Figure 8 – Keywords graph and occurrence mapping for all 64 articles selected on this review.



Source: the author (SANTANA; CRISTO; BRANCO, 2021)

1. the work presents a theoretical analysis (Q1);
2. the work presents practical results (Q2);
3. the work involves a real SDR-based UAV (Q3);
4. the work is centred on CR-based UAVs (Q4);
5. the work involves a real CR-based UAV (Q5).

For each publication, each aspect is analysed, and it is evaluated as "yes", if the aspect is present in the paper, or "no" otherwise. Table 2 presents all selected publications in this review, as well as their publication year and aspects analysis.

Table 2 – Reviewed publications and their explored topics. On the columns Q1 to Q5, cells filled in blue color represent "yes" for the respective column, and "no" otherwise (SANTANA; CRISTO; BRANCO, 2021).

| Publication | Q1 | Q2 | Q3 | Q4 | Q5 |
|---|---|---|---|---|---|
| (CHEN *et al.*, 2011) | ■ | ■ |  | ■ |  |
| (YOUNG; BOSTIAN, 2013) | ■ | ■ |  | ■ |  |
| (MIKO; NEMETH, 2013) | ■ |  |  |  |  |
| (HAROUNABADI *et al.*, 2015) | ■ |  |  | ■ |  |
| (BROWN; MCHENRY; JAROONVANICHKUL, 2015) | ■ |  |  | ■ |  |
| (REYES; GELLERMAN; KAABOUCH, 2015) | ■ |  |  | ■ |  |
| (GUEVARA *et al.*, 2015) |  |  | ■ |  |  |
| (ANDERSON; FREW; GRUNWALD, 2015) | ■ | ■ |  | ■ |  |
| (MIKó; NéMETH, 2015) | ■ | ■ |  |  |  |
| (ANDRYEYEV; ARTEMENKO; MITSCHELE-THIEL, 2015) | ■ |  |  | ■ |  |
| (SALEEM; REHMANI; ZEADALLY, 2015) | ■ |  |  | ■ |  |
| (VONEHR *et al.*, 2016) |  | ■ | ■ |  |  |

| | | | | | |
|---|---|---|---|---|---|
| (JACOB *et al.*, 2016) | ■ | | | ■ | |
| (TATO; MOSQUERA; GOMEZ, 2016) | ■ | ■ | ■ | | |
| (MURPHY; BROWN; SREENAN, 2017) | | ■ | ■ | | |
| (SBOUI *et al.*, 2017) | ■ | | | ■ | |
| (GUTIERREZ *et al.*, 2017) | ■ | ■ | | | |
| (GONZALEZ; FUNG, 2017) | | ■ | | | |
| (HORAPONG *et al.*, 2017) | | ■ | ■ | | |
| (ZHANG *et al.*, 2017) | ■ | | | | |
| (GHAZZAI *et al.*, 2017) | ■ | | | ■ | |
| (CAI *et al.*, 2017) | ■ | ■ | ■ | | |
| (NOBLE *et al.*, 2017) | ■ | ■ | | | |
| (PETROLO; LIN; KNIGHTLY, 2018) | ■ | ■ | ■ | | |
| (SHI *et al.*, 2018b) | | ■ | ■ | | |
| (HUANG *et al.*, 2018) | ■ | | | ■ | |
| (SHI *et al.*, 2018a) | ■ | ■ | ■ | | |
| (LIU *et al.*, 2018) | ■ | | | ■ | |
| (SKLIVANITIS *et al.*, 2018) | ■ | ■ | ■ | ■ | ■ |
| (PäRLIN; ALAM; MOULLEC, 2018) | ■ | | | | |
| (DUNNE; KEENLANCE, 2018) | | ■ | ■ | | |
| (SHAMAEI; KHALIFE; KASSAS, 2018) | ■ | ■ | ■ | | |
| (SANTANA *et al.*, 2018) | ■ | | | ■ | |
| (JADON *et al.*, 2018) | | ■ | ■ | | |
| (Torabi *et al.*, 2018) | ■ | ■ | ■ | | |
| (Xu *et al.*, 2019) | ■ | | | ■ | |
| (PAN; DA; HU, 2019) | ■ | | | ■ | |
| (Shen *et al.*, 2019) | ■ | ■ | | ■ | |
| (Aftab; Khan; Zhang, 2019) | ■ | ■ | | ■ | |
| (Adane, 2019) | | ■ | ■ | | |
| (Almasoud; Kamal, 2019) | ■ | | | ■ | |
| (Matheou *et al.*, 2019) | | ■ | ■ | | |
| (Wang *et al.*, 2019) | | ■ | | | |
| (Murphy; Sreenan; Brown, 2019) | | ■ | ■ | | |
| (Hasan *et al.*, 2019b) | | ■ | | ■ | |
| (Che; Luo; Wu, 2019) | ■ | | | ■ | |
| (Nie *et al.*, 2019) | ■ | ■ | | ■ | |
| (Radišić; Muštra; Andraši, 2019) | | ■ | ■ | | |
| (Hasan *et al.*, 2019a) | ■ | | | ■ | |

| | | | | | |
|---|---|---|---|---|---|
| (Yuheng; Yan; Yanyong, 2019) | 🟦 | | | 🟦 | |
| (D'Alterio *et al.*, 2019) | 🟦 | 🟦 | 🟦 | | |
| (Zhao *et al.*, 2019) | 🟦 | 🟦 | | 🟦 | |
| (Mohanti *et al.*, 2019) | 🟦 | 🟦 | 🟦 | | |
| (Liang *et al.*, 2020) | 🟦 | | | 🟦 | |
| (Kornprobst; Mauermayer; Eibert, 2020) | | 🟦 | 🟦 | | |
| (Bertizzolo *et al.*, 2020) | 🟦 | 🟦 | 🟦 | | |
| (Figueira; Niedermeier Belmonte; de Freitas, 2020) | | 🟦 | 🟦 | | |
| (HASAN *et al.*, 2020) | | 🟦 | | 🟦 | |
| (POWELL *et al.*, 2020) | | 🟦 | 🟦 | | |
| (AbdulCareem *et al.*, 2020) | 🟦 | 🟦 | 🟦 | | |
| (Zambrano; Bui; Landry, 2020) | 🟦 | 🟦 | | | |
| (Sommer *et al.*, 2020) | | 🟦 | 🟦 | | |
| (Liu *et al.*, 2020) | 🟦 | | | 🟦 | |
| (Krayani *et al.*, 2020) | 🟦 | 🟦 | | 🟦 | |

Many of these publications is centred on a variety of SDR applications in UAV contexts instead of CR-based UAVs. Although they do not directly study CR-based UAVs, they may add valuable information to the CR-based UAV research field. The reason for that is, as most of the CR schemes are based on SDR, it may be considered sometimes an earlier step to CR.

In (CHEN *et al.*, 2011), the authors proposed a distributed spectrum sensing with multiple sensing nodes in an SDR/UAV context. Hereof, the UAV serves as a natural collection point for the distributed measurements, and it is aided by ground sensing nodes, in order to enhance the UAVs decoding accuracy of compressive sensing. Through a real' world experiment, the authors showed that, as their proposed strategy easily tolerates wireless transmission losses, it is well adapted for an SDR/UAV scenario.

The authors in (GUEVARA *et al.*, 2015) presented the design and implementation of an SDR-based UAV that may be quickly deployed in emergency communication scenarios. This UAV is intended to serve as a GSM base station to provide cellular network coverage to nearby users, and it may also work to improve wireless throughput. The authors, however, did not present any real experiment validating their aircraft. The same subject is studied in (Radišić; Muštra; Andraši, 2019). Their results proved its feasibility, but further performance enhancement is needed, especially with regards to RF range.

In (VONEHR *et al.*, 2016), the authors proposed two different strategies for assisted wildlife tracking with SDR-based UAVs. Although the authors proposed two different approaches, only one was validated through real tests. Their experiment showed that the implemented strategy was able to improve the area of detection by more than a factor of two over ground searching.

Wildlife tracking was subject of study also in (Torabi *et al.*, 2018). There, the authors developed a UAV integrated with a VHF radio telemetry. Although the work they presented was still in an early stage of development, they could satisfactorily conduct real experiments using their prototype.

In (TATO; MOSQUERA; GOMEZ, 2016), the authors described an experiment to communicate a mobile platform with a base station through a medium Earth orbit satellite. SDR was used to implement the physical layer in both ends. Therefore, as the mobile platform was a UAV, it may be considered an SDR-based UAV. Through their experiment, the authors concluded that SDR technology is a promising technology to develop an adaptive satellite communication system in real conditions

The authors in (MURPHY; BROWN; SREENAN, 2017) proposed a system combining low-cost UAVs with SDR for GSM cellphone localisation in emergency scenarios. The system was validated through the localisation of a user device based on the reception of GSM. In (Murphy; Sreenan; Brown, 2019), they continued their work by adding a sophisticated algorithm for autonomous path-planning for efficient coverage of a search area by their SDR-based UAV. As future work, the authors intend to propose the inclusion of multiple UAVs to track non-mobile-phones wireless devices.

In (HORAPONG *et al.*, 2017), the authors present a UAS for assisting actual flights through a previous inspection of the radio navigation environment. For the radio environment inspection, the authors use an SDR platform mounted on a UAV. Although the authors tested this strategy in simulated and real scenarios, they concluded there is still much work to do to prove this operation in real use.

The authors in (CAI *et al.*, 2017) investigate the low altitude air-to-ground UAV wireless channel in a suburban scenario. They conducted a measurement for the wireless propagation using an SDR-based UAV. The measured frequencies were 5.76 GHz and 1.817 GHz. The main purpose of their work is to evaluate the impacts of mobility, radio environment, and obstacles to a UAV in a 5G context. Using SDR-based UAVs to enhance 5G is also subject of study by (D'Alterio *et al.*, 2019). On that work, the authors propose a quality-aware scheme for 5G by using SDR-based UAVs to optimise the network. Their results show that, not only UAVs can improve general network performance, but also they are be able to autonomously reposition themselves according to signal requirements. Perhaps combining these works with a complete algorithmic framework for distributed beamforming by a swarm of UAVs, as in (Mohanti *et al.*, 2019), and the automated distributed control for drone networks proposed by (Bertizzolo *et al.*, 2020) could achieve optimal results in future work.

In (PETROLO; LIN; KNIGHTLY, 2018) the authors proposed a UAV network called ASTRO. Its main features are: the capability of executing on-board machine learning missions based on UAV sensors data shared among other UAVs; the ability to use SDR to coordinate networked UAVs in autonomous flight; and off-grid tetherless flight without a base station or air-to-ground network. ASTRO was validated through sensing missions to find and track mobile spectrum cheater.

In (ZHANG *et al.*, 2017), the authors presented a design and implementation of an SDR able to send and receive channel data in real time. Their focus was mainly on multi-system avionic architecture. The authors used laboratory results, where they simulated real conditions, to demonstrate the system feasibility and to establish some performance metrics. However, according to the authors, further system optimisations are needed to reduce CPU resources. In (Zambrano; Bui; Landry, 2020). the authors continued their work proposing a technique to mitigate interference when deploying two UASs in the same region and sharing the same frequency range. They validated their work with practical experimentation.

In (SHI *et al.*, 2018b) and (SHI *et al.*, 2018a), the authors also built SDR-based UAVs testbeds for performing measurements in order to characterise the air-to-ground channel between aerial platforms and terrestrial users at various heights and distances. Their numerical results show that SDR-based UAVs can significantly improve throughput when compared with traditional UAVs. The development of SDR-based UAVs testbeds were also the subject of the study in (DUNNE; KEENLANCE, 2018), (ANDERSON; FREW; GRUNWALD, 2015) and (Sommer *et al.*, 2020).

The authors in (SHAMAEI; KHALIFE; KASSAS, 2018) studied the use of cellular *Long-Term Evolution* (LTE) downlink signals considering navigation purposes. They designed an SDR that is capable of acquiring, tracking, and producing ranges from LTE signals. Then, the developed SDR was embedded on a UAV for the experimental evaluation. Nonetheless, the authors concluded that developing the proposed receiver in hardware still need to be considered. LTE was also the focus of the authors in (Matheou *et al.*, 2019), where they deployed small UAVs in low-altitute and measured the impact of civilians use of LTE on their UAV.

In (JADON *et al.*, 2018), the authors described how to develop a UAS testbed, to work as a platform for networking and spectrum related research. It is embedded on commercial off-the-shelf hardware and open source software components. The main contribution by their work is the creation of a public database that can be used on new propagation models, and thus enabling more accurate UAV network simulations. The authors, however, conclude that further work should consider improvements on several hardware systems and software components to enhance the experimental capabilities, such as new functions and expansion of the set of questions explored.

In (WOLFE *et al.*, 2018), the authors deployed a testbed to evaluate adaptive links for 802.11 UAV uplink. They used an SDR and a reconfigurable antenna mounted on a UAV and, based on real experiments, they showed that the reconfigurable antenna with intelligent selection enhances the signal quality when compared to an omni-directional antenna.

The author in (FOUDA, 2018) presented a study on security vulnerabilities of cyberphysical UAS. Although most of his work involved general/traditional UAS, the author also contributed by outlining a series of vulnerabilities in SDR-based UAS.

In (PETITJEAN; MEZHOUD; QUITIN, 2018), the authors consider a scenario in which UAVs are used to replaced damaged network ground infrastructure in emergency situations. They developed an algorithm to help the UAV at locating the ground user and then serve as the flying base station to that user. Their real experiments showed that their algorithm succeed at both, locating the ground user, and locating the best spot when more than one ground user has to be served.

The authors in (Adane, 2019) focused their work in developing a software-defined transceiver especially designed for UAVs. Their transceiver lies on the use of cutting edge Field Programmable Gate Array (FPGA) technology. Although they have only tested their transceiver offboard an UAV, the authors made clear that the next step of their research is to embed it to an UAV prototype in order to prove that their technology will work in a real mission. Furthermore, the RF equipment proposed by (Kornprobst; Mauermayer; Eibert, 2020), due to its low-cost and light-weight features, could also have its use on UAVs experimented.

In (Wang *et al.*, 2019), the authors proposed the use of a UAV integrated with SDR technology to detect malicious WI-FI hotspots. They used well-known techniques for such detection, and they take advantage of the power of SDR and of UAV's high mobility to detect such malicious hotspots in a large area. Although their system was fully designed, no outdoor experiment was made. Also, their work could be further improved by using the signal detection technique presented by in (AbdulCareem *et al.*, 2020). This combination could help the UAV to plan its route more efficiently and autonomously.

The integration between SDR and UAV was also used by (Figueira; Niedermeier Belmonte; de Freitas, 2020). In their work, the authors presented an architecture for a Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR). Their proposed system uses SDR not only on the UAVs themselves, but also on the ground control station. They obtained important results with regards to producting and processing Intelligence, Surveillance and Reconnaissance (ISR) ISR data in real time.

Another group of publications rely on simulated results. However, they contribute as early and important steps towards efficient deployment of CR-based UAVs.

In (YOUNG; BOSTIAN, 2013), the authors proposed a new CR architecture aiming at decreasing the radio's cost, computational complexity, and size. Herein, the authors replaced the usual SDR part of a CR with a radio frequency application specific integrated circuit. The authors also encouraged researchers to evaluate similar radio frequency platform alternatives to enhance CR performance for UAV applications.

In the book chapter in (BROWN; MCHENRY; JAROONVANICHKUL, 2015), the authors explored the key role of CR technologies for UAS to use wider and different ranges of radio spectrum. To do so, the authors presented distinct architecture choices available for the design of CR-based UAS.

The authors in (HAROUNABADI *et al.*, 2015) proposed a *Trajectory Aware Geographical* (TAG) routing with UAV nodes to be used on CR ad hoc networks. It aimed to reduce the time consumed due to PU activity. According to the authors, TAG routing could also be applied to other kinds of wireless ad hoc networks, such as VANETs with autonomous vehicles. This application still have to be studied. Trajectory design is also subject of study in (Liu *et al.*, 2020).

In (REYES; GELLERMAN; KAABOUCH, 2015), the authors proposed a CR technology system to enhance the security and reliability of UASs/UAVs networks wireless communications. They argued and showed that their proposed solution is effective at detecting lost link and jamming, thus improving the reliability and security in the UAS/UAV. However, the authors results are strictly based on simulations, and no practical results were obtained.

The authors in (MIKó; NéMETH, 2015) developed a data communication system for UAVs through SDR architecture. The system has the following features: bi-directional data flow, radio navigation and ranging. The authors presented the system description, the hardware platform and the test results. However, further efficiency and power amplifier enhancement is needed.

The authors in (ANDRYEYEV; ARTEMENKO; MITSCHELE-THIEL, 2015) proposed the use of lightweight directional antennas with a fixed beam on small UAVs. They also evaluated, through software simulations, their performance. This approach aimed to enhance the system capacity in CR ad hoc networks. For further research, the authors proposed improvements of the approach.

In (GUTIERREZ *et al.*, 2017), the authors investigated the characteristics of time and frequency dispersion of UAS air-to-ground wireless channel at the frequency 5.8 GHz. To do so, the authors collected empirical measurements in mountainous desert terrains and outdoor residential areas. For further research, the authors proposed to conduct the experiments in different environments and compare the results in terms of channel phenomenologies.

The authors in (GONZALEZ; FUNG, 2017) developed an aeronautical surveillance system aiming at the use of UAVs for delivery using a heterogeneous SDR framework. For that purpose, they used Linux single board computers to integrate the SDR to a variety of platforms used in a UAV delivery, such as Google Earth and Gnu Radio. Their proposed system successfully decoded in real-time the location of aircraft.

In (ZHANG *et al.*, 2017), the authors presented a design and implementation of an SDR able to send and receive channel data in real time. Their focus was mainly on multi-system avionic architecture. The authors used laboratory results, where they simulated real conditions, to demonstrate the system feasibility and to establish some performance metrics. However, according to the authors, further system optimisations are needed to reduce CPU resources.

In (SBOUI *et al.*, 2017) and (GHAZZAI *et al.*, 2017), the authors focus on energy-efficient solutions for CR-based UAVs. They focus on efficient-energy management of CR-based UAVs, especially in terms of opportunistic spectrum access. Energy is a constraint in UAVs, and it is a major issue for the efficient deployment of CR-based UAVs. However, their work is based on simulated results.

The authors in (MIKO; NEMETH, 2013), (PäRLIN; ALAM; MOULLEC, 2018), and (NOBLE *et al.*, 2017) all worked on jamming applications in SDR and UAVs. They used SDR as a way to enhance UAVs safety by avoiding location jamming, to cause jamming to UAVs remote controls, and to execute jamming attacks to traditional combat net radios using SDR-based UAVs, respectvely. On the other hand, the authors in (Krayani *et al.*, 2020) focused on jamming attacks executed to disable UAV controls. rather than location jamming. Although all four works present promising results, they rely mostly on simulations, and no conclusive practical results were obtained.

The authors in (HUANG *et al.*, 2018) investigated a spectrum sharing between terrestrial wireless communication systems and a CR-based UAV. They proposed an algorithm to obtain a locally optimal solution to the non-convex problem of joint trajectory and power optimisation. Their numerical results showed that their proposed strategy performs more satisfactory than traditional methods. However, no practical results were presented.

In (LIU *et al.*, 2018), the authors worked on spectrum sensing optimisation for CR in UAVs, however, they had a different approach on integrating CR and UAVs. Their main idea is to use UAVs to improve CR spectrum sensing, by reducing fading and shadowing effects when the UAV is positioned in a high altitude during a flight. Their UAV performed circular flight around the PU which spectrum was being sensed. Therefore, their focus is more related to UAV-based CR than CR-based UAVs. It shows that, not only UAVs may benefit from CR, but also vice versa. Improving spectrum sensing for UAVs was also subject of study in (Xu *et al.*, 2019), (Shen *et al.*, 2019), (Nie *et al.*, 2019) and (PAN; DA; HU, 2019).

The authors in (CHEN *et al.*, 2018) undertook a theoretical analysis on spectrum sharing of UAVs with multiple ground PUs. Their analysis took into consideration false alarm and miss detection probabilities, as well as the total interference of UAVs to PUs. Their simulated results showed that as the probability of false alarm and the probability of miss detection are inversely proportional. They also showed that UAVs transmission power and the interference they cause to PUs are directly proportional, however at high heights and long distances UAVs cannot affect PUs communication. Spectrum sharing was also subject of study in (Che; Luo; Wu, 2019), but only numerical results are provided to validate their theoretical analysis, and no real-world experiments were executed.

In (GHORBEL *et al.*, 2018), the authors proposed an energy-efficient overlay CR approach for UAVs. Their strategy was centred on letting the UAV transmit on the PU channel while it is also supporting the PU communication. Their simulated results showed that the proposed strategy provides gains in energy efficiency and offers additional transmission opportunities when compared to traditional schemes.

In (Hasan *et al.*, 2019b), (Hasan *et al.*, 2019a) and (HASAN *et al.*, 2020), the authors undertake a series of analysis focused on provisioning wireless network using CR-based UAVs. First, the authors analyse the problem of deploying resilient connectivity using CR-based UAVs. Then, they propose an adaptive error control framework for that scenario. Finally, they proposed using CR-based UAVs to recover wireless network infrastructure in a disaster area. Although the authors achieved positive results in all three works, they relied on simulations rather than real-case experimentation.

The authors in (Aftab; Khan; Zhang, 2019) and (Almasoud; Kamal, 2019) all analysed CR-based UAVs in an IoT context. Their work focused on a self-organised clustering scheme, and data dissemination, respectively. Again, only simulated results were given. However, their methods may be of great value for future work deploying real CR-based UAVs in an IoT context, especially with regards to IoFT scenarios.

In (Zhao *et al.*, 2019), the authors propose the use of Hidden Markov Model to predict PU arrivals for CR-based UAVs. However, they only rely on simulated results. Furthermore, as I discussed in (Santana *et al.*, 2019), the HMM may not be suitable for real-world scenarios. My results, however, considered the use of ED, which is a step that has not to be taken for simulated results. Although further simulations should consider the step of detecting the PU itself, ideally such techniques should be assessed with real data.

The authors in (Liang *et al.*, 2020) proposed a method to optimise the throughput in cognitive UAV networks. They propose a method of a joint optimisation of three-dimensional location and spectrum sensing duration of a leading UAV, maximising a group of following UAVs' throughput. Their simulated results show that their proposed scheme is superior to currently deployed ones, with very little computational performance loss. Their future work shall consider three-dimensionally mobile UAV nodes.

CR aircraft applications are also the subject of recent surveys. In (JACOB *et al.*, 2016), the authors carried out a survey on CR for aeronautical applications. Although their survey is not directly related to UAVs, they present valuable information about studies involving CR and UAS. Notwithstanding, the authors in (SALEEM; REHMANI; ZEADALLY, 2015) undertook a survey on the integration of CR with UAVs. They discussed and highlighted a variety of challenges, issues and future research in the field. In (POWELL *et al.*, 2020), the authors provide a comparative overview of SDRs. They address specifications for SDR hardware, features of available SDR hardware that are acceptable for small UAVs, and measurements of power. They also present SDR software specifications, open-source SDR software available, and SDR software calibration/benchmarking. Finally, the authors present Aerial Experimentation and Research Platform for Advanced Wireless (AERPAW) as a case study, and address various different experiments that can be sponsored by SDRs on that platform to verify/test possible wireless advancements, protocols, and technologies. Finally, (SANTANA *et al.*, 2018) (see Appendix E) outline the state-of-the-art, opportunities, and future challenges in the field, As shown in Table 3.

Table 3 – A summary of challenges and opportunities in each issue (SANTANA *et al.*, 2018).

| Issues | Challenges and opportunities |
|---|---|
| **Energy consumption** | Energy-efficient spectrum sensing and spectrum handover are critical for CR-based UAVs to cover wide areas and/or long missions |
| **Hardware** | |
| *Embedded* | Conventional SDR hardware does not satisfy UAVs energy, resource and physical space constraints, thus further research in CR hardware platform for UAVs is needed |
| *Response time* | The implementation must be fast enough to perform Spectrum sensing and Handover in short response time |
| **Software** | |
| *PU arrivals* | Best suited transmitter detection for CR-based UAVs |
| *Data generator* | PU arrivals simulated data generator used for machine-learning algorithms training |
| **Spectrum mobility** | Due to their high mobility, UAVs face very dynamic spectrum environments, hence further works should target spectrum mobility in UAVs |
| **Spectrum sharing** | |
| *Underlay* | In underlay spectrum sharing, CR-based UAVs could achieve delay and energy consumption reductions |
| *Cooperation* | Cooperative sensing and transmission could be employed to reduce interference among CR nodes and delay |

The study in (SKLIVANITIS *et al.*, 2018), published in July 2018, is a pilot work. The authors designed, developed and validated through real indoor and outdoor experiments CR platform for UAVs. To the best of my knowledge, it is the first work involving a real CR-based UAV experiment. Their experiment involves on-ground CR nodes interacting with a CR-based UAV, and it shows that their proposed platform optimises wireless networks subject to interference, thus maximising their throughput. However, because this work involves a low-cost CR-based platform, it differs to their work. Moreover, this work's validation experiment includes security not present within the scope of their work.

## 3.3 Final Remarks

This chapter indicated the first steps taken towards integrating CR with UAV, and a review of the state-of-the-art of CR for UAV communications. Based on this review, it is clear that, although this field has been studied for several years, it has yet to reach its prime. Herein, I identify gaps, challenges, and works that could complement each other, in particular regarding the impact of CR to UAVs energy consumption, and the effects of UAVs mobility to CR spectrum mobility and spectrum sharing, as well as the need for real scenario experiments.

With regards to the analysed papers, in general, they can be separated in two groups: one using SDR-based UAVs for different applications; and other studying the impact of integrating CR technology with UAVs, mainly with theoretical analysis and simulation results. A notable exception to this is that publication (SKLIVANITIS *et al.*, 2018). Their work, however, demands a high level of investment and their strategy is suitable for investigating the behaviour of multiple CR-based UAVs deployed together. Although their work presents valuable strategies and results, the majority of the reviewed papers using simulated data do not require that level of complexity to perform their experiments in real scenario instead.

In the next chapter, the experiments and results of this work are shown. The strategy that was utilised in this work demands low levels of investment. It is also suitable for a number of experiments on the field, in particular those using simulated data to analyse CR-based UAVs spectrum mobility/handover strategies.

CHAPTER

4

# EXPERIMENTS AND RESULTS

## 4.1 Chapter Overview

Aiming at the global validation of CR for UAVs, it was necessary to execute major experiments. This chapter presents the main experiments accomplished in this work, as well as its results.

## 4.2 Scenario Specification

The first step of this work was to undertake a deep literature review. It is one of the main activities in this work. For example, through this literature review, it was possible to identify the major contribution of this work: the pioneering in creating a low-cost prototypical platform of a CR-based UAV.

Firstly, I examined works and research topics being conducted in the laboratory. Then, I chose a recent survey for each relevant research topic, to investigate gaps to explore in this work. Thus, an early systematic review was conducted regarding spectrum mobility in CR networks, inspired by a survey (SALEEM; REHMANI; ZEADALLY, 2015). The first systematic review exposed that much work has been done involving CR and UAVs separately, but the integration between the two is fairly unexplored.

This work presents the second systematic review I conducted. It focused on the study efforts for integrating CR with UAVs, and it revealed Alexander Young in his PhD dissertation (YOUNG, 2012) took the first notable steps towards CR-based UAVs. The recent publication in (SKLIVANITIS *et al.*, 2018) also presented a major contribution in the field. The main results of this project's review were presented in Chapter 2.

Although two systematic reviews were carried out, the literature review is a continuous process in this work. This continuity is especially processed using web paper alerts, but main authors, conferences and journals in the field are also followed.

Because of the paucity in works related to CR-based UAVs, the second step of this work was to evaluate possible compatibilities of existing CR technologies and strategies with UAVs. At this stage of the work, CR equipment was studied, classified, and characterised, to find compatibilities in terms of size, energy consumption, etc., so they can be integrated with a UAV. In this process, data sheets and parameters such as physical dimensions of the board, energy consumption, cost, bandwidth, radio frequency coverage, and half duplex / full duplex operation, which may influence the integration with the UAV, were taken into consideration.

There was also a need to execute a characterisation and evaluation of CR algorithms presented in the literature. They were studied, implemented, and evaluated, to define which algorithms and strategies are more suitable to UAVs. Aspects such as response time, accuracy, data throughput and energy efficiency were taken into consideration.

The next stage was to develop and test a CR platform with the purpose to integrate it with the UAV. It was developed with a Raspberry Pi 3 connected to an RTL SDR 820T2 (RTL-SDR, 2018) as the radio front-end with a basic antenna. The RTL SDR 820T2 is a simple and low-cost USB SDR receptor which frequency coverage varies from 30 MHz to 1.8 GHz. Figure 9 shows the CR platform; a picture taken in the laboratory.

Figure 9 – CR platform built for this work. This is equipped with a basic antenna, an RTL SDR 820T2 as the radio front-end, and a Raspberry Pi 3.

Source: the author

Although the RTL SDR 820T2 does not support wireless data transmission (it only supports wireless data reception), its low-cost feature makes it a valuable tool for CR experiments, as most of the gaps are not found in the transmission itself, but in the received data processing and decision-making. For example, to evaluate a given spectrum handover algorithm, a CR device is not required to transmit wireless data itself. It only needs to sense the environment and decide whether to vacate the channel.

A Parrot AR.Drone 2.0 (Parrot, 2018a) UAV was chosen to be integrated with the CR platform built for this work. Figure 10 shows the Parrot AR.Drone 2.0 UAV used in this project.

Figure 10 – The Parrot AR.Drone 2.0 UAV.

Source: the author

Because Parrot AR.Drone 2.0 is a typical commercial drone widely used for entertainment, it fits the "keep it simple" requirement of this project, and it is also appropriated to test the CR platform suitability to mini-UAVs. Because the Parrot AR.Drone 2.0 is not open in hardware nor in software (except for an SDK intended for the development of smartphones, smartwatches, or VR glasses applications (Parrot, 2018b)), it is not possible to make changes directly to the UAV. However, both the CR platform and the Parrot AR.Drone 2.0 run Linux operating systems (Parrot, 2018b), therefore this work results are equally valid for open-source/open-hardware Linux-based UAVs.

Moreover, this UAV provides a USB port on its top. This port will be the interface to connect the CR platform to it. Figure 11 shows a picture taken in the laboratory of the Parrot AR.Drone 2.0 without its hull, in which it is possible to see its USB port.

Because of the low energy supply provided by the the Parrot AR.Drone 2.0, it was

Figure 11 – The Parrot AR.Drone 2.0 without its hull, highlighting its USB port.

Source: the author (SANTANA; CRISTO; BRANCO, 2021).

necessary to efficiently adapt the CR platform. I changed its operational system to Ubuntu Mate, in order to have a better general compatibility with third parties software, and more control over unnecessary background processing. It was also integrated with RLTSDR-Scanner, which is an open-source cross platform Python frequency scanning tool for RTL SDR, whose source is available at (EARTOEAROAK, 2019).

Finally, it was possible to deploy the CR-based UAV testbed outdoor. Figure 12 the testbed developed and deployed in this work. Because of the influence that an indoor environment could cause to radio data collection (for instance, because of walls, other devices etc.), outdoor data collection is a key factor to determine the quality of the collected data.

## 4.3 Systematic Review

The first result obtained during this work is the literature review. It was published at the ICUAS'18 - The 2018 International Conference on Unmanned Aircraft Systems, with the title "Cognitive Radio for UAV communications: Opportunities and future challenges" (SANTANA *et al.*, 2018). The paper presents a review of the state-of-the-art of CR-based UAVs. It shows an overview on Spectrum Mobility for CR-based UAVs, and also their hardware and software constraints and requirements. Its main contribution is to highlight the demand of future research on special CR for UAVs, and to summarise opportunities and future challenges (a link for the full paper can be found in Appendix E).

The review results led me to contribute as a co-author of the paper "MARIO: A Cognitive Radio Primary User Arrivals Data Generator", published in the WoCCES'18 6th Workshop on Communications in Critical Embedded Systems, in conjunction with the ISCC'18 - IEEE Symposium on Computers and Communications (CRISTO *et al.*, 2018). The paper presents

Figure 12 – The CR-based UAV testbed developed for this work. It consists of a Parrot AR.Drone 2.0 (Parrot, 2018a) UAV with a CR platform embedded to it.

Source: the author (SANTANA; CRISTO; BRANCO, 2021).

MARIO, a simple and intuitive data generator tool of *Primary User* (PU) arrivals. It offers the opportunity of generating spectrum traffic data in a "keep it simple" concept, without the need of using a complex and counter-intuitive simulator (a link to the full paper can be found in Appendix E).

## 4.4 CR Platform

An additional result is the development of the CR platform shown in Figure 9. To validate the platform operation, first I deployed it as a sensor on Electrosense [1]. This sensor was deployed in the laboratory in which this work is under development. It is equipped with a basic antenna, an RTL SDR 820T2 (RTL-SDR, 2018) as the radio front-end, and a Raspberry Pi 3 (Raspberry Pi Foundation, 2018) with the Electrosense software. The main idea with deploying the CR platform as a sensor is to use it to detect and predict PU arrivals, as a way to validate the platform.

I used the Electrosense open API to collect five days of data from two different spectrum bands: from 144MHz to 148MHz, and from 806MHz to 824Mhz. According to the local Agency of Telecommunications (Anatel) (Anatel, 2018), those spectrum bands PUs are intended to serve *Amateur Radio* (AR) and *Mobile Phone* (MP), respectively (Anatel, 2018). Then, I applied the *Energy Detector* (ED) [2] in the collected data to determine the AR and the MP PU presence/absence thresholds: $\gamma_{AR}$ and $\gamma_{MP}$, respectively. Thus, I obtained as the outcome whether

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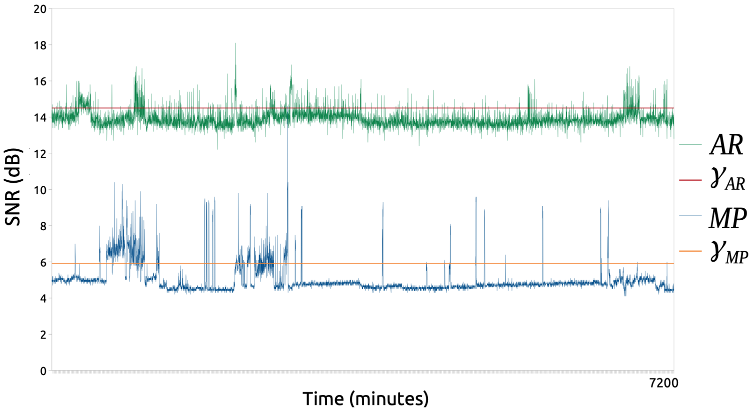
[1] More details on Electrosense can be found in Appendix A.

[2] More details on ED can be found in Appendix B.

the PU was present or not. As the data collected from the Electrosense contains the signal power and the *Hidden Markov Model* (HMM) [3] inputs are states, the ED is needed before to make such a conversion. In this work, the ED receives channel signal power through the time, and for each time slot two states are returned by the ED: busy channel or idle channel. These states are the HMM input. Finally, after applying the ED, the HMM is applied by considering that the first four collected days (80%) were used to train the algorithm, with the fifth day (20%) being used to test the prediction accuracy.

Figure 13 shows the collected spectrum data for five days in both spectrum bands: AR and MP. The calculated signal-to-noise ratio (SNR) thresholds, $\gamma_{AR} = 14.5Db$ and $\gamma_{MP} = 5.9Db$, are also presented. It is the data collected from our sensor via the Electrosense open API. As previously mentioned, $\gamma_{AR} = 14.5Db$ and $\gamma_{MP} = 5.9Db$ were calculated using the ED. Thus, the AR SNR over $\gamma_{AR} = 14.5Db$ are considered as the AR presence in its channel, whereas AR SNR values below $\gamma_{AR} = 14.5Db$ are considered as the AR absence. Analogously, the MP SNR values over $\gamma_{MP} = 5.9Db$ represent the MP presence, while MP SNR values below $\gamma_{MP} = 5.9Db$ represent the MP absence in its channel.

Figure 13 – Five days collected spectrum data from AR and MP with the resultant thresholds using the ED.



Source: the author (Santana *et al.*, 2019).

Figure 14 and Figure 15 present the results of the HMM applied to an AR and a MP, respectively. The first 80%-portion is only shown as channel data, as it was used only for training. The last 20%-portion is used to test and compare the prediction with the channel data. The colored vertical lines represent the channel as being busy; the channel is idle otherwise.

The experiment shows that, although the ED demanded low computational cost, it may not be suitable to be used for PU detection in a CR context. When the ED was applied to detect AR, AR transmission power was often too low, causing the threshold to result in a low value, thus channel noise was often detected as occupation of the channel by the AR. Furthermore, although MP had a high transmission power when arrived in the channel, the channel noise changed

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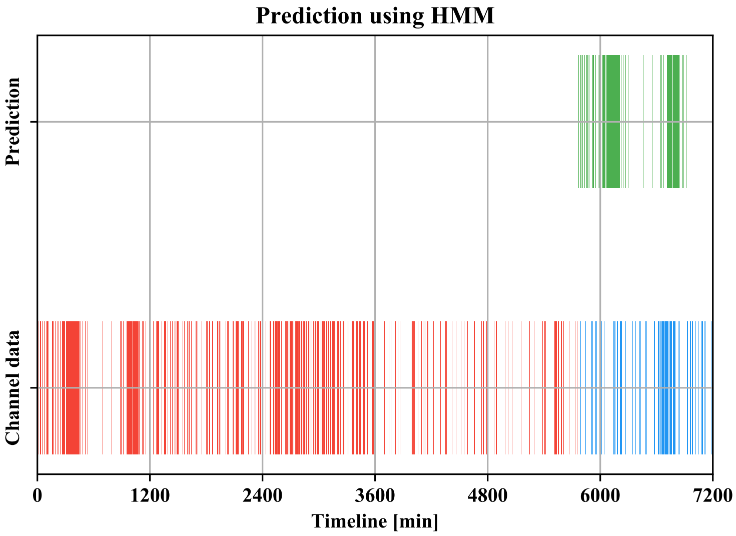
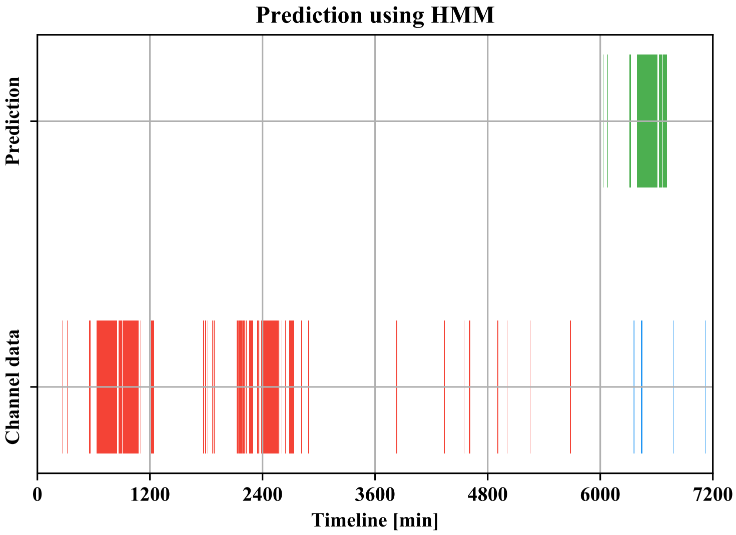
[3] More details on HMM can be found in Appendix C.

Figure 14 – Prediction of AR arrivals using HMM. The red corresponds to the 80%-portion of training and blue corresponds to the 20%-portion used to compare with the predicted sequence, in green.



Source: the author (Santana *et al.*, 2019).

Figure 15 – Prediction of MP arrivals using HMM. The red corresponds to the 80%-portion of training and blue corresponds to the 20%-portion used to compare with the predicted sequence, in green.



Source: the author (Santana *et al.*, 2019).

throughout the days. It led the threshold to be unbalanced in some periods. Other PU detection methods should consider more information besides channel noise and PU power. Therefore, the HMM cannot predict accurately AR and MP arrivals.

Furthermore, real PUs in general present no transmission or arrival pattern, usually with a random behaviour. Because simulated PUs are often developed following some arrival patterns, the HMM accuracy increases significantly when applied in a simulation. A PU should be classified as predictable or random. In stationary CR, it is possible to have prior information regarding the PU, hence predictable PUs could be identified and their data could be used for training. Each predictable PU might need a specific training algorithm. However, in mobile CR networks, it may be difficult to obtain any prior information on PUs, as there are different PUs in different geographic locations. Traditional prediction methods do not meet mobile CR application requirements. The first reason is a PU would have to be classified as predictable, and then its data would be collected and used for training. This is impracticable considering mobile CR time and resources constraints.

The first result obtained at this stage were published at the WoCCES'19 - The 2019 Workshop on Communications in Critical Embedded Systems (as part of IEEE ISCC 2019), with the title "A Case Study of Primary User Arrival Prediction Using the Energy Detector and the Hidden Markov Model in Cognitive Radio Networks" (Santana *et al.*, 2019) (a link to the full paper can be found in Appendix E).

## 4.5 CR-based UAV testbed

The final experiment conducted in this work comprises executing a typical jamming attack to the CR-based UAV testbed outdoor. The CR should detect the jammed frequency range as busy and then switch to a backup frequency, thus avoiding the jamming attack consequences.

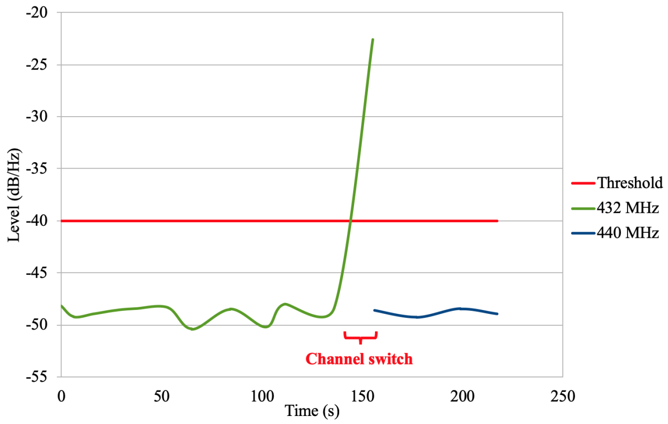
In this experiment, I used a jammer device capable of jamming the frequency 432MHz, and the CR-based UAV testbed. Firstly, I deployed the CR-based UAV sensing the 432MHz frequency. Secondly, I used the jammer device to execute the jamming attack in that frequency. The CR-based UAV then sensed the high signal level in that frequency and it automatically switched to its backup frequency. Although it was an outdoor experiment, it was important to isolate it, keeping it away from other variables. Hence, I experimentally defined its backup channel as 440MHz and its level threshold to -40dB. It was necessary to avoid that other PUs and/or SUs interfered in the experiment, and to reduce the incidence of false alarms.

The algorithm applied was reactive with a backup channel. It consists of keeping sensing the environment and checking whether the current channel signal ls lower than the prefixed threshold. It would only switch to the backup channel in case signal higher than the threshold is sensed. It would, then, stop sensing, immediately switch to the backup channel, and restart sensing. The validation of different algorithms for spectrum handover and PU detection are beyond the scope of this experiment.

Figure 16 shows that the CR-based UAV testbed performed as expected under a jamming attack.

For a clearer understanding of the radio spectrum environment within the frequency range from 432MHz to 441MHz, I used the CR platform to make a data collection during a jamming

Figure 16 – Data collected using the CR-based UAV. It kept using the 432MHz frequency until it sensed a transmission level over the threshold. It then switched to its backup channel at 440MHz.



Source: the author (SANTANA; CRISTO; BRANCO, 2021).

attack, in similar circumstances to the CR-based UAV testbed experiment. Figure 17 shows the data collected. It highlights the 432MHz frequency level discrepancy under the jamming attack, related to other frequencies within the measured range.

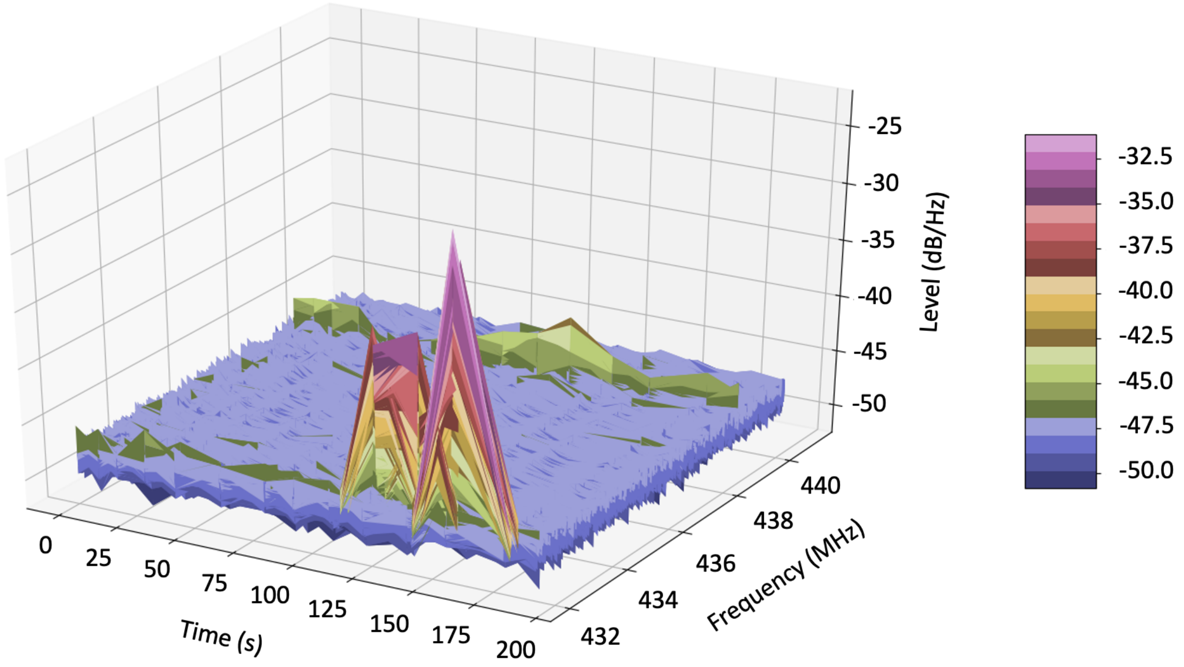
These results show that even switching to a channel around the same frequency bands could be enough to avoid a jamming attack, considering the attacker does not have access to the new channel. Also, note that we used a simple reactive algorithm based on static channel noise threshold, but especially proactive algorithms may benefit from such data collections, since Machine Learning techniques could be trained and tested over real-scenario data.

The results of the CR-based UAV tested, as well as an overview of CR-based UAVs, were published in the journal Sensors, in 2021, with the title "Integrating Cognitive Radio with Unmanned Aerial Vehicles: An Overview" (SANTANA; CRISTO; BRANCO, 2021) (a link to the full paper can be found in Appendix E).

## 4.6 Final Remarks

This chapter presented the relevant experiments and results obtained throughout this work. It started outlining publications as a result of literature review. Then it showed experiments and results from the use of the CR platform and the CR-based UAV. Next chapter presents the conclusions and future works.

Figure 17 – Data collected using the CR platform. It shows a map of the level in dB measured within the frequency range from 432MHz to 441MHz throughout the time.



Source: the author (SANTANA; CRISTO; BRANCO, 2021).

# CHAPTER 5

# CONCLUSIONS

UAVs demand technologies so they can not only fly autonomously, but also communicate with base stations, flight controllers, computers, devices or even other UAVs. Still, UAVs usually operate within unlicensed spectrum bands, competing against the increasing number of mobile devices and other wireless networks. Combining UAVs with CR may increase their general communication performance, thus allowing them to execute missions where the conventional UAVs face limitations. CR provides a smart wireless communication which, instead of using a transmission frequency defined in the hardware, uses software transmission. CR smartly uses free transmission channels and/or chooses them according with application's requirements. Moreover, CR is considered a key enabler for deploying technologies that require high connectivity, such as Smart Cities, 5G, IoT, and the IoFT.

However, CR-based UAVs are an emerging, though promising, research field taking it early steps towards a satisfactory integration. Several questions remain unclear, in particular regarding the impact of CR to UAVs energy consumption, and the effects of UAVs mobility to CR spectrum mobility and spectrum sharing.

This work not only highlighted gaps, issues and future challenges in the area, but it also addressed some of them. In particular, this work differs to the majority of the works in the field by having a real world approach. "Simulation-only" methods were quickly discard in order to prioritise the deployment of a pioneer low-cost CR-based UAV testbed in a real world scenario. The evaluation of CR algorithms and technologies was carried out with a focus on validating which methods fulfil the energy and physical space constraints of UAVs, following the same real world approach. It also aimed to improve the overall communication performance and security of UAVs.

The experiments executed in this work showed there is a huge gap between simulation and practical results when it comes to CR-based UAVs. The recent growth of works in the field might address such issues, by developing specific CR hardware, software, and algorithms suitable for UAVs. Future work might also use real world experiments as validation for the high number of simulated results.

## 5.1 Difficulties Found

The first difficulty was found during the literature review. It was supposed to be a review on works involving real CR-based UAVs; none was found at that time though. It was then necessary to change the review approach seeking for surrounding areas and researches.

The paucity of CR works addressing UAVs was a difficulty during all the project. Nearly no information on which CR hardware, software or algorithms were suitable for UAVs could be find within the literature. Every step taken in this project demeaned deep research in different surrounding fields to succeed.

The lack of totally open-source and open-hardware Linux based UAVs and CRs on the market was also a difficulty. Current CR hardware compatible with mini UAVs can barely be found, and it is even more scarce (or even nonexistent) when it comes to open-source and open-hardware Linux based compatible UAVs and CRs.

## 5.2 Contributions

In this work, firstly I presented an overview on CR-based UAVs, as well as their hardware and software requirements. I also indicated the first steps taken towards integrating CR with UAVs, and a review of the state-of-the-art of CR for UAV communications. This work has also shown that several questions remain unclear in the field.

Secondly, I described a low-cost CR platform for experiments. I used it to undertake a case study of two PUs arrivals prediction using the HMM in CR. I showed that the traditional method of combining the ED with the HMM for PU arrivals forecast may not be suitable in a real CR context, especially in mobile CR networks (e.g., VANETs and FANETs). Real life noise power data may vary throughout the time, causing the ED to detect noise as a PU. Additionally, in mobile CR networks, the PU transmission power varies in different spectrum environments. Moreover, real life PUs may present no pattern, thus significantly decreasing the HMM accuracy.

This work was also pioneer in proposing, developing, and deploying a low-cost CR-based UAV testbed suitable for experimentation. It was described and characterised. It was used to execute a mission in which it is performed as expected by avoiding a jamming attack, accordingly to the CR features.

## 5.3 Scientific Productions

### 5.3.1 Journal Papers

**Dias Santana, G.M.**; Cristo, R.S.d.; Lucas Jaquie Castelo Branco, K.R. Integrating Cognitive Radio with Unmanned Aerial Vehicles: An Overview. Sensors 2021, 21, 830. doi: 10.3390/s21030830.

### 5.3.2 Conference Papers

**G. M. D. Santana**, R. S. Cristo, C. Dezan, J. Diguet, D. P. M. Osorio and K. R. L. J. C. Branco, "Cognitive Radio for UAV communications: Opportunities and future challenges," 2018 International Conference on Unmanned Aircraft Systems (ICUAS), Dallas, TX, 2018, pp. 760-768, doi: 10.1109/ICUAS.2018.8453329.

R. S. Cristo, **G. M. D. Santana**, D. P. M. Osorio and K. R. L. J. C. Branco, "MARIO: A Cognitive Radio Primary User Arrivals Data Generator," 2018 IEEE Symposium on Computers and Communications (ISCC), Natal, 2018, pp. 01137-01142, doi: 10.1109/ISCC.2018.8538660.

**G. M. D. Santana**, R. S. Cristo, J. -P. Diguet, C. Dezan, O. Diana P. M. and B. Kalinka R. L. J. C., "A Case Study of Primary User Arrival Prediction Using the Energy Detector and the Hidden Markov Model in Cognitive Radio Networks," 2019 IEEE Symposium on Computers and Communications (ISCC), Barcelona, Spain, 2019, pp. 1195-1198, doi: 10.1109/ISCC47284.2019.8969632.

### 5.3.3 Poster Presentations

2o Encontro Paulista de Pós-Graduandos em Computação.Integrando rádio cognitivo a veículos aéreos não tripulados. 2018. *2nd Sao Paulo Meeting of Graduate Students in Computing. Integrating cognitive radio with unmanned aerial vehicles. 2018.*

## 5.4 Future Work Suggestions

Several future works shall complement this work, such as:

1. to analyse the impact of a UAV mobility to CR mobility algorithms;
2. to compare the energy consumption of a CR-based UAV and a traditional UAV in both overcrowded uncrowded radio environments;
3. to investigate PUs from different geographic locations and how other spectrum sensing and arrivals prediction methods (e.g., the MSM) can solve the question. Considering mobile CR, such as vehicular CR networks, would be a major contribution;

4. and to develop an open-source/open-hardware fixed wing UAV using a CR as its wireless unity.

# BIBLIOGRAPHY

ABDELRASSOUL, R.; FATHY, E.; ZAGHLOUL, M. S. Comparative study of spectrum sensing for cognitive radio system using energy detection over different channels. In: **2016 World Symposium on Computer Applications Research (WSCAR)**. [S.l.: s.n.], 2016. p. 32–35. Citations on pages 32 and 33.

AbdulCareem, M. A.; Gomez, J.; Saha, D.; Dutta, A. Rfeye in the sky. **IEEE Transactions on Mobile Computing**, p. 1–1, 2020. Citations on pages 43 and 46.

ABEYWARDANA, R. C.; SOWERBY, K. W.; BERBER, S. M. Simucrv: A simulation framework for cognitive radio enabled vehicular ad hoc networks. In: **2017 IEEE 85th Vehicular Technology Conference (VTC Spring)**. [S.l.: s.n.], 2017. p. 1–5. Citation on page 35.

Adane, Y. A smart digital software radio transceiver design concept for uav and autonomous vehicles application. In: **2019 Advances in Science and Engineering Technology International Conferences (ASET)**. [S.l.: s.n.], 2019. p. 1–6. Citations on pages 42 and 46.

Aftab, F.; Khan, A.; Zhang, Z. Hybrid self-organized clustering scheme for drone based cognitive internet of things. **IEEE Access**, v. 7, p. 56217–56227, 2019. Citations on pages 42 and 49.

AKPAKWU, G. A.; SILVA, B. J.; HANCKE, G. P.; ABU-MAHFOUZ, A. M. A survey on 5g networks for the internet of things: Communication technologies and challenges. **IEEE Access**, v. 6, p. 3619–3647, 2018. Citations on pages 22 and 27.

AKYILDIZ, I. F.; LEE, W. y.; VURAN, M. C.; MOHANTY, S. A survey on spectrum management in cognitive radio networks. **IEEE Communications Magazine**, v. 46, n. 4, p. 40–48, April 2008. ISSN 0163-6804. Citations on pages 33 and 83.

ALI, A.; HAMOUDA, W. Advances on spectrum sensing for cognitive radio networks: Theory and applications. **IEEE Communications Surveys Tutorials**, v. 19, n. 2, p. 1277–1304, Secondquarter 2017. Citation on page 83.

Almasoud, A. M.; Kamal, A. E. Data dissemination in iot using a cognitive uav. **IEEE Transactions on Cognitive Communications and Networking**, v. 5, n. 4, p. 849–862, 2019. Citations on pages 42 and 49.

ANANDAKUMAR, H.; UMAMAHESWARI, K. Supervised machine learning techniques in cognitive radio networks during cooperative spectrum handovers. **Cluster Computing**, v. 20, n. 2, p. 1505–1515, Jun 2017. ISSN 1573-7543. Available: <https://doi.org/10.1007/s10586-017-0798-3>. Citation on page 34.

Anatel. **Anatel - Agência Nacional de Telecomunicações**. 2018. Http://www.anatel.gov.br/. Accessed: 13 jun 2018. Citation on page 57.

ANDERSON, A.; FREW, E. W.; GRUNWALD, D. Cognitive radio development for uas applications. In: **2015 International Conference on Unmanned Aircraft Systems (ICUAS)**. [S.l.: s.n.], 2015. p. 695–703. Citations on pages 41 and 45.

ANDRYEYEV, O.; ARTEMENKO, O.; MITSCHELE-THIEL, A. Improving the system capacity using directional antennas with a fixed beam on small unmanned aerial vehicles. In: **2015 European Conference on Networks and Communications (EuCNC)**. [S.l.: s.n.], 2015. p. 139–143. Citations on pages 41 and 47.

ARJOUNE, Y.; KAABOUCH, N. A comprehensive survey on spectrum sensing in cognitive radio networks: Recent advances, new challenges, and future research directions. **Sensors**, MDPI AG, v. 19, n. 1, p. 126, Jan 2019. ISSN 1424-8220. Available: <http://dx.doi.org/10.3390/s19010126>. Citation on page 33.

ARNOSTI, S. Z.; PIRES, R. M.; BRANCO, K. R. L. J. C. Evaluation of cryptography applied to broadcast storm mitigation algorithms in fanets. In: **2017 International Conference on Unmanned Aircraft Systems (ICUAS)**. [S.l.: s.n.], 2017. p. 1368–1377. Citation on page 21.

AUSTIN, R. **Unmanned Aircraft Systems: UAVS Design, Development and Deployment**. [S.l.]: Wiley, 2010. (Aerospace Series). ISBN 9780470664803. Citations on pages 21 and 29.

BALDINI, G.; STURMAN, T.; BISWAS, A. R.; LESCHHORN, R.; GODOR, G.; STREET, M. Security aspects in software defined radio and cognitive radio networks: A survey and a way ahead. **IEEE Communications Surveys Tutorials**, v. 14, n. 2, p. 355–379, Second 2012. ISSN 1553-877X. Citation on page 27.

BANSAL, T.; LI, D.; SINHA, P. Opportunistic channel sharingin cognitive radio networks. **IEEE Transactions on Mobile Computing**, v. 13, n. 4, p. 852–865, April 2014. ISSN 1536-1233. Citation on page 35.

BARRADO, C.; MESSEGUER, R.; LOPEZ, J.; PASTOR, E.; SANTAMARIA, E.; ROYO, P. Wildfire monitoring using a mixed air-ground mobile network. **IEEE Pervasive Computing**, v. 9, n. 4, p. 24–32, October 2010. ISSN 1536-1268. Citation on page 23.

BENTO, M. d. F. (Ed.). **Unmanned aerial vehicles: an overview**. [S.l.]: Inside GNSS, 2008. 54-61 p. Citation on page 29.

Bertizzolo, L.; D'Oro, S.; Ferranti, L.; Bonati, L.; Demirors, E.; Guan, Z.; Melodia, T.; Pudlewski, S. Swarmcontrol: An automated distributed control framework for self-optimizing drone networks. In: **IEEE INFOCOM 2020 - IEEE Conference on Computer Communications**. [S.l.: s.n.], 2020. p. 1768–1777. Citations on pages 43 and 44.

BROWN, T. X.; MCHENRY, M.; JAROONVANICHKUL, S. Cognitive radio architectures for unmanned aircraft systems. In: ____. **Handbook of Unmanned Aerial Vehicles**. Dordrecht: Springer Netherlands, 2015. p. 813–844. ISBN 978-90-481-9707-1. Available: <https://doi.org/10.1007/978-90-481-9707-1_31>. Citations on pages 41 and 46.

CABRIC, D.; MISHRA, S. M.; BRODERSEN, R. W. Implementation issues in spectrum sensing for cognitive radios. In: **Conference Record of the Thirty-Eighth Asilomar Conference on Signals, Systems and Computers, 2004.** [S.l.: s.n.], 2004. v. 1, p. 772–776 Vol.1. Citation on page 33.

CAI, X.; GONZALEZ-PLAZA, A.; ALONSO, D.; ZHANG, L.; RODRíGUEZ, C. B.; YUSTE, A. P.; YIN, X. Low altitude uav propagation channel modelling. In: **2017 11th European Conference on Antennas and Propagation (EUCAP)**. [S.l.: s.n.], 2017. p. 1443–1447. Citations on pages 42 and 44.

Che, Y. L.; Luo, S.; Wu, K. Spectrum sharing based cognitive uav networks via optimal beamwidth allocation. In: **ICC 2019 - 2019 IEEE International Conference on Communications (ICC)**. [S.l.: s.n.], 2019. p. 1–6. Citations on pages 42 and 48.

CHEN, H.; KUNG, H. T.; VLAH, D.; HAGUE, D.; MUCCIO, M.; POLAND, B. Collaborative compressive spectrum sensing in a uav environment. In: **2011 - MILCOM 2011 Military Communications Conference**. [S.l.: s.n.], 2011. p. 142–148. ISSN 2155-7586. Citations on pages 41 and 43.

CHEN, X.; WEI, Z.; TIAN, H.; FENG, Z. Space-time spectrum sharing for unmanned aerial vehicle networks. In: **2018 IEEE/CIC International Conference on Communications in China (ICCC Workshops)**. [S.l.: s.n.], 2018. p. 126–130. ISSN 2474-9133. Citation on page 48.

CHOURABI, H.; NAM, T.; WALKER, S.; GIL-GARCIA, J. R.; MELLOULI, S.; NAHON, K.; PARDO, T. A.; SCHOLL, H. J. Understanding smart cities: An integrative framework. In: **2012 45th Hawaii International Conference on System Sciences**. [S.l.: s.n.], 2012. p. 2289–2297. ISSN 1530-1605. Citation on page 23.

CHRISTIAN, I.; MOH, S.; CHUNG, I.; LEE, J. Spectrum mobility in cognitive radio networks. **IEEE Communications Magazine**, v. 50, n. 6, p. 114–121, June 2012. ISSN 0163-6804. Citations on pages 32, 34, and 36.

CRISTO, R. S.; SANTANA, G. M. D.; OSORIO, D. P. M.; BRANCO, K. R. L. J. C. Mario: A cognitive radio primary user arrivals data generator. In: **6th Workshop on Communications in Critical Embedded Systems**. [S.l.: s.n.], 2018. p. 7–12. Citation on page 56.

D'Alterio, F.; Ferranti, L.; Bonati, L.; Cuomo, F.; Melodia, T. Quality aware aerial-to-ground 5g cells through open-source software. In: **2019 IEEE Global Communications Conference (GLOBECOM)**. [S.l.: s.n.], 2019. p. 1–6. Citations on pages 43 and 44.

DUNNE, B. E.; KEENLANCE, P. Drones and satellites: Identifying interdisciplinary capstone projects with other departments at your own university. In: **2018 ASEE Annual Conference & Exposition**. Salt Lake City, Utah: ASEE Conferences, 2018. Https://peer.asee.org/30345. Citations on pages 42 and 45.

Dà-Jiāng Innovations Science and Technology Co. Ltd. **DJI — The Future of Possible**. 2018. Https://www.dji.com/. Accessed: 28 aug 2018. Citations on pages 29 and 30.

EARTOEAROAK. **EarToEarOak/RLTSDR-Scanner: A cross platform Python frequency scanning GUI for the OsmoSDR rtl-sdr library**. 2019. Https://github.com/EarToEarOak/RTLSDR-Scanner. Accessed: 08 apr 2019. Citation on page 56.

ELECTROSENSE. **ElectroSense — Collaborative Spectrum Monitoring**. 2018. Https://electrosense.org/. Citation on page 81.

European Telecommunications Standards Institute. **TErms and Definitions Database Interactive (TEDDI)**. 2018. <https://webapp.etsi.org/Teddi/>. Accessed: 11 feb 2018. Citation on page 27.

Figueira, N. M.; Niedermeier Belmonte, G.; de Freitas, E. P. C4isr systems applied to amazonian constraints*. In: **2020 International Conference on Unmanned Aircraft Systems (ICUAS)**. [S.l.: s.n.], 2020. p. 568–572. Citations on pages 43 and 46.

FOUDA, R. M. Security vulnerabilities of cyberphysical unmanned aircraft systems. **IEEE Aerospace and Electronic Systems Magazine**, v. 33, n. 9, p. 4–17, Sep. 2018. ISSN 0885-8985. Citation on page 45.

GeorgiaTech. **NS-3 - A Discrete-Event Network Simulator for Internet Systems**. 2018. Https://www.nsnam.org/. Accessed: 2020-11-15. Citation on page 35.

GERSHENFELD, N.; KRIKORIAN, R.; COHEN, D. The internet of things. **Scientific American**, Scientific American, a division of Nature America, Inc., v. 291, n. 4, p. 76–81, 2004. ISSN 00368733, 19467087. Available: <http://www.jstor.org/stable/26060727>. Citation on page 21.

GHAFOOR, S.; SUTTON, P. D.; SREENAN, C. J.; BROWN, K. N. Cognitive radio for disaster response networks: survey, potential, and challenges. **IEEE Wireless Communications**, v. 21, n. 5, p. 70–80, October 2014. ISSN 1536-1284. Citation on page 23.

GHAZZAI, H.; GHORBEL, M. B.; KADRI, A.; HOSSAIN, M. J.; MENOUAR, H. Energy-efficient management of unmanned aerial vehicles for underlay cognitive radio systems. **IEEE Transactions on Green Communications and Networking**, v. 1, n. 4, p. 434–443, Dec 2017. Citations on pages 42 and 48.

GHORBEL, M. B.; GHAZZAI, H.; KADRI, A.; HOSSAIN, M. J.; MENOUAR, H. An energy efficient overlay cognitive radio approach in uav-based communication. In: **2018 IEEE Global Communications Conference (GLOBECOM)**. [S.l.: s.n.], 2018. p. 1–6. ISSN 2576-6813. Citation on page 48.

GKIONIS, G.; MICHALAS, A.; SGORA, A.; VERGADOS, D. D. An effective spectrum handoff scheme for cognitive radio ad hoc networks. In: **2017 Wireless Telecommunications Symposium (WTS)**. [S.l.: s.n.], 2017. p. 1–7. Citation on page 35.

GNU Radio. **The Free and Open Software Radio Ecosystem**. 2018. <https://www.gnuradio.org/>. Accessed: 11 feb 2018. Citation on page 35.

GONZALEZ, J. D. T.; FUNG, W. A pilot study on aeronautical surveillance system for drone delivery using heterogeneous software defined radio framework. In: **2017 IEEE International Conference on Real-time Computing and Robotics (RCAR)**. [S.l.: s.n.], 2017. p. 499–504. Citations on pages 42 and 47.

GUEVARA, K.; RODRIGUEZ, M.; GALLO, N.; VELASCO, G.; VASUDEVA, K.; GUVENC, I. Uav-based gsm network for public safety communications. In: **SoutheastCon 2015**. [S.l.: s.n.], 2015. p. 1–2. ISSN 1558-058X. Citations on pages 41 and 43.

GUPTA, L.; JAIN, R.; VASZKUN, G. Survey of important issues in uav communication networks. **IEEE Communications Surveys Tutorials**, v. 18, n. 2, p. 1123–1152, Secondquarter 2016. ISSN 1553-877X. Citation on page 31.

GUTIERREZ, R. M.; YU, H.; RONG, Y.; BLISS, D. W. Time and frequency dispersion characteristics of the uas wireless channel in residential and mountainous desert terrains. In: **2017 14th IEEE Annual Consumer Communications Networking Conference (CCNC)**. [S.l.: s.n.], 2017. p. 516–521. ISSN 2331-9860. Citations on pages 42 and 47.

HANIF, I.; ZEESHAN, M.; AHMED, A. Traffic pattern based adaptive spectrum handoff strategy for cognitive radio networks. In: **2016 10th International Conference on Next Generation Mobile Applications, Security and Technologies (NGMAST)**. [S.l.: s.n.], 2016. p. 18–23. Citation on page 37.

Hardkernel Co., Ltd. **ODROID | Hardkernel**. 2018. Https://www.hardkernel.com/. Accessed: 08 aug 2018. Citation on page 28.

HAROUNABADI, M.; PUSCHMANN, A.; ARTEMENKO, O.; MITSCHELE-THIEL, A. Tag: Trajectory aware geographical routing in cognitive radio ad hoc networks with uav nodes. In: MITTON, N.; KANTARCI, M. E.; GALLAIS, A.; PAPAVASSILIOU, S. (Ed.). **Ad Hoc Networks**. Cham: Springer International Publishing, 2015. p. 111–122. ISBN 978-3-319-25067-0. Citations on pages 41 and 47.

HASAN, N.; VALSALAN, P.; FAROOQ, U.; BAIG, I. On the recovery of terrestrial wireless network using cognitive uavs in the disaster area. **International Journal of Advanced Computer Science and Applications**, v. 11, n. 4, p. 819–822, 2020. Cited By 0. Citations on pages 43 and 49.

Hasan, N. u.; Ejaz, W.; Farooq, U.; Baig, I.; Zghaibeh, M. Adaptive error control framework for a multihop cognitive radio based uavs for disaster management. In: **2019 IEEE 5th International Conference on Mechatronics System and Robots (ICMSR)**. [S.l.: s.n.], 2019. p. 87–91. Citations on pages 42 and 49.

Hasan, N. U.; Zghaibeh, M.; Ejaz, W.; Shahid, A.; Anpalagan, A. On provision of resilient connectivity in cognitive unmanned aerial vehicles. In: **2019 IEEE International Conference on Communications Workshops (ICC Workshops)**. [S.l.: s.n.], 2019. p. 1–6. Citations on pages 42 and 49.

HERWITZ, S.; JOHNSON, L.; DUNAGAN, S.; HIGGINS, R.; SULLIVAN, D.; ZHENG, J.; LOBITZ, B.; LEUNG, J.; GALLMEYER, B.; AOYAGI, M.; SLYE, R.; BRASS, J. Imaging from an unmanned aerial vehicle: agricultural surveillance and decision support. **Computers and Electronics in Agriculture**, v. 44, n. 1, p. 49 – 61, 2004. ISSN 0168-1699. Available: <http://www.sciencedirect.com/science/article/pii/S0168169904000456>. Citation on page 23.

HORAPONG, K.; CHANDRUCKA, D.; MONTREE, N.; BUAON, P. Design and use of "drone" to support the radio navigation aids flight inspection. In: **2017 IEEE/AIAA 36th Digital Avionics Systems Conference (DASC)**. [S.l.: s.n.], 2017. p. 1–6. ISSN 2155-7209. Citations on pages 42 and 44.

HOSSAIN, E.; NIYATO, D.; KIM, D. I. Evolution and future trends of research in cognitive radio: a contemporary survey. **Wireless Communications and Mobile Computing**, v. 15, n. 11, p. 1530–1564, 2015. ISSN 1530-8677. Available: <http://dx.doi.org/10.1002/wcm.2443>. Citation on page 32.

HOSSEINI, N.; MATOLAK, D. W. Software defined radios as cognitive relays for satellite ground stations incurring terrestrial interference. In: **2017 Cognitive Communications for Aerospace Applications Workshop (CCAA)**. [S.l.: s.n.], 2017. p. 1–4. Citation on page 24.

HUANG, Y.; XU, J.; QIU, L.; ZHANG, R. Cognitive uav communication via joint trajectory and power control. In: **2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)**. [S.l.: s.n.], 2018. p. 1–5. ISSN 1948-3252. Citations on pages 42 and 48.

INSTRUMENTS, N. **LabVIEW - Laboratory Virtual Instrument Engineering Workbench**. 2018. Http://www.ni.com/en-us/shop/labview.html. Accessed: 2020-11-15. Citation on page 35.

JACOB, P.; SIRIGINA, R. P.; MADHUKUMAR, A. S.; PRASAD, V. A. Cognitive radio for aeronautical communications: A survey. **IEEE Access**, v. 4, p. 3417–3443, 2016. ISSN 2169-3536. Citations on pages 42 and 49.

JADON, A.; WILLIAMS, Z. T.; KAFKA, C.; ROTTA, H.; ROY, S.; LUM, C. W. A database system architecture for air-to-ground uas link characterization. In: **2018 AIAA Information Systems-AIAA Infotech @ Aerospace**. Salt Lake City, Utah: American Institute of Aeronautics and Astronautics, 2018. Citations on pages 42 and 45.

KANISTRAS, K.; MARTINS, G.; RUTHERFORD, M. J.; VALAVANIS, K. P. A survey of unmanned aerial vehicles (uavs) for traffic monitoring. In: **2013 International Conference on Unmanned Aircraft Systems (ICUAS)**. [S.l.: s.n.], 2013. p. 221–234. Citation on page 23.

KAPOOR, S.; RAO, S.; SINGH, G. Opportunistic spectrum sensing by employing matched filter in cognitive radio network. In: **2011 International Conference on Communication Systems and Network Technologies**. [S.l.: s.n.], 2011. p. 580–583. Citation on page 33.

KIM, H.; SHIN, K. G. In-band spectrum sensing in cognitive radio networks: Energy detection or feature detection? In: **Proceedings of the 14th ACM International Conference on Mobile Computing and Networking**. New York, NY, USA: ACM, 2008. (MobiCom '08), p. 14–25. ISBN 978-1-60558-096-8. Available: <http://doi.acm.org/10.1145/1409944.1409948>. Citations on pages 33 and 83.

Kornprobst, J.; Mauermayer, R. A. M.; Eibert, T. F. Versatile low-cost and light-weight rf equipment for field measurements. In: **2020 14th European Conference on Antennas and Propagation (EuCAP)**. [S.l.: s.n.], 2020. p. 1–3. Citations on pages 43 and 46.

Krayani, A.; Baydoun, M.; Marcenaro, L.; Gao, Y.; Regazzoni, C. S. Smart jammer detection for self-aware cognitive uav radios. In: **2020 IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications**. [S.l.: s.n.], 2020. p. 1–7. Citations on pages 43 and 48.

LERTSINSRUBTAVEE, A.; MALOUCH, N.; FDIDA, S. Controlling spectrum handoff with a delay requirement in cognitive radio networks. In: **2012 21st International Conference on Computer Communications and Networks (ICCCN)**. [S.l.: s.n.], 2012. p. 1–8. ISSN 1095-2055. Citation on page 37.

LI, L.; ZHOU, X.; XU, H.; LI, G. Y.; WANG, D.; SOONG, A. Energy-efficient transmission in cognitive radio networks. In: **2010 7th IEEE Consumer Communications and Networking Conference**. [S.l.: s.n.], 2010. p. 1–5. ISSN 2331-9852. Citation on page 25.

Liang, X.; Xu, W.; Gao, H.; Pan, M.; Lin, J.; Deng, Q.; Zhang, P. Throughput optimization for cognitive uav networks: A three-dimensional-location-aware approach. **IEEE Wireless Communications Letters**, v. 9, n. 7, p. 948–952, 2020. Citations on pages 43 and 49.

Liu, B.; Wan, Y.; Zhou, F.; Wu, Q.; Hu, R. Q. Robust trajectory and beamforming design for cognitive miso uav networks. **IEEE Wireless Communications Letters**, p. 1–1, 2020. Citations on pages 43 and 47.

LIU, X.; GUAN, M.; ZHANG, X.; DING, H. Spectrum sensing optimization in an uav-based cognitive radio. **IEEE Access**, v. 6, p. 44002–44009, 2018. ISSN 2169-3536. Citations on pages 42 and 48.

MALIK, S.; SHAH, M.; DAR, A.; HAQ, A.; KHAN, A.; JAVED, T.; KHAN, S. Comparative analysis of primary transmitter detection based spectrum sensing techniques in cognitive radio systems. **Australian Journal of Basic and Applied Sciences**, v. 4, n. 9, p. 4522–4531, 2010. Citation on page 32.

MARIANI, A.; GIORGETTI, A.; CHIANI, M. Energy detector design for cognitive radio applications. In: **2010 International Waveform Diversity and Design Conference**. [S.l.: s.n.], 2010. p. 000053–000057. ISSN 2150-4652. Citation on page 83.

Matheou, K. J.; Apaza, R. D.; Downey, A. N.; Kerczewski, R. J.; Jung, J.; Ippolito, C. A.; Modi, H. Analysis of at-altitude lte power spectra for small unmanned aircraft system c2 communications. In: **2019 Integrated Communications, Navigation and Surveillance Conference (ICNS)**. [S.l.: s.n.], 2019. p. 1–12. Citations on pages 42 and 45.

MathWorks. **Simulink - Simulation and Model-Based Design**. 2018. Https://www.mathworks.com/products/simulink.html. Accessed: 2020-11-15. Citation on page 35.

MATINMIKKO, M.; SER, J. D.; RAUMA, T.; MUSTONEN, M. Fuzzy-logic based framework for spectrum availability assessment in cognitive radio systems. **IEEE Journal on Selected Areas in Communications**, v. 31, n. 11, p. 2173–2184, November 2013. ISSN 0733-8716. Citation on page 33.

MICROELECTRONICS, H. **RFM22B FSK Transceiver**. 2018. Http://www.hoperf.com/rf$_transceiver/modules/RFM22BW.html.Accessed : 31jan2018.Citationonpage$31.

MIKO, G.; NEMETH, A. Combined communication and radio navigation system for small uavs. In: **2013 23rd International Conference Radioelektronika (RADIOELEKTRONIKA)**. [S.l.: s.n.], 2013. p. 284–287. Citations on pages 41 and 48.

MIKó, G.; NéMETH, A. Scfdm based communication system for uav applications. In: **2015 25th International Conference Radioelektronika (RADIOELEKTRONIKA)**. [S.l.: s.n.], 2015. p. 222–224. Citations on pages 41 and 47.

MITOLA, J. Cognitive radio: An integrated agent architecture for software defined radio, doctor of technology. **Royal Inst. Technol**, p. 271–350, Jan 2000. Citation on page 22.

Mohanti, S.; Bocanegra, C.; Meyer, J.; Secinti, G.; Diddi, M.; Singh, H.; Chowdhury, K. Airbeam: Experimental demonstration of distributed beamforming by a swarm of uavs. In: **2019 IEEE 16th International Conference on Mobile Ad Hoc and Sensor Systems (MASS)**. [S.l.: s.n.], 2019. p. 162–170. Citations on pages 43 and 44.

MOTLAGH, N. H.; BAGAA, M.; TALEB, T. Uav-based iot platform: A crowd surveillance use case. **IEEE Communications Magazine**, v. 55, n. 2, p. 128–134, February 2017. ISSN 0163-6804. Citation on page 22.

MURPHY, S. O.; BROWN, K. N.; SREENAN, C. Demo: Cellphone localisation using an autonomous unmanned aerial vehicle and software defined radio. In: **Proceedings of the 2017 International Conference on Embedded Wireless Systems and Networks**. USA: Junction Publishing, 2017. (EWSN &#8217;17), p. 254–255. ISBN 978-0-9949886-1-4. Available: <http://dl.acm.org/citation.cfm?id=3108009.3108067>. Citations on pages 42 and 44.

Murphy, S. O.; Sreenan, C.; Brown, K. N. Autonomous unmanned aerial vehicle for search and rescue using software defined radio. In: **2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring)**. [S.l.: s.n.], 2019. p. 1–6. Citations on pages 42 and 44.

Nie, R.; Xu, W.; Zhang, Z.; Zhang, P.; Pan, M.; Lin, J. Max-min distance clustering based distributed cooperative spectrum sensing in cognitive uav networks. In: **ICC 2019 - 2019 IEEE International Conference on Communications (ICC)**. [S.l.: s.n.], 2019. p. 1–6. Citations on pages 42 and 48.

NIR, V. L. **CogWave: Open-Source Software Framework for Cognitive Radio Waveform Design**. 2018. Https://github.com/vlenircissrma/CogWave. Accessed: 2020-11-15. Citation on page 35.

NIR, V. L.; SCHEERS, B. Evaluation of open-source software frameworks for high fidelity simulation of cognitive radio networks. In: **2015 International Conference on Military Communications and Information Systems (ICMCIS)**. [S.l.: s.n.], 2015. p. 1–6. Citation on page 32.

NOBLE, J.; LIEM, D. T.; TUAN, N. Q.; LUAT, D.; ASHARIF, M. R. Battalion-organic electronic fires: A tactical application of commercial unmanned systems and software-defined radios. In: **2017 Third Asian Conference on Defence Technology (ACDT)**. [S.l.: s.n.], 2017. p. 20–25. Citations on pages 42 and 48.

NOOR, N. M.; DIN, N. M.; AHMED, E.; KADIR, A. N. A. Omnet++ based cognitive radio simulation network. In: **2016 7th IEEE Control and System Graduate Research Colloquium (ICSGRC)**. [S.l.: s.n.], 2016. p. 28–33. Citation on page 35.

ONER, M.; JONDRAL, F. On the extraction of the channel allocation information in spectrum pooling systems. **IEEE Journal on Selected Areas in Communications**, v. 25, n. 3, p. 558–565, April 2007. ISSN 0733-8716. Citation on page 33.

OpenSim Ltd. **INET framework for OMNeT++**. 2018. Https://inet.omnetpp.org/. Accessed: 2020-11-15. Citation on page 35.

____. **Omnet++: Discrete Event Simulator**. 2018. Https://www.omnetpp.org/. Accessed: 2020-11-15. Citation on page 35.

PAN, Y.; DA, X.; HU, H. Joint optimization of sensing time and power allocation for uav cognitive radio systems. In: **Proceedings of the 5th International Conference on Communication and Information Processing**. New York, NY, USA: Association for Computing Machinery, 2019. (ICCIP '19), p. 254–258. ISBN 9781450372589. Available: <https://doi.org/10.1145/3369985.3370034>. Citations on pages 42 and 48.

Parrot. **Camera drones and applications | Official Parrot site**. 2018. Https://www.parrot.com/. Accessed: 19 aug 2018. Citations on pages 15, 55, and 57.

____. **Parrot for Developers**. 2018. Https://developer.parrot.com/. Accessed: 22 aug 2018. Citation on page 55.

PATHAK, M.; DHURANDHER, S. K.; WOUNGANG, I.; TUSHIR, B.; KUMAR, V.; TAKIZAWA, M.; BAROLLI, L. Power control scheme for underlay approach in cognitive radio networks. In: **2016 19th International Conference on Network-Based Information Systems (NBiS)**. [S.l.: s.n.], 2016. p. 114–118. Citation on page 35.

PERERA, L. N. T.; HERATH, H. M. V. R. Review of spectrum sensing in cognitive radio. In: **2011 6th International Conference on Industrial and Information Systems**. [S.l.: s.n.], 2011. p. 7–12. ISSN 2164-7011. Citation on page 32.

PETITJEAN, M.; MEZHOUD, S.; QUITIN, F. Fast localization of ground-based mobile terminals with a transceiver-equipped uav. In: **2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)**. [S.l.: s.n.], 2018. p. 323–327. ISSN 2166-9589. Citation on page 46.

PETROLO, R.; LIN, Y.; KNIGHTLY, E. Astro: Autonomous, sensing, and tetherless networked drones. In: **Proceedings of the 4th ACM Workshop on Micro Aerial Vehicle Networks, Systems, and Applications**. New York, NY, USA: ACM, 2018. (DroNet'18), p. 1–6. ISBN 978-1-4503-5839-2. Available: <http://doi.acm.org/10.1145/3213526.3213527>. Citations on pages 42 and 44.

PHAM, C.; TRAN, N. H.; DO, C. T.; MOON, S. I.; HONG, C. S. Spectrum handoff model based on hidden markov model in cognitive radio networks. In: **The International Conference on Information Networking 2014 (ICOIN2014)**. [S.l.: s.n.], 2014. p. 406–411. ISSN 1550-445X. Citation on page 34.

____. Spectrum handoff model based on hidden markov model in cognitive radio networks. In: **The International Conference on Information Networking 2014 (ICOIN2014)**. [S.l.: s.n.], 2014. p. 406–411. ISSN 1550-445X. Citation on page 85.

PIGATTO, D. F.; RODRIGUES, M.; FONTES, J. V. C.; PINTO, A. S. R.; SMITH, J.; BRANCO, K. R. L. J. C. The internet of flying things. In: ____. **Internet of Things A to Z**. Wiley-Blackwell, 2018. chap. 19, p. 529–562. ISBN 9781119456735. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119456735.ch19>. Citations on pages 21 and 24.

PIRES, R. d. M.; ARNOSTI, S. Z.; PINTO, A. S. R.; BRANCO, K. R. L. J. C. Experimenting broadcast storm mitigation techniques in fanets. In: **2016 49th Hawaii International Conference on System Sciences (HICSS)**. [S.l.: s.n.], 2016. p. 5868–5877. ISSN 1530-1605. Citation on page 21.

POPOOLA, J. J.; OLST, R. van. Application of neural network for sensing primary radio signals in a cognitive radio environment. In: **AFRICON, 2011**. [S.l.: s.n.], 2011. p. 1–6. ISSN 2153-0025. Citation on page 33.

POWELL, K.; ABDALLA, A. S.; BRENNAN, D.; MAROJEVIC, V.; BARTS, R. M.; PANICKER, A.; OZDEMIR, O.; GUVENC, I. Software radios for unmanned aerial systems. In: **Proceedings of the 1st International Workshop on Open Software Defined Wireless Networks**. New York, NY, USA: Association for Computing Machinery, 2020. (OpenWireless'20), p. 14–20. ISBN 9781450380119. Available: <https://doi.org/10.1145/3396865.3398692>. Citations on pages 43 and 49.

PäRLIN, K.; ALAM, M. M.; MOULLEC, Y. L. Jamming of uav remote control systems using software defined radio. In: **2018 International Conference on Military Communications and Information Systems (ICMCIS)**. [S.l.: s.n.], 2018. p. 1–6. Citations on pages 42 and 48.

QUARITSCH, M.; KRUGGL, K.; WISCHOUNIG-STRUCL, D.; BHATTACHARYA, S.; SHAH, M.; RINNER, B. Networked uavs as aerial sensor network for disaster management applications. **e & i Elektrotechnik und Informationstechnik**, v. 127, n. 3, p. 56–63, Mar 2010. ISSN 1613-7620. Available: <https://doi.org/10.1007/s00502-010-0717-2>. Citation on page 23.

RABINER, L. R. A tutorial on hidden markov models and selected applications in speech recognition. **Proceedings of the IEEE**, v. 77, n. 2, p. 257–286, Feb 1989. ISSN 0018-9219. Citation on page 85.

Radišić, T.; Muštra, M.; Andraši, P. Design of an uav equipped with sdr acting as a gsm base station. In: **2019 International Conference on Systems, Signals and Image Processing (IWSSIP)**. [S.l.: s.n.], 2019. p. 31–34. Citations on pages 42 and 43.

RAJENDRAN, S.; CALVO-PALOMINO, R.; FUCHS, M.; BERGH, B. V. den; CORDOBES, H.; GIUSTINIANO, D.; POLLIN, S.; LENDERS, V. Electrosense: Open and big spectrum data. **IEEE Communications Magazine**, v. 56, n. 1, p. 210–217, Jan 2018. ISSN 0163-6804. Citation on page 81.

Raspberry Pi Foundation. **Raspberry Pi — Teach, Learn, and Make with Raspberry Pi**. 2018. Https://www.raspberrypi.org/. Accessed: 08 aug 2018. Citations on pages 28 and 57.

RESEARCH, E. **USRP - Universal Software Radio Peripheral**. 2018. Https://www.ettus.com/. Accessed: 31 jan 2018. Citations on pages 28, 29, and 31.

REYES, H.; GELLERMAN, N.; KAABOUCH, N. A cognitive radio system for improving the reliability and security of uas/uav networks. In: **2015 IEEE Aerospace Conference**. [S.l.: s.n.], 2015. p. 1–9. ISSN 1095-323X. Citations on pages 22, 23, 41, and 47.

RTL-SDR. **RTL-SDR (RTL2832U) and software defined radio news and projects. Also featuring Airspy, HackRF, FCD, SDRplay and more**. 2018. Https://www.rtl-sdr.com/. Accessed: 13 jun 2018. Citations on pages 54 and 57.

SALEEM, Y.; REHMANI, M. H.; ZEADALLY, S. Integration of cognitive radio technology with unmanned aerial vehicles: Issues, opportunities, and future research challenges. **Journal of Network and Computer Applications**, v. 50, p. 15 – 31, 2015. ISSN 1084-8045. Available: <http://www.sciencedirect.com/science/article/pii/S1084804514002811>. Citations on pages 22, 23, 24, 29, 30, 36, 41, 49, and 53.

SANTANA, G. M. D.; CRISTO, R. S.; DEZAN, C.; DIGUET, J.-P.; OSORIO, D. P. M.; BRANCO, K. R. L. J. C. Cognitive radio for uav communications: Opportunities and future challenges. In: **2018 International Conference on Unmanned Aircraft Systems**. [S.l.: s.n.], 2018. p. 7–12. Citations on pages 42, 50, and 56.

Santana, G. M. D.; Cristo, R. S.; Diguet, J. P.; Dezan, C.; Diana P. M., O.; Kalinka R. L. J. C., B. A case study of primary user arrival prediction using the energy detector and the hidden markov model in cognitive radio networks. In: **2019 IEEE Symposium on Computers and Communications (ISCC)**. [S.l.: s.n.], 2019. p. 1195–1198. Citations on pages 49, 58, 59, and 60.

SANTANA, G. M. D.; CRISTO, R. S. d.; BRANCO, K. R. L. J. C. Integrating cognitive radio with unmanned aerial vehicles: An overview. **Sensors**, v. 21, n. 3, 2021. ISSN 1424-8220. Available: <https://www.mdpi.com/1424-8220/21/3/830>. Citations on pages 28, 32, 37, 40, 41, 56, 57, 61, and 62.

SBOUI, L.; GHAZZAI, H.; REZKI, Z.; ALOUINI, M. Energy-efficient power allocation for uav cognitive radio systems. In: **2017 IEEE 86th Vehicular Technology Conference (VTC-Fall)**. [S.l.: s.n.], 2017. p. 1–5. Citations on pages 42 and 48.

SHAMAEI, K.; KHALIFE, J.; KASSAS, Z. M. Exploiting lte signals for navigation: Theory to implementation. **IEEE Transactions on Wireless Communications**, v. 17, n. 4, p. 2173–2189, April 2018. ISSN 1536-1276. Citations on pages 42 and 45.

Shen, F.; Ding, G.; Wang, Z.; Wu, Q. Uav-based 3d spectrum sensing in spectrum-heterogeneous networks. **IEEE Transactions on Vehicular Technology**, v. 68, n. 6, p. 5711–5722, 2019. Citations on pages 42 and 48.

SHI, Y.; ENAMI, R.; WENSOWITCH, J.; CAMP, J. Uabeam: Uav-based beamforming system analysis with in-field air-to-ground channels. In: **2018 15th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)**. [S.l.: s.n.], 2018. p. 1–9. ISSN 2155-5494. Citations on pages 42 and 45.

SHI, Y.; WENSOWITCH, J.; WARD, A.; BADI, M.; CAMP, J. Building uav-based testbeds for autonomous mobility and beamforming experimentation. In: **2018 IEEE International Conference on Sensing, Communication and Networking (SECON Workshops)**. [S.l.: s.n.], 2018. p. 1–5. ISSN 2155-5494. Citations on pages 42 and 45.

SKLIVANITIS, G.; GANNON, A.; TOUNTAS, K.; PADOS, D. A.; BATALAMA, S. N.; REICHHART, S.; MEDLEY, M.; THAWDAR, N.; LEE, U.; MATYJAS, J. D.; PUDLEWSKI, S.; DROZD, A.; AMANNA, A.; LATUS, F.; GOLDSMITH, Z.; DIAZ, D. Airborne cognitive networking: Design, development, and deployment. **IEEE Access**, p. 1–1, 2018. ISSN 2169-3536. Citations on pages 23, 42, 50, 51, and 53.

SOLEIMANI, M. T.; KAHVAND, M.; SARIKHANI, R. Handoff reduction based on prediction approach in cognitive radio networks. In: **2013 15th IEEE International Conference on Communication Technology**. [S.l.: s.n.], 2013. p. 319–323. Citation on page 85.

Sommer, D.; Chandra Reddy Irigireddy, A. S.; Parkhurst, J.; Nastrucci, E. R. Sdr- and uav-based wireless avionics intra-communication testbed. In: **2020 AIAA/IEEE 39th Digital Avionics Systems Conference (DASC)**. [S.l.: s.n.], 2020. p. 1–5. Citations on pages 43 and 45.

SUN, Z.; WANG, P.; VURAN, M. C.; AL-RODHAAN, M. A.; AL-DHELAAN, A. M.; AKYILDIZ, I. F. Bordersense: Border patrol through advanced wireless sensor networks. **Ad Hoc Networks**, v. 9, n. 3, p. 468 – 477, 2011. ISSN 1570-8705. Available: <http://www.sciencedirect.com/science/article/pii/S1570870510001484>. Citation on page 23.

TATO, A.; MOSQUERA, C.; GOMEZ, I. Link adaptation in mobile satellite links: field trials results. In: **2016 8th Advanced Satellite Multimedia Systems Conference and the 14th Signal Processing for Space Communications Workshop (ASMS/SPSC)**. [S.l.: s.n.], 2016. p. 1–8. Citations on pages 42 and 44.

Tavares, C. H. A.; Marinello, J. C.; Proenca Jr, M. L.; Abrao, T. Machine learning-based models for spectrum sensing in sooperative radio networks. **IET Communications**, v. 14, n. 18, p. 3102–3109, 2020. Citation on page 33.

Texas Instruments. **BeagleBoard.org - community supported open hardware computers for making**. 2018. Https://beagleboard.org/. Accessed: 08 aug 2018. Citations on pages 28 and 31.

The Institute. **Will Delivery By Drone Become a Reality?** 2018. <http://theinstitute.ieee.org/ieee-roundup/members/achievements/will-delivery-by-drone-become-a-reality>. Accessed: 11 feb 2018. Citation on page 23.

THOMAS, J.; MENON, P. P. A survey on spectrum handoff in cognitive radio networks. In: **2017 International Conference on Innovations in Information, Embedded and Communication Systems (ICIIECS)**. [S.l.: s.n.], 2017. p. 1–4. Citation on page 23.

Torabi, A.; Shafer, M. W.; Vega, G. S.; Rothfus, K. M. Uav-rt: An sdr based aerial platform for wildlife tracking. In: **2018 IEEE 88th Vehicular Technology Conference (VTC-Fall)**. [S.l.: s.n.], 2018. p. 1–6. Citations on pages 42 and 44.

TRIGUI, E.; ESSEGHIR, M.; MERGHEM-BOULAHIA, L. Multi-agent systems negotiation approach for handoff in mobile cognitive radio networks. In: **2012 5th International Conference on New Technologies, Mobility and Security (NTMS)**. [S.l.: s.n.], 2012. p. 1–5. ISSN 2157-4952. Citation on page 34.

TRINDADE, O.; NERIS, L. de O.; BARBOSA, L. C. P.; BRANCO, K. R. L. J. C. A layered approach to design autopilots. In: **2010 IEEE International Conference on Industrial Technology**. [S.l.: s.n.], 2010. p. 1415–1420. Citation on page 29.

UNIVERSITY, R. **WARP — Wireless Open-Access Research Platform**. 2018. Http://warpproject.org/. Accessed: 31 jan 2018. Citations on pages 28 and 31.

URKOWITZ, H. Energy detection of unknown deterministic signals. **Proceedings of the IEEE**, v. 55, n. 4, p. 523–531, April 1967. ISSN 0018-9219. Citation on page 83.

VALAVANIS, K. P.; VACHTSEVANOS, G. J. (Ed.). **Handbook of Unmanned Aerial Vehicles**. Dordrecht: Springer Netherlands, 2015. 3022 p. ISBN 978-90-481-9706-4. Citations on pages 21 and 29.

VALENTE, J.; SANZ, D.; BARRIENTOS, A.; CERRO, J. d.; RIBEIRO, A.; ROSSI, C. An air-ground wireless sensor network for crop monitoring. **Sensors**, v. 11, n. 6, p. 6088–6108, 2011. ISSN 1424-8220. Available: <http://www.mdpi.com/1424-8220/11/6/6088>. Citation on page 23.

VONEHR, K.; HILASKI, S.; DUNNE, B. E.; WARD, J. Software defined radio for direction-finding in uav wildlife tracking. In: **2016 IEEE International Conference on Electro Information Technology (EIT)**. [S.l.: s.n.], 2016. p. 0464–0469. ISSN 2154-0373. Citations on pages 41 and 43.

Wang, J.; Juarez, N.; Kohm, E.; Liu, Y.; Yuan, J.; Song, H. Integration of sdr and uas for malicious wi-fi hotspots detection. In: **2019 Integrated Communications, Navigation and Surveillance Conference (ICNS)**. [S.l.: s.n.], 2019. p. 1–8. Citations on pages 42 and 46.

WOLFE, S.; BEGASHAW, S.; LIU, Y.; DANDEKAR, K. R. Adaptive link optimization for 802.11 uav uplink using a reconfigurable antenna. In: **MILCOM 2018 - 2018 IEEE Military Communications Conference (MILCOM)**. [S.l.: s.n.], 2018. p. 1–6. ISSN 2155-7586. Citation on page 45.

WU, Y.; CARDEI, M. A cognitive radio approach for data collection in border surveillance. In: **2016 IEEE 35th International Performance Computing and Communications Conference (IPCCC)**. [S.l.: s.n.], 2016. p. 1–8. Citation on page 35.

WU, Y.; YANG, Q.; LIU, X.; KWAK, K. S. Delay-constrained optimal transmission with proactive spectrum handoff in cognitive radio networks. **IEEE Transactions on Communications**, v. 64, n. 7, p. 2767–2779, July 2016. ISSN 0090-6778. Citation on page 38.

XIE, J.; WAN, Y.; KIM, J. H.; FU, S.; NAMUDURI, K. A survey and analysis of mobility models for airborne networks. **IEEE Communications Surveys Tutorials**, v. 16, n. 3, p. 1221–1238, Third 2014. ISSN 1553-877X. Citation on page 36.

Xu, W.; Wang, S.; Yan, S.; He, J. An efficient wideband spectrum sensing algorithm for unmanned aerial vehicle communication networks. **IEEE Internet of Things Journal**, v. 6, n. 2, p. 1768–1780, 2019. Citations on pages 42 and 48.

YOUNG, A. Unified multi-domain decision making: Cognitive radio and autonomous vehicle convergence [ph.d. thesis]. **Virginia Polytechnic Instute and State University**, p. 271–350, Jan 2012. Citation on page 53.

YOUNG, A. R.; BOSTIAN, C. W. Simple and low-cost platforms for cognitive radio experiments [application notes]. **IEEE Microwave Magazine**, v. 14, n. 1, p. 146–157, Jan 2013. ISSN 1527-3342. Citations on pages 28, 31, 41, and 46.

Yuheng, Z.; Yan, W.; Yanyong, X. Optimal sensing slots determination for uav under correlated log-normal shadowing. In: **2019 IEEE 11th International Conference on Communication Software and Networks (ICCSN)**. [S.l.: s.n.], 2019. p. 318–321. Citation on page 43.

Zambrano, J.; Bui, T.; Landry, R. J. Digital interference mitigation technique for the interoperability of two airborne two satcom systems for small aircraft. In: **2020 AIAA/IEEE 39th Digital Avionics Systems Conference (DASC)**. [S.l.: s.n.], 2020. p. 1–8. Citations on pages 43 and 45.

ZARCO-TEJADA, P.; BERNI, J. A. J.; SUáREZ, L.; FERERES, E. A new era in remote sensing of crops with unmanned robots. 01 2008. Citation on page 23.

ZENG, K.; RAMESH, S. K.; YANG, Y. Location spoofing attack and its countermeasures in database-driven cognitive radio networks. In: **2014 IEEE Conference on Communications and Network Security**. [S.l.: s.n.], 2014. p. 202–210. Citation on page 24.

ZHANG, E.; ZAMBRANO, J.; AMRHAR, A.; LANDRY, R.; AJIB, W. Design and implementation of a wideband radio using sdr for avionic applications. In: **2017 Integrated Communications, Navigation and Surveillance Conference (ICNS)**. [S.l.: s.n.], 2017. p. 2D2–1–2D2–9. Citations on pages 42, 45, and 47.

ZHANG, T.; WU, M.; LIU, C. Cooperative spectrum sensing based on artificial neural network for cognitive radio systems. In: **2012 8th International Conference on Wireless Communications, Networking and Mobile Computing**. [S.l.: s.n.], 2012. p. 1–5. ISSN 2161-9646. Citation on page 33.

Zhao, Y.; Luo, S.; Yuan, Z.; Lin, R. A new spectrum prediction method for uav communications. In: **2019 IEEE 5th International Conference on Computer and Communications (ICCC)**. [S.l.: s.n.], 2019. p. 826–830. Citations on pages 43 and 49.

ZHENG, J.; CHEN, C. h.; CHENG, J. y.; SHI, L. Cognitive radio: Methods for the detection of free bands. In: **2009 International Conference on Networks Security, Wireless Communications and Trusted Computing**. [S.l.: s.n.], 2009. v. 2, p. 343–345. Citations on pages 32 and 33.

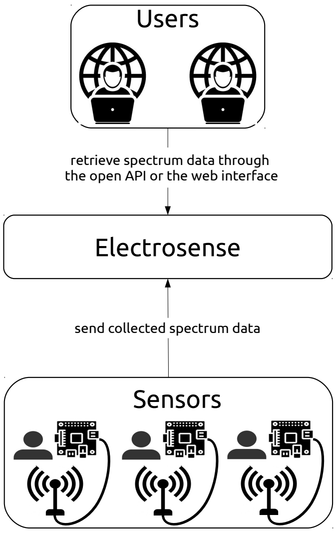
# APPENDIX A

# ELECTROSENSE

The Electrosense (RAJENDRAN *et al.*, 2018; ELECTROSENSE, 2018) is an open source collaborative spectrum monitoring tool based on the crowd-sourcing paradigm to collect and analyse spectrum data. On Electrosense, users from different geographic areas may deploy their own SDR sensors, so other users may remotely access those sensors data by using the open API or the web interface.

Figure 18 illustrates the operation of Electrosense. Therein, different users deploy their sensors and send the data to Electrosense. Then, the data is processed by Electrosense, and a public access is provided. Users may access data from different sensors through the open API by using custom applications, or via web interface. The data is available in different forms, e.g., a user may retrieve data from a specific sensor and for different time and frequency ranges.[1]

Figure 18 – An overview of the Electrosense operation.



Source: the author

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[1] This text is part of a paper currently under submission process.

# APPENDIX

# B

# ENERGY DETECTOR

The ED (URKOWITZ, 1967) is a low-computational method for detecting a PU in a given channel. Therefore, outcomes of this method are "true" in case a PU is detected (i.e., PU signal present) or "false" otherwise (i.e., PU signal absent).

We denote $H_0$ as the hypothesis PU signal is absent, and $H_1$ if PU signal is present. The received signal is then given as

$$r(t) = \begin{cases} v(t), & H_0 \\ v(t)+s(t), H_1 \end{cases}, \tag{B.1}$$

where $v(t)$ represents the additive white Gaussian noise (AWGN) component and $s(t)$ is the bandpass received signal (MARIANI; GIORGETTI; CHIANI, 2010). A detection threshold $\gamma$ has to be determined to decide whether the received signal is in the $H_0$ form or in the $H_1$ form. The detection threshold $\gamma$ for a given $P_{FA}$ is given by

$$\gamma = N_d B \left(1+\frac{Q^{-1}(P_{FA})}{\sqrt{M}}\right), \tag{B.2}$$

where $N_d$ is the noise power spectral density, $B$ the signal bandwidth, $Q(.)$ the $Q$-function, $P_{FA}$ the false alarm probability, and $M$ the number of samples. The miss-detection probability $P_{MD}$ for a $\gamma$ is given as

$$P_{MD} = Q\left(\frac{\sqrt{M}}{(P+N_d B)}[(P+N_d B)-\gamma]\right). \tag{B.3}$$

where $P$ is the signal power (KIM; SHIN, 2008).

The ED does not require prior information about the PU signal. However, the main drawback in this approach is that the threshold $\gamma$ is fixed, thus it does not tolerate noise power and PU power variations (KIM; SHIN, 2008; ALI; HAMOUDA, 2017; AKYILDIZ *et al.*, 2008).[1]

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[1] This text is part of a paper currently under submission process.

# APPENDIX C

# HIDDEN MARKOV MODEL

The HMM is a statistical Markov model consisting of two processes: the variation of the unobserved (i.e., hidden) states is a Markov process, and the observation under a specific hidden state is a normal random process (RABINER, 1989). A Markov process is a random process whose future probabilities are determined by its most recent values and they are not affected by past values.

One of the most traditional applications of the HMM is in machine recognition of speech. However, due to the HMM's rich mathematical structure and practical efficiency, it is widely used in distinct Machine Learning applications. In CR, the sensing result returns the channel occupancy hidden state as busy or idle (SOLEIMANI; KAHVAND; SARIKHANI, 2013; PHAM *et al.*, 2014b).

Details of the HMM procedure applied in this work are given in (RABINER, 1989).[1]

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[1] This text is part of a paper currently under submission process.

# APPENDIX D

# QUERY STRINGS

The following strings were used to query the respective digital library sources.

**TRB**

("internet of flying things" OR "IoFT" OR "unmanned aerial system" OR "UAS" OR "UASs" OR "unmanned aerial systems" OR "unmanned aircraft system" OR "unmanned aircraft systems" OR "unmanned aerial vehicles" OR "drone" OR "drones" OR "UAV" OR "UAVs" OR "unmanned aerial vehicle") AND ("cognitive radio" OR "cognitive radio network" OR "cognitive radio networks" OR "CR" OR "CRN" OR "CRNs" OR "software defined radio" OR "SDR")

**ACM**

+("internet of flying things" "IoFT" "unmanned aerial system" "UAS" "UASs" "unmanned aerial systems" "unmanned aircraft system" "unmanned aircraft systems" "unmanned aerial vehicles" "drone" "drones" "UAV" "UAVs" "unmanned aerial vehicle") +("cognitive radio" "cognitive radio network" "cognitive radio networks" "CR" "CRN" "CRNs" "software defined radio" "SDR")

**Scopus**

TITLE-ABS-KEY ( ( "internet of flying things" OR "IoFT" OR "unmanned aerial system" OR "UAS" OR "UASs" OR "unmanned aerial systems" OR "unmanned aircraft system" OR "unmanned aircraft systems" OR "unmanned aerial vehicles" OR "drone" OR "drones" OR "UAV" OR "UAVs" OR "unmanned aerial vehicle" ) AND ( "cognitive radio" OR "cognitive radio network" OR "cognitive radio networks" OR "CR" OR "CRN" OR "CRNs" OR "software defined radio" OR "SDR" ) )

**IEEE**

("internet of flying things" OR "IoFT" OR "unmanned aerial system" OR "UAS" OR "UASs" OR "unmanned aerial systems" OR "unmanned aircraft system" OR "unmanned aircraft systems" OR "unmanned aerial vehicles" OR "drone" OR "drones" OR "UAV" OR "UAVs" OR "unmanned aerial vehicle") AND ("cognitive radio" OR "cognitive radio network" OR "cognitive radio networks" OR "CR" OR "CRN" OR "CRNs" OR "software defined radio" OR "SDR")

# APPENDIX E

# PAPERS

**Dias Santana, G.M.**; Cristo, R.S.d.; Lucas Jaquie Castelo Branco, K.R. Integrating Cognitive Radio with Unmanned Aerial Vehicles: An Overview. Sensors 2021, 21, 830. doi: 10.3390/s21030830.
<https://doi.org/10.3390/s21030830>

**G. M. D. Santana**, R. S. Cristo, J. -P. Diguet, C. Dezan, O. Diana P. M. and B. Kalinka R. L. J. C., "A Case Study of Primary User Arrival Prediction Using the Energy Detector and the Hidden Markov Model in Cognitive Radio Networks," 2019 IEEE Symposium on Computers and Communications (ISCC), Barcelona, Spain, 2019, pp. 1195-1198, doi: 10.1109/ISCC47284.2019.8969632.
<https://doi.org/10.1109/ISCC47284.2019.8969632>

R. S. Cristo, **G. M. D. Santana**, D. P. M. Osorio and K. R. L. J. C. Branco, "MARIO: A Cognitive Radio Primary User Arrivals Data Generator," 2018 IEEE Symposium on Computers and Communications (ISCC), Natal, 2018, pp. 01137-01142, doi: 10.1109/ISCC.2018.8538660.
<https://doi.org/10.1109/ISCC.2018.8538660>

**G. M. D. Santana**, R. S. Cristo, C. Dezan, J. Diguet, D. P. M. Osorio and K. R. L. J. C. Branco, "Cognitive Radio for UAV communications: Opportunities and future challenges," 2018 International Conference on Unmanned Aircraft Systems (ICUAS), Dallas, TX, 2018, pp. 760-768, doi: 10.1109/ICUAS.2018.8453329.
<https://doi.org/10.1109/ICUAS.2018.8453329>

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