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Ph.D. THESIS SUMMARY

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Using the Radio Source Localization Methods in Drone Detection, Tracking and Neutralization Systems

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Content

1. Introduction

The existence of a large number of applications based on the determination of the angle of incidence of radio signals coming from a source whose location is of interest, as well as the emergence and rapid evolution of technologies to support or combat drones were the main reasons for choosing this PhD thesis. Based on the latest technological innovations in radio communications, we chose the use of Software Defined *Radio* (SDR) platforms as suitable to support the applications developed in this thesis [1].

For applications involving the location of goods or people, it has been found that it is necessary to estimate as accurately as possible the direction from which the signal is arriving and then the position of the source, even in transmissions that are not in direct radio visibility - NLOS (*Non-Line-Of-Sight*) or in the case of multichannel propagation [2].

Some of the most important technological contributions in the world of modern engineering can be found in the field of wireless communications and in the development of intelligent systems with multiple applications, especially in the military environment. These can be used for both friendly applications and as combat solutions. With the development of these systems has come the need to develop countermeasures to keep pace with these developments. In both cases, the requirements imposed by limited radio spectrum resources must be respected [3].

1.1 Presentation of the PhD thesis field

Determining the location of a radio source has demonstrated its usefulness in several applications in the military and security environment for emergency calls, criminal tracking, road traffic management, intelligent transportation systems, etc.[1]. In this context, in my PhD research I aimed to design and develop methods for the physical implementation of architectures based on SDR platforms to neutralize threats from the use of UAV systems of malicious entities.

Within this framework, in order to create the prerequisites for the realization of a versatile drone detection system, we have addressed the research and development of systems using SDR platforms. It should be noted that although the use of SDR platforms and radio signal detection in these systems seems to be an optimal solution for implementation, we have identified in the literature many different approaches including those using video, thermal, audio, radar detection.

With these considerations in mind, we have decided that the research domain of this paper will be passive detection of RF signals associated with drones, and contributions to method development will be presented in the following sections.

In the technical literature it is found that AoA estimation using SDR is performed using localization algorithms (MUSIC, ROOT MUSIC, CAPON (MVDR), ESPRIT). It is useful to evaluate them in terms of performance, reliability, redundancy, etc.

Following signal analysis with cognitive radio systems, signal replication can be performed [12]. By using these replicas, the command of the target UAV system can be replaced, it can be brought to the ground without having to be destroyed, and then data/metadata analysis can be performed.

1.2 Scope of the PhD thesis

Noting that in recent times, UAV systems, due to their specific characteristics such as small size, agility, easy control, operator safety, etc., have found applications in more and more fields such as: military, commercial, industrial, public safety, etc. This has inevitably led to the emergence of problems such as the possibility of using them to create threats and exploit possible security breaches at civilian or even military targets.

Analysing the context, we formulated the following main objectives at the start of the research activity:

Main objective : Contributions to the improvement of algorithms for locating objects that are sources of radio signals; their study through simulation and experiment using SDR technology. Contributions to the use of such algorithms in applications related to the identification, location and combat of flying objects such as drones.

Secondary objectives:

- to carry out an extensive study on the current state of research in the field of usable methods for locating a radio signal source and its use in systems to combat UAV systems - used in an unauthorised manner;
- to perform a comparative analysis by simulation and experiment of radio source localization algorithms in order to identify the optimal algorithm for implementing a feasible system for drone localization;
- using programming environments such as MATLAB and GNU-radio, Labview for the analysis of the previous objective;
- design, development (as an experimental model) and validation of a system for detecting, locating and combating drones.

1.3 Content of the PhD thesis

The PhD thesis will be structured in **six chapters** and will describe in detail the processes and the level to which the proposed objectives have been achieved, as follows:

The first chapter will contain a brief introduction. This will cover the presentation of the research area, the aim, motivation, objectives and content of the PhD thesis.

The second chapter will summarise the current state of research in the field of drone development and the fight against unauthorised use of UAV systems.

In chapter three the main methods used for locating radio signal sources will be discussed as well as the signal parameters involved. In this section the theoretical basis for understanding the concepts and principles associated with these methods will be presented and a summary of the current state of research in the field will be given.

This chapter will also present and analyse the most important algorithms used for localisation and a comparative analysis of their performance in terms of the number of receiving antennas and the number of sources to be located, etc. It will aim to identify the most suitable algorithms for the application under consideration.

Chapter four will present the main ways of realising an integrated solution on an SDR platform. Here the evolution and need for the development of SDR equipment and a classification of SDR equipment will be presented.

It will also present a comparison of some SDR platforms and analyse the results of practical implementations on the platforms considered. The conclusions will highlight which would be the optimal variant for implementing a drone localization algorithm.

Chapter five will consist of a description of the research work we conducted in a project (DRONEND) that involved the implementation of an integrated system based on SDR technologies for identifying, locating and countering drones with hostile intent. Contributions to the realisation of two variants of anti-drone system are highlighted: a ground-based and an airborne system. Aspects of the evolution of the solutions and their experimental validation will be described.

Chapter six will present the most significant results, personal contributions, published work and prospects for further research.

2. Current state of research

Technological innovations are growing exponentially and causing rapid and major changes in modern society at all levels. These changes, driven by the possibilities offered by new technologies, affect citizens, governments as well as all public and private sectors of industry.

With these innovations has come the increasing use of small, low-cost *Unmanned A*erial Vehicles (UAVs), commonly known as drones, in a variety of applications [13]. The use of UAVs has introduced new participants into the airspace, rapidly evolving beyond their military origins to become powerful tools with not always beneficial roles [14,15].

UAV applications range from recreational to commercial and military, including entertainment, hobbies, drone games, home video entertainment, movies [16-18], low-altitude flying stations [19] and UAV operations for military purposes [20-25].

The following questions have been formulated for this synthesis:

- What functions would a drone detection, tracking and countermeasures system (DDDS) need to have to demonstrate its functionality?

- What are the most popular methods used in implementing DDDSs?
- What are the main parameters that should be considered in this research?
- What gaps exist in current research on DDDSs?

To answer these questions, a widely used systematic literature review methodology - PRISMA - was used. PRISMA is one of the best guidelines for research and design of literature systematics and meta-analyses [26].

To do this, we conducted successive searches in several literature databases. These included scientific databases comprising prestigious journals and conferences such as IEEE Xplore, ScienceDirect, ACM Digital Library, Springer Link and SAGE Journals Online. The searches found the most relevant scientific articles and journals on the topic of drone detection and defence systems.

We used the following search phrases to discover publications and articles relevant to our research: ('Drone' OR 'UAV') AND (Counter) in the fields of electrical engineering, applied physics, telecommunications, defense, and information systems for a six-year period (2016-2022). In total, we gathered a set of 7,349 potentially relevant publications, excluding grey literature and drafts.

We have carefully studied the selected publications after the completion of the literature selection procedure in order to determine the applications for the described issues. The results of the analysis are presented in the following sections, which form the core of this systematic literature review on drone defence systems.

2.1 The necesityfor DDDS. Incidents and legislation

The rapid growth of production and sales in the UAV industry has gone beyond secure operations, making them a symbol of terrorism, crime and destruction [27].

The use of UAV systems has gained increasing attention as a threat to safety and security as they enter civilian technology. As a consequence, it has led to the development of anti-drone (or counter-drone) technologies. Anti-drone systems are designed to stop or prevent accidents or terrorist acts in which they are used. To be effective, these anti-drone systems will need to evolve alongside the development of future UAV systems [28].

Although UAVs were originally used in a variety of military actions, there have been numerous instances where non-military UAV systems have endangered civilian aircraft, people and property on the ground.

2.1.1 Recently reported incidents

The need for DDDS systems is justified by the large number and potential risk generated by events similar to those in *Table 2.1*.

Table 2.1 List of recent events involving UAV systems.

Type of incident	Date and location of the incident	Brief description of the incident	Follow	References
Air collisions	17 April 2016/UK, London, Heathrow International Airport	An A320 aircraft hit a Metropolitan Police UAV system as it was approaching landing	No major damage reported	[31]
	21 September 2017/USA, Staten Island, New York City	A civilian UAV system was hit by a Black Hawk military helicopter	The helicopter suffered no major damage and could have landed safely	[32]
	12 October 2017/ Canada, Jean Lesage Airport, Quebec	A private Skyjet Aviation Beech King Air A100 aircraft hit a UAV system	The aircraft landed safely with minor damage to one wing.	[33]
	13 December 2018/ Mexico, Tijuana International Airport	Boeing 737-800 aircraft on flight 773 hit a drone	After the safe landing, it turned out that the front of the aircraft had been damaged. The cause of the incident has not been identified, but investigation suggests a collision with a drone.	[34]
	10 August 2021/ United Kingdom, Buttonville Municipal Airport	Cessna 172 aircraft with tail number C-GKWL struck a drone operated by York Regional Police	Cessna aircraft landed safely but with significant damage	[35]
Risk of air collision	January 2017/P.R. China, Hangzhou Xiaoshan International Airport	A 23-year-old man has been arrested after posting that he was flying a drone in the vicinity of incoming aircraft	The drone company DJI - which produced and donated the drone used in this incident - issued a statement condemning the illegal use of drones for this purpose	[36]
	25 March 2018/New Zealand, Auckland Airport	A UAV came within 5m of a Boeing 777-200 aircraft before it landed	The pilots of the transport aircraft observed the drone on the final landing slope when any evasive maneuver is impossible.	[37]
	19 December 2018/UK, Gatwick	A deliberate and repeated intrusion of drones has been observed in the vicinity of the airport	Suspension of all take-offs and landings for approximately 24 hours	[38]
Other incidents targeting strategic targets and high-ranking officials	April 2015/Japan	A small drone carrying radioactive material "dropped" the payload on the roof of the house where the Japanese prime minister lived	Not only could the drone not be detected, but it was left unnoticed for about two weeks.	[39]
	October 2016/ Syria	ISIS group used two small drones purchased on Amazon to assassinate two Iranian nationals in Syria	This is the first incident in which the terrorist group executed its mission using commercial equipment	[40]
	August 2018/ Venezuela	Two drones carrying bombs failed to assassinate Venezuelan President Nicolas MADURO during an open-air demonstration	This incident is the first in which drones have been used to carry out an assassination. The incident shows the importance of anti-drone technologies.	[41]

In addition to the incidents highlighted, the number of small incidents caused by unauthorized or illegal drones invading restricted regions is increasing day by day [42]. This is yet another reason why anti-drone technology is becoming increasingly important. Since regulations on drone use are also a significant issue to consider when designing a drone detection, tracking and countermeasures (DDDS) system, in the next subsection we will discuss this in detail.

2.1.2 Regulations on the use of drones

The most important agencies regulating the use of drones (e.g. *European* Aviation Safety Agency (EASA), Federal Communications Commission (FCC*)*, Australian Communications *And* Media Authority (ACMA), Civil Aviation Authority (CAA), etc.) have adopted action plans to protect critical targets from illegal drone use [42-44].

In addition, the European Union has endorsed EASA's standard European guidelines to enable the safe integration and operation of UAVs in the aviation system. The rules that apply to drones are set out in Regulation (EU) 2019/94735 on rules and procedures for the operation of unmanned aerial vehicles (UAVs) and Regulation (EU) 2019/945 on unmanned aerial vehicles and third country operators of unmanned aerial systems (UAVs).

According to the document, there are three main types of violations of drone use that endanger civil aviation, as follows: non-criminal motivation, gross negligence and criminal/terrorist motivation [42].

2.2 Drone Detection and Defence Systems: Classification, Sensors, Countermeasures

In this section, I will highlight the classification of drone detection and defence systems according to different criteria by comparing the different types of sensors that can be used to detect the presence of drones in the monitored area, by classifying the countermeasures that can be adopted to neutralise detected drones, and by the regulations on the use of jamming as a countermeasure.

2.2.1 Classification of DDDS

First, it is necessary to classify drone detection and defence systems (DDDS) to understand their capabilities, as summarised in *Table 2.3*.

Table 2.2 Classification of DDDS

Categories	Definition
Ground based - fixed	Systems designed for use from fixed locations [45]
Ground based - mobile	Systems designed to be installed on mobile platforms and can be operated on the move [45].
Portable	Systems designed to be operated by one person, usually manually operated. Often weapon-shaped [46]
Airborne (UAV)	Systems designed to be docked on other UAV platforms [46]
UAV- swarm	Systems designed to use multiple drones [47]

A DDDS involves different technologies available for target detection, tracking and classification, and neutralisation techniques. The recommended core elements of a DDDS are considered to be detection, tracking and classification of target drones [42,46]. The different technologies used to enable drone detection are summarised in *Table 2.4*.

Table 2.3 Technologies used for DDDS detection

Technology	**Description**
Acoustics	The presence and tracking of drones is achieved through the use of a network of microphones
Imagine (EO/IR)	Presence and tracking of drones is achieved through the use of EO/IR cameras
Radar	Presence and tracking of drones is achieved by radar signature identification
Radio Frequency (RF)	The presence and tracking of drones is achieved by monitoring the radio frequencies used for communications; this technology can locate the drone and the pilot.
Hybrid	Combination of two or more of the above technologies.

2.2.2 Classification of detection sensors

All types of sensors currently used in DDDS systems have specific advantages and limitations. Consequently, such a system needs to incorporate several sensors of different types to achieve a higher detection rate [45].

A brief description of each sensor category is given below, and the various advantages and disadvantages for each category are summarised in *Table 2.5*.

Table 2.4 Advantages and disadvantages of sensors used in DDDS

Tip	**Advantages**	**Disadvantages**
Acoustic	• Covers the spectrum between 20 Hz-20 kHz; • The acoustic signature library can be easily updated every flight; • They are not very heavy and can easily be combined with other types of sensors.	• Limited radius; • Vulnerable to environmental noise; • Easy to cheat.
Imagine	• Covers the visible and IR spectrum (3 MHz-300 GHz); • IR cameras can operate in foggy or cloudy conditions during day and night; • They can be assisted by computational and AI-based technologies.	• Generates only 2D images; • Limitations related to weather conditions and ambient temperature; • Dependent on geo-referenced data • LoS is mandatory.
Radar	• Bandwidth used: 3 MHz-300 GHz; • They can operate in all weather conditions day and night; • Provides information on the speed of the target; • Can recognize micro-Doppler signatures (MDS) • Provides great coverage; • Increased accuracy; • Can be designed compact and mobile - necessary for tactical applications; • Increased reliability.	• Requires a radar footprint of ordinal $\lambda/2$; • Difficult to discriminate birds from UAVs; • Limited performance for low altitudes and low speeds. • Ineffective in the dead cone area • Can easily interfere with small objects and birds; • LoS is necessary; • High cost.

RF	It can capture communication signals between the drone and the UAV operator; Low complexity - easy to implement; It can operate in all weather conditions day and night; Easily upgradable due to modularity of receive antennas and signal processing units used for implementation; Ability to locate the drone pilot.	Prior knowledge of the radio footprint related to communications between the drone and the operator (frequency bands, modulations, etc.) is required; AoA is determined with low accuracy; Problematic in use in urban areas due to fading and multi-scale phenomena; Vulnerable to malicious or illegal use by using frequency bands that exceed the system's capabilities.

2.2.3 Classification of countermeasures

The need for a DDDS first arose in military applications, under special regulations that exceed the capabilities and responsibilities of other governments or structures. As a result, neutralization techniques outnumber detection techniques [42].

The main advantages and disadvantages of each countermeasure technique are presented in *Table 2.6*.

Table 2.5 Features and limitations of countermeasures

Tip	**Advantages**	**Disadvantages**
Electromagnetic pulse	Can burn or interfere with the target drone's internal systems by stopping its operation It works in all frequency bands (narrow/wide).	The accuracy of the direction of the jamming is difficult to achieve; The outcome of the countermeasure is difficult to estimate.
Drone interceptors	It has search and track capabilities; They can be used as aerial platforms for weapons and ammunition.	Requires very close proximity to the target; It has considerable latency.
LASER	Can operate with low power (dazzlers) to shut down the target drone's camera systems or with high power to destroy the target; The target can be easily tracked. Safer and cheaper than any other physical countermeasure	Sensitive to weather conditions; A very good knowledge of the target drone's position is required; High-power lasers can interfere with other systems.
Magnetic	Their development and implementation does not require large sums of money; Can effectively block multiple targets simultaneously	Protects small targets; May interfere with other systems.
Birds of prey	It does not require complex technologies; There is no need for many human operators.	This countermeasure is only feasible for small drones that do not travel at very high speeds; Can lead to bird injury.
Projectile/ Please launch/ Water cannons	Effective against any type of UAV; Works in all weather conditions; It's a quick reaction method.	May cause collateral damage; High implementation costs; Requires professional operators.
RF/GNSS jamming	It can neutralize a group of targets simultaneously, degrading the signal-to-noise ratio - SNR;	Ineffective against autonomous drones; Ineffective against drones using *Inertial*

	• The frequencies and bands used by GNSS are well known and relatively easy to jam; • The directivity diagram of the jamming signal is very accurate.	Navigation Systems (INS); • Ineffective against drones using encrypted communications; • Effective only for short distances; • Noise can interfere with other equipment.
Spoofing	• Signal processing algorithms and AI can reproduce the control signals of the target drone with increased accuracy in a relatively short time; • It can exploit vulnerabilities in a wide range of UAV systems.	• A consistent analysis of the target UAV system is required with respect to frequencies and how it works. • Spectral detection algorithms are required.

Neutralizing a drone using one of the methods listed above is only half the answer. It is important to discover and apprehend the operator of the drone flying illegally in order to solve the problem completely. Without this, a motivated operator will surely return with a newer and better drone capable of causing even more disruption and damage [47].

2.2.4 Regulations on the use of jamming in DDDS

For most of the categories of countermeasures mentioned above, there are currently no rules in place. However, for the case of RF interference, there are several regulations in force, which will be detailed in the following paragraphs.

Neutralising drones using jamming systems is not yet (in most countries) legally permitted and is currently the subject of much regulatory discussion.

EU authorities were among the first organisations to take a position on the use of jamming devices. Directive 2014/53/EU prohibits the use of such devices which may cause harmful interference to authorised radio communications or hinder the normal functioning of communications using radio frequencies [158]. This Directive has been transposed into the legislation of all Member States.

"Directive 2014/53/EU was transposed into Romanian law by Government Decision no. 740/2016. According to this Decision, the manufacture, import, possession, advertising, placing on the market, making available on the market, putting into service and/or use of radio equipment or devices designed to cause harmful interference (jammers) are prohibited and punishable by fines" [159].

Despite the lack of regulations on the use of RF jamming signals against drones and some risks that should be considered, this method is one of the most effective.

2.3 Detection and DDDS based on RF methods

As mentioned in *Section 2.1*, one of the most widely used methods for drone detection is the identification of RF signals that are exchanged between the drone and another entity (ground station/operator). Neutralisation of detected drones can also be achieved by RF methods, by transmitting sufficiently strong interference signals that can disrupt communication between the drone and its operator (as mentioned in *Section 2.2*).

Typically, military drones use specific frequencies, but most commercial drones operate in the 433 MHz and 2.4/5.8 GHz industrial, scientific and medical (ISM) frequency bands. Therefore, most modern RF sensing systems provide detection and identification of the unique RF footprint generated by communications between the pilot/base station and the UAV or the data protocol used.

There are two main functions required for drone detection:

- identifying the presence of drones by scanning the frequency spectrum and locating drones;
- Neutralisation function - necessary to enable defence against detected drones, can be achieved by means of RF jamming with the aim of interrupting communication between drones and their operators.

Table 2.7 summarises the main elements related to the implementation of these systems. In the following paragraphs, each of these categories will be detailed.

Table 2.6 DDDS based on radio frequency method

References	**Implemented functions**	**Methods**	**SDR platforms used (producer / country of origin)**
[164]	Identify Location	RF amperage (FSS, WEE, PSE) AoA (MUSIC, RAP MUSIC)	USRP-X310 (Ettus Research,/ USA)
[165]	Identify	RF amperage (DRNN)	USRP-X310 (Ettus Research / USA)
[166]	Identify	RF Ampacity (CNN)	USRP-X310 (Ettus Research / USA)
[167]	Identify	RF amperage (KNN)	USRP-B210 (Ettus Research / USA)
[168]	Identify	RF Amp (KNN, XGBoost)	-
[169]	Identify	RF (Wi-Fi) footprint	-
[170]	Identify	RF Amperage	LimeSDR (Lime Microsystems / UK)
[171]	Identify	RF Amperage	-
[172]	Location	Signal strength at reception Received-Signal Strength (RSS)	USRP N210 (Ettus Research / USA)
[173]	Location	RSS	AD-FMCOMMS5-EBZ Evaluation Board (Analog Devices / USA)
[174-176]	Neutralisation	RF jamming	BladeRF (Nuand / USA)
[177]	Neutralisation	RF jamming	Great Scott Gadgets HackRF One

Almost all implementations used to validate the solutions proposed in the literature are based on SDR (Software-Defined Radio) platforms due to significant advantages offered by this category of platforms, such as:

- Low or moderate cost;
- Extended frequency range, which can typically cover all frequency bands used by commercial drones;
- Scalability, allowing the platform to be extended, depending on the intended functions;
- Flexibility, allowing processing of RF signals corresponding to different communication standards.

2.4 Challenges and perspectives of DDDS

One of the challenges we face in deploying a DDDS is the ability to identify and subsequently neutralize not just one target drone, but several. In recent years, many applications have used multiple drones [178], which is why this feature becomes important for a DDDS. Depending on the sensors used in the system, the possibility to detect multiple target drones may or may not exist. There are several examples of systems that include this feature in the literature.

Another challenge faced by a DDDS, especially if the area where the system is installed is residential and there are several households nearby, is avoiding interference or damage to nearby equipment (in the case of RF and EMP interference) and respecting the privacy of nearby neighbours (in the case of image sensors). In the case of RF interference, this could be solved if the antennas used can create very narrow directive patterns and can be pointed directly at targets.

When referring to a DDDS based on RF methods, one of the main challenges we have to face is related to the legal aspects of using interference as a countermeasure, as mentioned in *Section 2.3*.

Another important limitation of RF-based DDDSs is related to the impossibility of detecting and neutralising autonomous drones in cases where they have a predefined flight path and no active data communications path with a ground-based operator.

2.5 Conclusions on the current state of research

In this chapter, we have carried out a review of the state of the art of drone detection and defence systems. Within the analysis we have included different aspects such as regulatory issues and reported incidents involving drones. We carried out a classification of drone detection systems based on the type of sensors used. We conducted a detailed description of RF-based drone detection and defence systems, with a focus on the use of SDR platforms to implement these systems.

3. Theoretical aspects of DoA

3.1 Methods for determining the location of a radio source

In order to realize applications for determining the direction of arrival of radio signals, it is necessary to estimate the position as accurately as possible, even in transmissions that are not in direct NLoS (*Non-Line-of-Sight*) or multichannel radio vision [184].

Position estimation can be defined as the process of estimating the position of a target node transmitting or receiving radio signals from other reference nodes. This process can be performed either by the target node (self-localization) or by a central point collecting information from multiple reference stations[185].

Also, depending on how the location is determined using the signals transmitted between the two nodes, there are two implementation options

- Direct position estimation;
- Two-step position estimation.

Direct localisation refers to the process of determining the position of a node using information obtained only from signals transmitted between this node and other reference nodes. This type of location is based only on the information available in the system, without the need for other external information.

On the other hand, the two-stage localization method involves estimating the position via a central point that receives information from several reference stations, although this approach may be suboptimal and perform less well than direct localization. However, for frequencies in the upper bands or with fairly high Signal *to* Noise Ratios (SNR), this technique can lead to reasonably accurate position estimation. Therefore, this method is commonly used in most radio location determination systems [186].

In the first step of this algorithm, signal parameters such as *Time of Arrival* (ToA) and *Received Signal Strength* (RSS) are estimated and then mapping or statistical methods are used depending on accuracy requirements and system constraints.

3.1.1 Parameters used to determine location

The parameters used for location determination are the first step of the location determination algorithm and consist of estimating the parameters of the signal that is transmitted between the target node and one or more reference nodes.

Depending on accuracy requirements and system constraints, several reference signal parameters are highlighted for radio location estimation. In general, these are closely related to power, direction and/or time at reception.

- Received Signal Strength (RSS)
- Angle of Arrival (AoA)
- Time of Arrival (TOA)
- Time Difference on Arrival (TDOA)
- Other parameters

In some systems for determining the position of a radio source, two or more of the above parameters may be used to obtain a more precise location of the target node. Examples of such hybrid schemes are TOA/AOA, TOA/RSS and TDOA/AOA.

3.1.2 Position estimation

As stated above the second step of the estimation algorithm is performed using the parameters estimated previously, by the above mentioned procedures. Depending on the presence/absence of a database, two estimation techniques are noted:

- Mapping technique..
- Geometric and statistical techniques.

3.2 Analysis and description of radio direction estimation algorithms

Wireless communications stands out as one of the areas that stands out in the light of technological progress in the modern engineering world. As technology in wireless communications has progressed, the need has arisen to develop equipment to support this evolution and to solve the problems caused by the limited resources of the electromagnetic spectrum.

Global coordination is essential for the efficient allocation of electromagnetic spectrum resources. This coordination is achieved through international organisations such as the *International Telecommunication Union* (ITU), which have established standards and regulations for the use of electromagnetic spectrum.

Quadratic DOA algorithms, such as CAPON (*Minimum Variance Distortionless Response - MVDR*), are based on the decomposition of the covariance matrix of signals. These algorithms are influenced by the physical size of the antenna, which can lead to less accurate and lower resolution results.

DOA algorithms based on subspace separation are based on the decomposition of the signal covariance matrix into eigenvectors. Representative algorithms for this type are MUSIC, ROOT MUSIC and ESPRIT. They offer higher accuracy than quadratic algorithms and are not limited by the physical dimensions of the antennas.

In this chapter, we present the operating principles and highlight the performance of the most commonly used algorithms for estimating the characteristic parameters of the received radio signal, such as MUSIC, ROOT MUSIC, ESPRIT and CAPON. To achieve this, we will use the MATLAB simulation environment, which will allow us to implement and evaluate these algorithms in a controlled environment.

3.2.1 DoA estimation algorithm: MUSIC

The MUSIC (*Multiple Signal Classification*) algorithm is one of the most accurate DOA algorithms based on subspace separation. It is used to estimate the number and direction of signals reaching the receiver. The MUSIC algorithm is based on the decomposition of the autocorrelation matrix into two eigenvectors: one for the noise subspace and one for the signal subspace. The vector of received incident wavefronts is included in the signal subspace, making the noise subspace orthogonal to it. Thus, the MUSIC algorithm can identify the direction of arrival of the signal with high accuracy. [200], [201].

3.2.2 DoA estimation algorithm: Root MUSIC

ROOT-MUSIC (*Root Multiple Signal Classification*) algorithm. It is a variant of the MUSIC algorithm that provides more information about the direction of arrival of the signal. Unlike the MUSIC algorithm, which involves plotting the pseudospectrum as a function of the angle of incidence of the incoming wavefront and identifying peaks, the ROOT-MUSIC algorithm uses a method based on polynomial root search. This allows accurate identification of the signal direction by determining the roots of the characteristic polynomial associated with the signal autocorrelation matrix [200][201].

3.2.3 DoA estimation algorithm: ESPRIT

The ESPRIT (*Estimation of Signal Parameters via Rotational Invariance Technique*) estimation algorithm involves decomposing a string of N elements into two identical substrings, each with S elements, where S is the number of elements in the antenna array. The purpose of this algorithm is to estimate the angle of incidence at reception by determining the rotation operator Φ relating the two subsets.

By combining data from the antenna pairs, the algorithm estimates the direction of arrival of the signal and uses these estimates to determine the position of the transmitting source. It is effective in situations where the antenna array arrangement is non-uniform and allows accurate estimates of signal arrival direction in these cases.

3.2.4 DoA estimation algorithm: MVDR / Capon

The MVDR (*Minimum Variance Distortionless Response*) / Capon algorithm, involves estimating the noise subspace of the correlation matrix based on projecting a string of M direction vectors. These direction vectors represent the ideal response of the receiver to a string of ideal sources.

By using these direction vectors, the Capon algorithm allows deriving the signal from the sources by orthogonally projecting the direction vectors onto the noise subspace. Thus, the Capon algorithm estimates the direction of arrival of the signal and separates it from the noise present in the receiving system. This leads to a more accurate estimation of the desired signal and an improvement in the performance of the communication system [203] [205].

The angle of incidence of the received signal is estimated by detecting the peaks in the spectrum generated by this algorithm.

3.3 Performance analysis of DoA algorithms

Detailed analysis of DoA radio incidence angle estimation algorithms finds its utility in DDDS research and development activities.

The efficiency of countermeasure systems depends to a large extent on the performance of the implemented estimation algorithm. This subchapter discusses the performance of four such algorithms (MUSIC, Root-MUSIC, ESPRIT and CAPON). These algorithms will be analysed based on variations in spectrum error.

Identifying the most suitable DoA algorithm for use in UAV countermeasures systems is a critical aspect of system design. The choice of DoA algorithm can significantly influence the system's detection, localization, tracking and neutralization capabilities. It is important to note that there is no single algorithm that is universally suitable for all situations. Instead, the choice depends on a variety of factors such as the environment (urban, rural, etc.), signal characteristics, hardware constraints and performance requirements (accuracy, resolution, computational complexity, etc.) [206][207].

3.3.1 DoA determination in MATLAB simulation environment

In this scenario implemented in MATLAB simulation environment, to analyze the performance of DoA MUSIC, Root-MUSIC, ESPRIT and MVDR/Capon's estimation algorithms we simulated two distinct cases for a 2,4,6 and 8 element antenna array as follows:

- a transmitter placed at an azimuth of -20° to the orientation of the antenna array;
- two transmitters placed at azimuths of -30 and 70^{0} to the antenna orientation.

The simulation will allow us to understand how the number of elements of a receive antenna array and the number of sources influence the determination error for each algorithm.

Our objective is to understand how each of these algorithms works in terms of spectral error.

Spectral error is the deviation of the estimated spectrum from the true spectrum and is a key measure as it directly influences the accuracy of the DoA estimate. A lower spectral error typically leads to a more accurate DoA estimate, which is essential in applications such as drone combat systems.

3.3.2 Performance evaluation after MATLAB simulation

MUSIC provides high resolution estimates of DoA and is effective when the number of sources is less than the number of antennas. For arrays with only two antennas, MUSIC may not be the best option if there is more than one source. A est algorithm may be a good choice if high resolution estimates are required and computational resources are sufficient.

Root-MUSIC also requires the number of sources to be less than the number of antennas, so may not be suitable for arrays with only two antennas if there are more than two sources. For arrays with a larger number of elements (with 4, 6 or 8 antennas), Root-MUSIC may be a good choice if high resolution estimates are required where computational resources are not a major constraint.

ESPRIT also provides high-resolution estimates. However, it requires a specific antenna array geometry (such as a uniform linear array with a half-wave spacing between antenna elements) and may not be suitable for arrays with fewer antennas (such as those with 2 antennas). With 4, 6 or 8 antennas, ESPRIT may be a good choice, provided the antenna array geometry requirement is met.

MVDR/CAPON forms a narrow beam in the direction of the desired signal. While they can be effective with a small number of antennas, they require accurate estimation of the covariance matrix, which can be difficult in fast-changing or non-stationary environments. These methods can provide a good balance between performance and computational complexity for antenna matrices with sizes from 2 to 8.

3.3.3 Analysis of results

In conclusion, because the flight of a UAV is very fast and unpredictable, the algorithm to be used must be very fast in computation and accurate.

In summary, for applications with a small to moderate antenna array size (2 to 8 antennas) where high resolution is required and computational resources are not a constraint, methods such as MUSIC, Root-MUSIC or ESPRIT may be more suitable.

3.4 Conclusions

In this chapter the most important algorithms used for radio location determination have been presented. This section has also illustrated the performance of these algorithms, using MATLAB software, as a function of the variation of the spectral error and the number of antenna array elements used for signal reception.

Thus we can say that the four algorithms presented (MUSIC, ROOT MUSIC, ESPRIT and CAPON) are high accuracy algorithms. This accuracy is supported by low spectral error at reception. Also, the analysis of the four radio direction estimation algorithms showed that they have a high sensitivity to error. At the same time, it is found that the performance of these algorithms increases with the number of antenna array elements used for reception and the number of sources.

Thus, for the implementation of a DDDS whose goal is to neutralize a target whose versatility is high I conclude that the best algorithm for such an implementation is MUSIC because it offers relatively good performance requiring computational complexity (high speed of radio incidence angle determination).

At the same time, the performance evaluation of radio estimation algorithms in [200,201, 203] presents the MUSIC algorithm as being suitable for applications where single source localization is needed.

It also operates at a high SNR level which makes the decision to have a drone present a much safer one, given that so much other equipment operates in the ISM signal bands.

4 Introduction, description and analysis of SDR performance

4.1 Introduction to SDR technology. Ways of making SDR equipment.

In a Software Defined Radio (SDR) system, the traditional hardware functions of a communications system, such as mixers, filters, amplifiers or modulators/demodulators, are implemented in the software domain using a personal computer (PC) or embedded *Digital Signal Processing (*DSP) or *Field-Programmable Gate Array* (FPGA) systems.

By using SDR technology, it allows flexibility and the possibility to reconfigure the communication system through software. This means that the functions and parameters of the communication system can be changed or updated via software without the need for hardware modifications. This approach offers advantages such as adaptability to different communication standards and protocols, reduced development and maintenance costs, and increased system efficiency and performance.

These benefits reflect the advantages of the SDR concept for both radio manufacturers and end-users, such as cost savings, flexibility in use and the possibility of customisation and adaptability.

4.2 Evolution of SDR

In a conventional receiver, received radio signals are converted to baseband through conversion processes. This process involves the use of analogue components such as amplifiers, mixers and oscillators. The purpose of conversion is to bring the signal down to a lower frequency so that it can be demodulated later.

The functionality and performance of these receivers depends only on their hardware components. In the SDR industry nomenclature this type of receiver is referred to as *Tier* Zero, i.e. a level at which no software components are used.

4.2.1 First generation of software defined radio equipment

Computing systems have increasingly found their usefulness in all fields and platform manufacturers have found a new way to implement them, bringing more benefits to traditional radio platforms.

For this model, the basic functions: filtering and demodulation, remained hardware-dependent, but the software component was represented by operator-friendly graphical user interfaces and signal processing was performed by the computer sound card.

4.2.2 Second generation of SDR

The second generation of SDR receivers takes the integration of radio platforms and computing systems to the next level by incorporating an analogue-to-digital converter (ADC) into the basic receiver structure. This has resulted in improved signal processing performance (compared to that of a PC processor), while the increased processing power of the computing systems has made this fusion of radio and PC rival dedicated digital signal *processing* (DSP).

This type of receiver belongs to a higher class in the nomenclature of SDR platforms, also referred to as Tier Two SDR (*SDR* - tier *two*) or *Software* Reconfigurable Radio equipment. In this class of receivers, the software component is used to control and redefine a variety of modulation techniques, signal band of interest, amplification, signal-to-noise ratio, etc. [212].

4.3 Derived technologies based on SDR

Software Defined Radio (SDR) platforms are the key to a variety of reconfigurable radio equipment, and are the pioneer for this type of technology.

Thus, SDR platforms have been implemented in several types of equipment ensuring high flexibility to reach the maximum potential of the equipment, with the benefits of reduced cost and increased efficiency of the realized systems [210].

- Adaptive Radio equipment
- Cognitive Radio equipment
- Intelligent radio equipment

4.4 Functions to be performed by the SDR

An SDR must meet one or more of the following characteristics: [211]

- Multiband;
- Multiple carriers (multicarrier);
- Multi-mode operation;
- Multi-salted;
- Variable bandwidth.

In addition, digital filters have the ability to achieve other characteristics not possible with filters made in the analogue domain. Digital filters can also be tailored to reduce interference and compensate for distortion on the transmission channel, both of which are difficult features for analogue filters to achieve.

4.5 Comparative analysis of SDR platforms

In this subsection, comparisons will be made between various SDR platforms, focusing on RF front-end reception performance. Various measurements in different frequency bands were performed using SDR platforms, with a spectrum analyzer used as a reference point. The results are analysed and discussed considering the use of such a platform for the implementation of spectrum sensing applications - an essential aspect in equipment design.

There are several SDR platforms available on the market, the best known of which is the Universal Software Radio Peripheral (USRP) range developed by Ettus Research. For narrowband and low-cost applications, affordable devices such as the RTL-SDR range are available at prices as low as $25.

4.5.1 Details of the SDR platforms to which the study applies

The proposed experimental scenario compares the RF front-end performance of four different SDR platforms [221]. Three of these platforms are part of the USRP family (USRP N210 [222] with WBX RF backplane [223], USRP X310 [224] with CBX RF backplane [13] and USRP B200 mini [226]), while the fourth platform is HackRF One [227], produced by Great Scott Gadgets. A detailed description of each RF interface is given, together with a theoretical calculation of the global noise figure (NF - *Noise Figure*) for each case, taking into account the performance parameters of the components used. An experimental performance evaluation is carried out, based on measurement results in four different frequency bands, using a spectrum analyser as a reference instrument [213].

For each SDR platform, we present a block diagram of the RF front-end, along with a table listing the performance of each block used. To calculate the overall noise factor for an n-stage SDR platform, we used the Friis noise factor formula [221].

To express the performance differences of each SDR platform considered for this study below is a block diagram for the RF front-end section, a table with the NF values respectively the gain of each block. In this scenario we considered the receive gain values at a maximum level.

USRP N210 equipped with WBX RF expansion boards

The USRP N210 SDR platform [222] is part of the USRP product suite developed by Ettus Research (USA).

USRP X310 equipped with CBX RF expansion boards

The USRP X310 SDR platform [222] offers scalable performance and is intended for the design and deployment of next-generation wireless communication systems.

The hardware architecture supports two expansion card slots with extended bandwidth up to 6 GHz and a base bandwidth of up to 120 MHz. It also features several high-speed interface options (PCIe, Dual 1/10 GigE) and a user-programmable Kintex-7 FPGA.

USRP B200-mini

The USRP B200 mini [226] is an extremely compact and adaptable SDR platform with a small footprint that was designed and manufactured by Ettus Research. The USRP B200 Mini is suitable for a variety of applications and supports a wide range of frequencies, based on a hardware architecture that relies on a user-programmable Xilinx Spartan-6 FPGA.

SDR HackRF One platform

The HackRF One platform [227], designed and developed by Grand Scott Gadgets, is an SDR platform that can transmit or receive radio signals in the 1 MHz to 6 GHz frequency range.

Using the Friis total noise factor formulae for each element of the frontend parts of each SDR platform resulted in the following total noise factor values:

- SDR USRP N 210 (WBX RF): 1.62 dB (100 MHz), 1.45 (1GHz), 2.01 dB (2.5 GHz);
- SDR USRP X310 (CBX RF): 1.73 dB (2.5 GHz);
- SDR USRP B200-mini: 2.35 dB (100 MHz), 2.35 (1GHz), 3.35 dB (2.5 GHz);
- SDR HackRF One: 5.52 dB (below 1 GHz), 5.84 (above 1 GHz).

4.5.2 Description of the measurement scenario

The setup used to perform the measurements described in the following section involved the four SDR platforms presented in *Section 4.5.1*, together with an Agilent E4402B spectrum analyzer (9kHz-3GHz), which was used as reference equipment [213].

It should be noted that a single wideband antenna (MP 08-ANT-0861, 25MHz-6GHz) was used for all measurements, which was linked to the RF inputs of the SDR platforms via a 4-port RF splitter (Mini-Circuits ZN4PD1-63HP-S). Each SDR platform was connected to a host computer, through which we operated the platform and collected the resulting data [213].

GNU Radio scripts were used to perform the above functions. A *Low* Noise Amplifier (LNA) (Mini-Circuits ZX60-V63+) was used only to collect RF data for the spectrum analyzer, for the 2500-2690 MHz frequency band. For each frequency band and each SDR platform, 300 measurements were made, corresponding to a measurement time of approximately 5 minutes. The same digital signal processing procedures were applied for all devices tested.

4.5.3 Measurement results and analysis

The experimental measurement setup described in the previous section was used to perform measurements in the mentioned frequency bands. For each of the SDR platforms the instantaneous bandwidth is limited by either the RF front-end or the interface between the platform and the host computer.

Of the four bands mentioned in *Table 4.6*, only the 90-100 MHz band is narrow enough to be captured in a single slot. For all other bands, GNU Radio scripts collected the necessary information for the entire bandwidth by concatenating frequency sub-bands of 10 MHz each.

Since the detection and false alarm performance in spectral detection depends significantly on the signal-to-noise ratio, by analysing the NF values obtained and presented in *section 4.5.1*, we can conclude that the best performance should be expected from the N210 USRP with the WBX board, as it shows an overall NF between 1.45 and 1.62 dB for frequency bands 1-3 (see *Table 4.6*) (the frequency of band 4 exceeded the range of the WBX board and was not measured with this SDR platform).

4.6 Conclusions

In this chapter we have performed a comparison between four different SDR platforms, considering the behaviour of these platforms when used for spectrum sensing applications. A theoretical calculation of the noise figure for the receive side of the RF front-end of each platform was performed. The results of measurements in four different frequency bands were presented and discussed. The lowest noise figure values among all platforms was obtained for the SDR platforms of the USRP family and thus these platforms are recommended as optimal solutions for spectrum sensing applications.

As future research directions, we intend to apply different spectrum detection algorithms on RF data captured with various SDR platforms considered in this paper and we will compare the performance of the algorithms (detection probabilities and false alarm) that can be obtained in each case. In order to be able to control the signal-to-noise ratio, known test signals will be used. Since there are many applications for which low-cost SDR platforms are suitable, we also intend to perform a comparison of several such platforms in narrowband scenarios.

5. Design and implementation of a DDDS system - DRONEND

The proposed project will use a ground or airborne platform in which detection, identification, localization and neutralization (jamming) subsystems using SDR technologies will be integrated. It should be noted that this project started from the current state of research in this field and sought to improve and optimize existing solutions in order to achieve greater efficiency to meet current and future security requirements.

In view of the above considerations, in my research I have been involved in a project that integrated a drone defence system. The system was built using SDR platforms and will have capabilities to detect, monitor, locate and neutralize one or more hostile drones.

In this chapter, two drone detection and defence systems - DDDS, designed and implemented by members of the steering committee together with a research team from the cyber security company Cyberwall [230], will be presented. Both variants of the system were developed as part of the DronEnd research project [231]. Preliminary details of the project have been presented in [232] and [233].

5.1 DRONEND - Ground-based DDDS

The purpose of the DronEnd ground defence system is to secure a specific area against the unauthorised presence of drones. To achieve this goal, the DronEnd system scans the RF spectrum to detect the presence of drones in the area under surveillance, identifies the location of the drone using AoA algorithms and annihilates the drone using RF jamming methods. The block diagram of the implemented DronEnd ground defense system is shown in *Figure 5.1*.

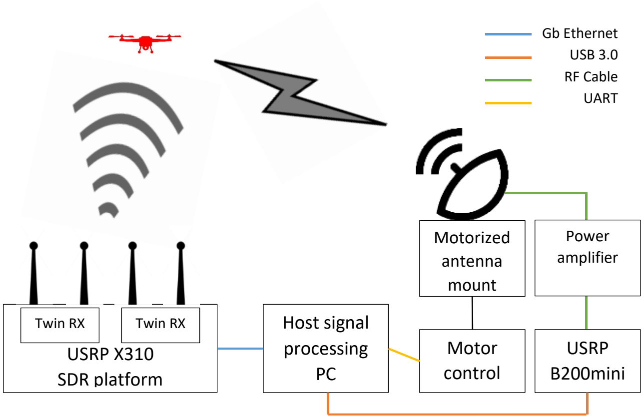

Figure 5.1 Block diagram of DRONEND DDDS - ground based

In the following subsections, all the elements of the system will be detailed, outlining the steps required to achieve the functions of detection, localization and drone annihilation by jamming.

5.1.1 Identification of drone presence using spectral detection algorithms

The first step required to identify the presence of a drone in RF-based defence systems is to monitor the radio spectrum using a spectral detection process to identify the signals transmitted by the drone. [234]

In the implementation of the spectral detection process in the DronEnd system, energy detection algorithms such as 3EED (*Three-Event Energy Detection*) [235] and 3EED with an adaptive threshold [236], which offer improved performance compared to the classical energy detection algorithm (CED - *Classic Energy Detection*) [237], were used to identify the presence of drones in the monitored area.

The aforementioned algorithms were implemented on SDR platforms of the USRP USRP X310 family [238] equipped with Twin-RX RF expansion boards [239] with a frequency range of 10-6000 MHz).

The frequency bands used by the drones used for testing the DronEnd system - DJI Mavic Air [240], DJI Phantom 4 Pro v2.0 [241] and DJI Mini 2 [242]) were the 2.4 GHz (2400-2500 MHz) and 5 GHz (5730-5830 MHz) ISM bands, which can be covered using the aforementioned SDR platforms capable of receiving signals at frequencies up to 6 GHz. As the position of the target drones was initially unknown, omnidirectional antennas were used in this step.

RF data capture was performed using a GNU Radio Python script. Since the instantaneous bandwidth captured using the Twin-RX RF expansion board is less than 100 MHz, to cover the 100 MHz bandwidth of the 2.4 GHz and 5 GHz ISM bands, several sub-bands were concatenated.

Once the signal transmitted by the target drone is detected, the next step is triggered, which consists of locating the angle of arrival of the received signal, as will be discussed in the next subsection.

5.1.2 Drone localization using AoA algorithms

After identifying the communication frequency used by the drone, the next necessary step was to collect data on the drone's position. This was done using AoA algorithms to detect the angle of incidence of the RF signal.

The SDR platform used as hardware to provide the RF receive front end was the USRP X310 [238], on which two Twin-RX RF expander boards [239] (frequency range covered from 10 to 6000 MHz, 80 MHz instantaneous bandwidth) were mated. Each of these Twin-RX modules provides two coherent receive channels, with the local oscillator that can be distributed between the two boards, resulting in a total of four phase-aligned coherent receive channels.

The antenna array used was a linear array of four antennas, spaced at a distance equal to half the wavelength of the minimum frequency at which the drones communicate (2.4 GHz). Estimating the initial phase difference between the four receive channels required a calibration step after each system start-up, involving the transmission of a test signal to be received by RF cables of equal length on all four receive channels.

A ZN4PD1-63HP-S+ [243] 5-port Mini-Circuits RF splitter was used to distribute the signals.

After completion of the calibration phase, the four VERT2450 [244] dipole antennas that are part of the antenna system were connected to the four receive channels of the USRP X310 SDR platform and, based on the phase difference of the received signals, the incidence angle corresponding to the drone position could be identified using AoA algorithms. We used one of the classical AoA algorithms - the MUSIC algorithm.

The positioning obtained in this way was in the azimuthal plane because the antenna system used was placed horizontally. By using a second system placed in a vertical plane, the height of the drone could also be estimated.

5.1.2 Neutralizing a drone using RF jamming

The next step is to transmit a jamming signal to the target drone in order to interrupt communications between the drone and the ground controller. Since the jamming signal should only be transmitted in the direction of the target drone, to avoid interference with other equipment in the area, a directional antenna was used.

Once the angle of incidence was detected by the AoA algorithm, it was processed (filtered) using a script in the Matlab simulation environment to remove any erroneous clues related to the drone's position and was then transmitted via a serial interface (UART - *Universal Asynchronous Receiver / Transmitter*) to the motor control module (MCM - *Motor Control Module*), which controls the stepper motors used to move the motorised mount for positioning the jamming antenna.

The SDR platform used to generate the interference signal was the USRP B200mini (frequency range 70-6000 MHz) [245].

Since the maximum power that can be obtained at the output of the SDR platform is 10 dBm, a Mini-Circuits ZHL-2W-63-S+ power amplifier [246]) was used to amplify the interference signal and extend the range of the system, giving an amplification of 42 dB and a maximum output power of 2 W. The antenna used to transmit the interference signal was an Ubiquiti UMA-D directional antenna [247], which covers the 2.4-2.5 GHz and 5.1-5.9 GHz frequency bands and provides an amplification of 10 dBi in the 2.4 GHz band and 15 dBi in the 5.8 GHz band.

By using a directional antenna targeting the location of the drone to transmit the interfering signal, interference from other nearby communication systems is minimised. Furthermore, the transmission amplification can be adjusted according to the size of the area to be protected.

The tests were conducted in an outdoor suburban scenario using the DJI Mavic Air, DJI Phantom 4 Pro v2.0 and DJI Mini 2 drones as targets, and drone annihilation, resulting in a forced landing in the position where the drone was when the jamming signal was activated, was possible for distances of 40 meters from the area where the DronEnd ground system was located.

5.2 DRONEND - DDDS aerial

The DronEnd aerial system aims to extend the reach and capabilities of the DronEnd GROUND platform, detailed in depth in *Subsection 5.1*.

5.2.1 Description of the USRP E-312 SDR platform

A standalone SDR USRP E312 platform was used to implement the DronEnd aerial system [248].

5.2.2 Description of the DDDS - DRONEND aerial solution and functions

A block diagram of the proposed system architecture for the DronEnd aerial platform is shown in *Figure 5.9*. The system consists of a proper aerial platform, highlighted in black, on which a stand-alone USRP E312 SDR platform is attached.

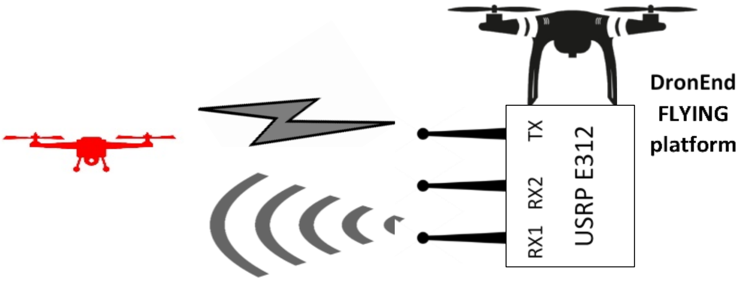

Figure 5.2 Block diagram of DDDS-aerial DRONEND

The system must perform the following three main functions:

- Detection: Identification of the presence of the target drone based on the exchange of data via radio channels between the target drone and a ground-based operator. Spectral detection algorithms are used to implement this function;

- Location: Determining the relative direction of the target drone, using its own aerial platform as a reference. AoA determination algorithms are used to implement this function;

- Defence: Neutralisation of detected target drone by transmitting a jamming signal in the frequency band used for target drone communications.

5.2.3 Detailing DRONEND-aerial functions

The first step involves identifying the presence of the drone by monitoring the frequency bands used for communication between the target drone and a ground-based operator. Most commercial drones use the 2.4 GHz and 5 GHz industrial, scientific and medical (ISM) frequency bands, so these bands were considered in the design of the DronEnd airborne system. Spectral detection algorithms were used to identify the signals transmitted by the target drone.

From the hardware perspective, a VERT2450 dual-band omnidirectional antenna [249] (2.4-2.5 and 4.9-5.9 GHz) was used.

The result of this step (the frequency band in which the target drone was detected) is transmitted to the radio direction identification module and the jamming module, as shown in *Figure 5.10*.

The second step is to identify the relative direction of the target drone. This process is carried out by analysing the phase difference of the signals received on the two receive channels available on the USRP E312 SDR platform.

Algorithms for determining the angle of radio incidence - AoA, such as MUSIC and ROOT MUSIC, can be used to obtain an estimate of the relative direction.

The features of the relative direction identification subsystem are as follows:

- The SDR platform's two receiving antennas can locate a single target UAV at a time.
- The wavelengths (λ) corresponding to the frequency bands used for commercial drone control are between 10 and 20 cm, which implies placing receiving antennas at distances equal to multiples of λ/2.

The third step is to use the data obtained from the processes described above to emit a jamming signal in the frequency band in which the target drone has been identified. The purpose of this jamming signal is to break the radio link controlling the target drone, induce a loss of control of the target drone and force it to land.

Considering that the maximum power that the USRP E312 SDR platform can emit is less than 10 dBm, the jamming signal emitted has the ability to interfere with the radio link between the operator and the target drone, given the distance between our own air defence platform and the target drone, which is in the order of tens of meters.

5.2.4 Hardware implementation details of DRONEND - aerial

The hardware architecture consists of the following components:

- Your own UAV, which can be either a DJI Phantom 4 v2.0 defence platform (*Figure 5.13*) or a DJI Matrice 600 Pro (*Figure 5.14*).
- USRP E312 SDR platform equipped with two VERT2450 antennas.
- a docking system made using a 3D printer, designed to provide the connection between the UAV and the SDR.

The tests were successfully conducted in a rural environment, where communication between the target drone and the ground controller was interrupted when our defence drone approached within a few dozen metres of the target drone. Initially, video communication between the target drone and the operator was disrupted and subsequently the target drone was forced to land. On the project website, https://dronend.ro, you can watch a video illustrating these tests.

5.3 Conclusions

As a result of the activities carried out in the DronEnd project, two prototypes have been created, one for the DronEnd ground system and the other for the DronEnd air system. These prototypes demonstrated effectiveness in detecting, locating and jamming target drones that entered the surveyed area.

These prototypes validated the project goals, i.e. detection and location of target drones entering the monitored area, as well as their neutralisation using jamming techniques, all of which were achieved without requiring significant investment, through the use of Software Defined Radio (SDR) platforms. Another advantage of this approach is the flexibility and scalability of the system, which can be adapted according to different requirements specific to different usage scenarios.

6. Conclusions

In this PhD thesis we have outlined options for the use of the main methods of locating a radio source in drone detection, tracking and combat systems. Also, as a result of the research we have determined the most suitable methods and systems for designing a system to combat unauthorised use of drones.

This research is justified by the increasing unauthorised use of drones which has inevitably led to threats and potential security breaches arising from the use of these technologies.

Thus, in order to protect strategic and national security objectives, it is necessary to approach research in this field using appropriate means and methods.

To this end, in this thesis we have implemented, together with members of the DRONEND project, a ground and an airborne system incorporating detection, identification, localization and neutralization (jamming) subsystems using SDR technologies.

It should be noted that this project started from the current state of research in this field and aimed to improve and optimise existing solutions in order to achieve greater efficiency to meet current and future security requirements.

It is noted that in the research work related to algorithms for localization of radio signal sources and the use of SDR - USRP equipment for signal detection and processing and, finally, for the realization and validation of systems to combat drones with hostile intent we have achieved the objectives stipulated in the beginning of the work, both ***main objectives***:

- Contributions to the improvement of algorithms for locating objects that are sources of radio signals; their study by simulation and experiment using SDR - USRP technology;
- contributions to the use of such algorithms in applications related to the identification, location and countering of flying objects such as drones.

and secondary objectives:

- to carry out an extensive study on the current state of research in the field of usable methods for locating a radio signal source and its use in systems to combat unauthorised UAV systems;
- to perform a comparative analysis by simulation and experiment of radio source localization algorithms in order to identify the optimal algorithm for implementing a usable system for drone localization;
- use of programming environments such as MATLAB and GNU-radio, Labview for the analysis of the previous objective;

- design, development (as an experimental model) and validation of a system for detecting, locating and combating drones.

6.1 Results achieved

The PhD thesis has a logical structure consisting of six chapters describing in detail the processes, the current state of research, the research methodology and examples of their implementation. The introductory part of the thesis provides a brief overview of the research area, i.e. the aim, motivation, objectives and content of the PhD thesis.

Chapter two presents the current state of research in the field of combating unauthorised use of UAV systems.

From the research of chapter two we conducted a systematic literature review using the PRISMA methodology in order to obtain as accurate as possible the current state of the art of drone detection and defence systems.

The analysis considered:

- Classification of drone detection systems based on the type of sensors used;
- Detailed description of RF-based drone detection and defence systems, with emphasis on the use of SDR platforms for the implementation of these systems;
- a list of reported incidents caused by unregulated use of UAV systems;
- aspects of international regulations in the field.

From this systematic literature review, the purpose, role and necessity of the design of the drone detection, localization and combat system - DRONEND - emerges.

Chapter three reviews the main methods and signal parameters used for locating radio signal sources.

In this chapter the most important algorithms used for radio location determination have been reviewed:

- MUSIC;
- ROOT MUSIC;
- ESPRIT;
- CAPON.

These algorithms were analysed in the MATLAB software application according to the variation of the spectrum error and the number of antenna array elements used for signal reception.

This section also illustrated the performance of these algorithms using MATLAB software.

Thus, we can say that the four algorithms presented (MUSIC, ROOT MUSIC, ESPRIT and CAPON) are high accuracy algorithms.

The results showed that the four radio direction estimation algorithms that exhibit high sensitivity to error. It is found that the performance of these algorithms increases with the number of antenna array elements used for reception.

The simulations showed that the best algorithms for the DRONEND system for detecting, locating and combating drones are MUSIC because they offer relatively good performance with low computational complexity (high speed of radio incidence angle determination) in the context of a target drone with a very high versatility of movement.

Chapter four presents the main ways of realising an integrated solution on an SDR platform. Here the evolution and need for the development of SDR equipment and a classification is presented.

Also presented here is a comparison and analysis resulting from practical implementations for several SDR platforms.

In this chapter:

- We conducted a comparison between four different SDR platforms, considering the behaviour of these platforms when used for spectrum sensing applications;
- a theoretical noise figure calculation was performed for the receive side of the RF front-end of each platform.
- the results of measurements in four different frequency bands were presented and discussed.

The lowest noise figure of all platforms was obtained for the USRP N210 with the WBX RF board, so this platform is recommended as the optimal solution for spectrum sensing applications.

We took the measurement results into account and thus for the implementation of the drone tracking, detection and combat system we used the USRP X-310 with CBX RF boards covering the ISM bands used for high performance drone control and communications.

Chapter five describes the activities related to the implementation of integrated systems based on SDR technologies for the identification, location and annihilation of hostile drone activities in two different designs: ground-based and airborne. These activities were carried out in the framework of the DronEnd project and resulted in the development of two prototypes, one for the ground-based system and one for the airborne system. Here I should mention that my research activity during my PhD internship was greatly enhanced by my involvement in the DRONEND project coordinated by Prof. Dr. Eng. Alexandru Marțian.

The DRONEND project was carried out with funds from the Romanian Ministry of Education and Research - CCCDI-UEFISCDI, project number: PN-III-P2-2.1-PED-2019-1951 from PNCDI III.

They contributed to the two prototypes that confirmed the detection, localization and jamming functionalities for target drones entering the monitored area. It has been verified that such equipment can be realised without requiring high costs by using Software Defined Radio (SDR) platforms. Another advantage of this approach is the flexibility and scalability of the system, which can be adapted according to various requirements specific to different usage scenarios.

I participated with members of the research team at the Polytechnic University of Bucharest, in the analysis carried out with partners from Cyberwall SRL, on the prospects of producing marketable variants of the system. There are many cases where such a system could be required, such as securing sports events taking place in stadiums/arenas, protecting airspace over private homes, securing airports or corporations, protecting critical infrastructure or prisons.

Chapter six presents the most significant findings of this PhD thesis.

6.2 Personal contributions

1. We conducted a theoretical synthesis on the state of evolution of counter-drone applications using the PRISMA model for systematic literature reviews using keywords such as "drone", "counter-drone", "counter-UAS", "UAV" [13].

The results were interpreted and disseminated in the journal Sensors [13] - impact factor 3.9 (Q1 at that time)

2. We have highlighted the need for drone countermeasures systems by highlighting recent incidents involving unauthorized and/or negligent drone use [13].
3. We have studied and highlighted the legislative framework in Romania regarding the use of drones and radio jamming countermeasures [13].
4. Following the systematic literature review we classified drone countermeasure systems according to the types of sensors used, respectively the countermeasures that can be used with emphasis on those using RF detection and radio frequency jamming [13];
5. We participated in a training course and obtained the license for the use of drones in urban areas A1 and A3 necessary for the test piloting of the drone - related to the DRONEND project;
6. We have made a theoretical briefing to describe how the localization of a radio source can be achieved

The results were reported in the first research report and in [234];

7. We have summarized and highlighted the most important algorithms for DoA estimation - MUSIC, ROOT MUSIC, ESPRIT and CAPON;
8. We performed a spectrum performance analysis for the DoA estimation algorithms described above using the MATLAB simulation environment.

This analysis led to the decision to use the MUSIC algorithm for the implementation of DRONEND land and air;

9. We have produced a summary on the evolution and ways of realising SDR platforms.

These findings were reported in the first research report.

10. We collaborated on a performance analysis between multiple SDR platforms in a lab scenario using MATLAB and GNU RADIO. Performance criteria were evaluated based on the calculation of the total noise figure (NF) of the front-end of the reception for each SDR.

The results were published in [215] and the second research report.

11. We actively participated in the construction of DRONEND in its two construction variants: DRONEND - land and air.

The results have been presented in [13, 233], respectively research reports 3 and 4.

12. I actively participated in writing the necessary code in Python -necesar language for programming DRONEND's SDR platforms [13, 233]:

13. We contributed to preliminary laboratory results for the SDR platforms that were used [13, 215, 233].

14. The project team has filed a patent application entitled: "System for detection, localization and jamming of a target drone by another defense drone and a ground station (DronEnd) at the State Office for Inventions and Trademarks (OSIM).

6.3 List of original works

Research reports:

a) **First research report** - Contributions on methods for locating a radio source;
b) **Second research report** - Comparative analysis of SDR platforms for spectral sensing applications;
c) **Third research report** - Aspects of the design and implementation of a drone defence system based on SDR (DronEnd-Ground) platforms;
d) **Fourth research report -** Aspects of the design and implementation of a drone defence system based on SDR (DronEnd -Flying) platforms

List of published works:

1. A. Martian, **F. Lucian Chiper**, O. Mohammed Khodayer Al-Dulaimi, M. Jalal Ahmad Al Sammarraie, C. Vladeanu and I. Marghescu, "Comparative Analysis of Software Defined Radio Platforms for Spectrum Sensing Applications," 2020 13th International Conference on Communications (COMM), Bucharest, Romania, 2020, pp. 369-374, doi: 10.1109/COMM48946.2020.9142024.
   (Accession Number: WOS:000612723900065, IEEEXplore)
2. A. Martian, **F. -L. Chiper**, R. Craciunescu, C. Vladeanu, O. Fratu and I. Marghescu, "RF Based UAV Detection and Defense Systems: Survey and a Novel Solution," 2021 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom), 2021, pp. 1-4, doi: 10.1109/BlackSeaCom52164.2021.9527871.
   (Accession Number: WOS: 000892556200069, IEEExplore)

3. **Chiper, F.-L.**; Martian, A.; Vladeanu, C.; Marghescu, I.; Craciunescu, R.; Fratu, O. Drone Detection and Defense Systems: Survey and a Software-Defined Radio-Based Solution. Sensors 2022, 22, 1453. https://doi.org/10.3390/s22041453 (ISIThompson, WOS:000765140800001)
4. **Florin-Lucian Chiper**, Alexandru Martian, Daniel-Ionut Muscalu, Calin Vladeanu and Ion Marghescu. Aerial Drone Defense System Based on Software Defined Radio Platforms) to 2022 14th International Conference on Communications (COMM) doi: 10.1109/COMM54429.2022.9817314.
5. Omer Mohammed Khodayer Al-Dulaimi, **Florin-Lucian Chiper**, Călin Vladeanu and Alexandru Martian Triple-Threshold Energy Detection With Adaptive Intermediate Threshold for Cooperative Spectrum Sensing to 2022 14th International Conference on Communications (COMM) doi: 10.1109/COMM54429.2022.9817314.

6.4 Perspectives for research development

As directions for further research, I intend to continue comparing the performance of different drone detection algorithms using radio spectrum analysis (detection probability and false alarm). I will explore the possibility of combining several detection algorithms (video, radar, RF) to increase reliability and reduce the cases where detection cannot take place.

I also want to continue research to implement an autonomous drone countermeasures system that performs the three functions: detection, localization and neutralization.

Bibliography

[1] Y. Zeng, R. Zhang, and T. J. Lim, "Wireless Communications with Unmanned Aerial Vehicles: Opportunities and Challenges," IEEE Communications Magazine, vol. 54, no. 5, May 2016, pp. 36-42.

[2] J. Gezici, Z. Tian, G. B. Giannakis, H. Kobayashi, A. F. Molisch, H. V. Poor, and Z. Sahinoglu, \Localization via ultra-wideband radios: a look at positioning aspects for future sensor networks," IEEE Signal Processing Mag, vol. 22, no. 4, pp. 70-84, July 2005.

[3] G. Yang, X. Shi, L. Feng, S. He, Z. Shi and J. Chen, "CEDAR: A Cost-effective Crowdsensing System for Detecting and Localizing Drones," in IEEE Transactions on Mobile Computing, Early Access Article, 2019, doi: 10.1109/TMC.2019.2921962.

[12] J. J. Caffery, Wireless Location in CDMA Cellular Radio Systems. Boston: Kluwer Academic Publishers, 2000.

[13] Chiper, F.-L.; Martian, A.; Vladeanu, C.; Marghescu, I.; Craciunescu, R.; Fratu, O. Drone Detection and Defense Systems: Survey and a Software-Defined Radio-Based Solution. Sensors 2022, 22, 1453. https://doi.org/10.3390/s22041453

[14] World Economic Forum. Drones and Tomorrow's Airspace. 2020. Available online: https://www.weforum.org/communities/drones-and-tomorrow-s-airspace (accessed on 11 February 2022).

[16] Germen, M. Alternative cityscape visualisation: Drone shooting as a new dimension in urban photography. In Proceedings of the Electronic Visualisation and the Arts (EVA), London, UK, 12-14 July 2016; pp. 150-157.

[17] Kaufmann, E.; Gehrig, M.; Foehn, P.; Ranftl, R.; Dosovitskiy, A.; Koltun, V.; Scaramuzza, D. Beauty and the beast: Optimal methods meet learning for drone racing. In Proceedings of the IEEE International Conference on Robotics and Automation, Montreal, QC, Canada, 20-24 May 2019; pp. 690-696.

[18] Kaufmann, E.; Loquercio, A.; Ranftl, R.; Dosovitskiy, A.; Koltun, V.; Scaramuzza, D. Deep drone racing: Learning agile flight in dynamic environments. In Proceedings of the Conference on Robot Learning (CoRL), Zürich, Switzerland, 29-31 October 2018; pp. 133-145.

[19] Ahmad, A.; Cheema, A.A.; Finlay, D. A survey of radio propagation channel modelling for low altitude flying base stations.Comput. Netw. 2020, 171, 107122.

[20] Tozer, T.; Grace, D.; Thompson, J.; Baynham, P. UAVs and HAPspotential convergence for military communications. In Proceedings of the IEEE Colloquium on Military Satellite Communications, London, UK, 6 June 2000; pp. 10-1-10-6.

[21] Schneiderman, R. Unmanned drones are flying high in the military/aerospace sector. IEEE Signal Process. mag. 2012, 29, 8-11.

[22] Chen, J.Y.C. UAV-guided navigation for ground robot tele-operation in a military reconnaissance environment. Ergonomics 2010, 53, 940-950.

[23] Coffey, T.; Montgomery, J.A. The emergence of mini UAVs for military applications. def. Horiz. 2002, 22, 1.

[25] Iscold, P.; Pereira, G.A.S.; Torres, L.A.B. Development of a hand launched small UAV for ground reconnaissance. IEEE Trans. Aerosp. Electron. Syst. 2010, 46, 335348.

[26] Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tezlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ 2021, 372, n71. https://doi.org/10.1136/bmj.n71. Available online: http://www.prisma-statement.org/ (accessed on 11 February 2022).

[27] Butt, A.; Shah, S.I.A.; Zaheer, Q. Weapon launch system design of anti-terrorist UAV. In Proceedings of the International Conference on Engineering Technology (ICEET), Lahore, Pakistan, 21-12 February 2019; pp. 1-8.

[28] EY India. What's the Right Strategy to Counter Rogue Drones? Available online: https://www.ey.com/en_in/emergingtechnologies/whats-the-right-strategy-to-counter-rogue-drones (accessed on 12 January 2022).

[31] Drone Hits Plane at Heathrow Airport, Says Pilot. Available online: https://www.theguardian.com/uk-news/2016/apr/17/drone-plane-heathrow-airport-british-airways (accessed on 12 January 2022).

[32] Alex Silverman, Drone Hits Army Helicopter Flying Over Staten Island. Available online: https://newyork.cbslocal.com/2017/09/22/drone-hits-army-helicopter/ (accessed on 12 January 2022).

[33] Drone Collides with Commercial Aeroplane in Canada. Available online: https://www.bbc.com/news/technology-41635518 (accessed on 12 January 2022).

[34] Boeing 737 Passenger Jet Damaged in Possible Mid-Air Jet. Available online: https://www.bloomberg.com/news/articles/2018-12-13/aeromexico-737-jetliner-damaged-in-possible-midair-drone-strike (accessed on 12 January 2022).

[35] Plane Damaged after Being Hit by York Police Drone at Buttonville Airport. Available online: https://toronto.ctvnews.ca/plane-damaged-after-being-hit-by-york-police-drone-at-buttonville-airport-1.5554617 (accessed on 12 January 2022).

[36] Drone's Operator Detained for Flying Near Chinese Airplane. Available online: https://edition.cnn.com/2017/01/17/asia/china-drone-passenger-plane-near-miss/ (accessed on 12 January 2022).

[37] Air New Zealand Calls for Drone Legislation after Near Miss. Available online: https://www.bbc.com/news/world-asia-43551373.amp (accessed on 12 January 2022).

[38] Gatwick Drones: As it Happened. Available online: https://www.bbc.com/news/live/uk-england-sussex-46564814 (accessed on 12 January 2022).

[39] Ripley, C.W. Drone with Radioactive Material Found on Japanese Prime Minister's Roof. 2015. Available online: https://edition.cnn.com/2015/04/22/asia/japan-primeminister- rooftop-drone/index.html (accessed on 12 January 2022).

[40] Gibbons-Neff, T. ISIS Used an Armed Drone to Kill Two Kurdish Fighters and Wound French Troops, Report Says. 2016. Available online: https://www.washingtonpost.com/news/checkpoint/wp/2016/10/11/isis-used-an-armed-drone-to-kill-twokurdish-ghters-and-wound-french-troops-report-says/ (accessed on 12 January 2022).

[41] BBC. Venezuela President Maduro Survives Drone Assassination Attempt. 2018. Available online: https://www.bbc.com/news/world-latin-america-45073385 (accessed on 12 January 2022).

[42] Drone Incident Management at Aerodromes. Available online: https://www.easa.europa.eu/sites/default/files/dfu/drone_incident_management_at_aerodromes_part1_website_suitable.pdf (accessed on 12 January 2022).

[43] FCC Enforcement Advisory, Cell Jammers, GPS Jammers, and Other Jamming Devices, document FCC RCD 1329(4.2); FCC: Washington, DC, USA, 2011.

[44] Radiocommunications Exemption Arrangements for Drone Jamming Devices. Available online: https://www.acma.gov.au/sites/default/files/2019-08/IFC-4-2019-Consultation%20Paper%20-%20Radiocommunications%20exemption%20arrangements%20for%20drone%20jamming%20devices.docx (accessed on 12 January 2022).

[45] Markarian, G.; Staniforth, A. Countermeasures for Aerial Drones; ARTECH HOUSE: Norwood, MA, USA, 2021, ISBN 13: 978-1-63081-801-2.

[46] Michel, A.H. Counter-Drone Systems, 2nd ed.; Report from the Center of the Study of the Drone at Bard College: Annandale-On-Hudson, NY, USA, 2019. Available online: https://dronecenter.bard.edu/files/2018/02/CSD-Counter-Drone-Systems-Report.pdf (accessed on 11 February 2022).

[47] Brust, M.R.; Danoy, G.; Stolfi, D.H.; Pascal B. ; Swarm-based counter UAV defense system. Discov Internet Things 2021, 1, 2. https://doi.org/10.1007/s43926-021-00002-x.

[48] Alsok. 2020. Available online: https://www.alsok.co.jp/en/ (accessed on 12 January 2022).

[49] Ottoy, G.; de Strycker, L. An improved 2D triangulation algorithm for use with linear arrays. IEEE Sens. J. 2016, 16, 8238-8243.

[50] Shi, Z.; Chang, X.; Yang, C.; Wu, Z.; Wu, J. An Acoustic-Based Surveillance System for Amateur Drones Detection and Localization. IEEE Trans. Veh. Technol. 2020, 69, 2731-2739. https://doi.org/10.1109/TVT.2020.2964110.

[51] Mezei, J.; Fiaska, V.; Molnar, A. Drone sound detection. In Proceedings of the 16th IEEE International Symposium on Computational Intelligence and Informatics (CINTI), Budapest, Hungary, 19-21 November 2015; pp. 333-338.

[52] Hilal, A.A.; Mismar, T. Drone Positioning System Based on Sound Signals Detection for Tracking and Photography. In Proceedings of the 11th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), Vancouver, BC, Canada, 4-7 November 2020; pp. 0008-0011. https://doi.org/10.1109/IEMCON51383.2020.9284851.

[53] Kim, J.; Kim, D. Neural network based real-time UAV detection and analysis by sound. J. Adv. Inf. Technol. Converg. 2018, 8, 43-52.

[54] Busset, J.; Perrodin, F.; Wellig, P.; Ott, B.; Heutschi, K.; Rühl, T.; Nussbaumer, T. Detection and tracking of drones using advanced acoustic cameras. Unmanned/Unattended Sensors Sensor Netw. XI. Adv. Free- Space Opt. Commun. Techn. Appl. 2015, 9647, 96470F.

[55] Christnacher, F.; Hengy, S.; Laurenzis, M.; Matwyschuk, A.; Naz, P.; Schertzer, S.; Schmitt, G. Optical and acoustical UAV detection; Electro-Opt. Remote Sens. X 2016, 9988, 99880B.

[56] Seo, Y.; Jang, B.; Im, S. Drone detection using convolutional neural networks with acoustic STFT features. In Proceedings of the 15th IEEE International Conference on Advanced Video and Signals-based Surveillance (AVSS), Auckland, New Zealand, 27-30 November 2018; pp. 1-6.

[57] Bernardini, A.; Mangiatordi, F.; Pallotti, E.; Capodiferro, L. Drone detection by acoustic signature identication. Electron. Imag. 2017, 2017, 60-64.

[58] Hauzenberger, L.; Ohlsson, E.H. Drone Detection Using Audio Analysis. Master's Thesis, Department of Electrical and Information Technology, Faculty of Engineering, departments at LTHLund, Sweden, 2015.

[59] Harvey, B.; O'Young, S. Acoustic detection of a xed-wing UAV. Drones 2018, 2, 4-22.

[60] Yang, C.; Wu, Z.; Chang, X.; Shi, X.; Wo, J.; Shi, Z. DOA Estimation Using Amateur Drones Harmonic Acoustic Signals. In Proceedings of the 2018 IEEE 10th Sensor Array and Multichannel Signal Processing Workshop (SAM), Sheffield, South Yorkshire, 8-11 July 2018; pp. 587-591. https://doi.org/10.1109/SAM.2018.8448797.

[61] Kim, J.; Park, C.; Ahn, J.; Ko, Y.; Park, J.; Gallagher, J.C. Real-time UAV sound detection and analysis system. In Proceedings of the 2017 IEEE Sensors Applications Symposium (SAS), Glassboro, NJ, USA, 13-15 March 2017; pp. 1-5.

[62] Siriphun, N.; Kashihara, S.; Fall, D.; Khurat, A. Distinguishing Drone Types Based on Acoustic Wave by IoT Device. In Proceedings of the 2018 22nd International Computer Science and Engineering Conference (ICSEC), Chiang Mai, Thailand, 21-24 November 2018; pp. 1-4. https://doi.org/10.1109/ICSEC.2018.8712755.

[63] Droneshield. Dronesentry. 2020. Available online: https://www.droneshield.com/sentry (accessed on 11 February 2022).

[64] Chang, X.; Yang, C.; Wu, J.; Shi, X.; Shi, Z. A surveillance system for drone localization and tracking using acoustic arrays. In Proceedings of the IEEE 10th Sensor Array Multichannel Signal Process Workshop (SAM), Sheffield, UK, 8-11 July 2018; pp. 573-577.

[65] Al-Emadi, S.; Al-Ali, A.; Mohammad, A.; Al-Ali, A. Audio based drone detection and identication using deep learning. In Proceedings of the 15th International Wireless Communications & Mobile Computing Conference (IWCMC), Tangier, Morocco, 24-28 June 2019; pp. 459-464.

[116] Shi, X.; Yang, C.; Xie, W.; Liang, C.; Shi, Z.; Chen, J. Anti-drone system with multiple surveillance technologies: Architecture, implementation, and challenges. IEEE Commun. Mag. 2018, 56, 68-74.

[126] Robin Radar Systems. Available online: https://www.robinradar.com/press/blog/9-counter-drone-technologies-to-detect-and-stop-drones-today?fbclid=IwAR2Mnxiqbl1JLYmQJ5FXOe-UCKHfoi9jf8T6HbXW7b-LNzX4YkEphGqigEM, (accessed on 2 February 2022).

[141] Lin, J.; Singer, P. Drones, Lasers, and Tanks: China Shows Off Its Latest Weapons. 2017. Available online: https://www.popsci.com/china-new-weapons-lasers-drones-tanks/ (accessed on 12 January 2022).

[142] Josh Spires, Dubai-Made Magnetic Counter-Drone System to Launch Soon. 2021. Available online: https://dronedj.com/2021/01/04/dubai-made-magnetic-counter-drone-system-to-launch-soon/?fbclid=IwAR3e5Lk5TQZzxU_ovMRYqJ6rDm2XU4_T247rZSH9rJlNotDHMQQQkWQIByU (accessed on 12 January 2022).

[143] Atherton, K.D. Trained Police Eagles Attack Drones on Command. 2016. Available online: https://www.popsci.com/eagles-attackdrones- at-police-command/ (accessed on 12 January 2022).

[158] Directive 2014/53/EU of the European Parliament and of the Council of 16 April 2014. Available online: https://www.ancom.ro/en/uploads/links_files/Directive_RED_2014_53_UE.pdf (accessed on 12 January 2022).

[159] Decision on the Provision of Radio Equipment on the Market. Available online: https://www.ancom.ro/uploads/articles/file/industrie/Echipamente%20radio/HG_740_2016_privind_punerea_la_dispozitie_pe_piata_a_echipamentelor_radio_in_vigoare_din_08_08_2019EN.pdf (accessed on 12 January 2022).

[178] Skorobogatov, G.; Barrado, C.; Salami, E. Multiple UAV systems: A survey. Unmanned Syst. 2020, 8, 149-169.

[184] J. Gezici, Z. Tian, G. B. Giannakis, H. Kobayashi, A. F. Molisch, H. V. Poor, and Z. Sahinoglu, \Localization via ultra-wideband radios: a look at positioning aspects for future sensor networks," IEEE Signal Processing Mag, vol. 22, no. 4, pp. 70{84, July 2005.

[185] A. J. Weiss, "Direct position determination of narrowband radio frequency transmitters," IEEE Signal Processing Letters, vol. 11, no. 5, pp. 513{516,May 2004.

[186] Y. Qi, H. Kobayashi, and H. Suda, \Analysis of wireless geolocation in a non-line-of-sight environment," IEEE Trans. Wireless Commun., vol. 5, no. 3, pp.672{681, Mar. 2006.

[200] A. Vesa, "Direction of arrival estimation using music and root-music algorithm," in 18th Telecommunication forum TELFOR, November 2010.

[201] X. Gu and Y. H. Zhang, "Resolution threshold analysis of music algorithm in radar range imaging," Progress In Electromagnetics Research B, vol. 31, pp. 297-321, 2011.

[203] C. R. Dongarsane, A. N. Jadhav, and S. M. Hirikude, "Performance analysis of esprit algorithm for smart antenna system," International Journal of Communication Networks and Security, vol. 1, pp. 34-37, 2012.

[204] G. Tsoulos, "Smart Antennas for Mobile Communication Systems: Benefits and Challenges," IEE Electron. Commun Eng. Journal, ll(4.2): pp. 84-94, Apr. 1999.

[205] J. Capon, "High-resolution frequency-wave number spectrum analysis, IEEE Proc, 57, pp. 1408-1418, 1969.

[206] R. Schmidt, "Multiple Emitter Location and Signal Parameter Estimation," in IEEE Transactions on Antennas and Propagation, vol. 34, no. 3, pp. 276-280, March 1986, doi: 10.1109/TAP.1986.1143830.

[207] L. C. Godara, "Applications of Antenna Arrays to Mobile Communications, Part I: Performance Improvement, Feasibility, and System Considerations," in Proceedings of the IEEE, vol. 85, no. 7, pp. 1031-1060, July 1997, doi: 10.1109/5.611107.

[210]http://www.wirelessinnovation.org/assets/documents/SoftwareDefinedRadio.pdf, accessed 14.05.2023.

[211]http://www.radioamator.ro/articole/view.php?id=783#7 accessed on 13.06.2023

[213]https://spectrum5g.radio.pub.ro , accessed 28.04.2023

[214] A. Marțian, "Evaluation of Spectrum Occupancy in Urban and Rural Environments of Romania", in Revue Roumaine des Sciences Techniques - Serie Electrotechnique et Energetique, no. 1, pp 87-96, Jan.-Mar. 2014.

[215] A. Martian, F. Lucian Chiper, O. Mohammed Khodayer Al-Dulaimi, M. Jalal Ahmad Al Sammarraie, C. Vladeanu and I. Marghescu, "Comparative Analysis of Software Defined Radio Platforms for Spectrum Sensing Applications," 2020 13th International Conference on Communications (COMM), Bucharest, Romania, 2020, pp. 369-374, doi: 10.1109/COMM48946.2020.9142024.

[221] H. T. Friis, "Noise Figures of Radio Receivers," in Proceedings of the IRE, vol. 32, no. 7, pp. 419-422, July 1944.

[222] Ettus Research USRP N210 SDR platform, available online at: https://www.ettus.com/all-products/un210-kit/, accessed in Mar. 2020.

[223] Ettus Research WBX RF daughterboard, available online at: https://www.ettus.com/all-products/wbx/, accessed in Mar. 2020.

[224] Ettus Research USRP X310 SDR platform, available online at: https://www.ettus.com/all-products/x310-kit/, accessed in Mar. 2020.

[225] Ettus Research CBX RF daughterboard, available online at: https://www.ettus.com/all-products/cbx/, accessed in Mar. 2020.

[226] Ettus Research USRP B200-mini SDR platform, available online at: https://www.ettus.com/all-products/usrp-b200mini/, accessed in Mar. 2020.

[227] Great Scott Gadgets HackRF One SDR platform, available online at: https://greatscottgadgets.com/hackrf/one/, accessed in Mar. 2020.

[228] 5G Strategy for Romania, available at: http://www.ancom.org.ro/uploads/links_files/Strategia_5G_pentru_Romania.pdf, accessed in Mar. 2020.

[229] E. Dobre, A. Marțian and C. Vlădeanu, "USRP-based experimental platform for energy detection in cognitive radio systems," 2016 International Conference on Communications (COMM), Bucharest, 2016, pp. 185-188.

[230] Cyberwall. Available online: http://cyberwall.ro (accessed on 12 January 2022).

[231] DronEnd Research Project. Available online: http://dronend.ro (accessed on 12 January 2022).

[232] Martian, A.; Chiper, F.-L.; Craciunescu, R.; Vladeanu, C.; Fratu, O.; Marghescu, I. RF Based UAV Detection and Defense Systems: Survey and a Novel Solution. In Proceedings of the 2021 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom), Bucharest, 16-18 June, 2021; pp. 1-4. https://doi.org/10.1109/BlackSeaCom52164.2021.9527871.

[233] F. -L. Chiper, A. Martian, D. -I. Muscalu, C. Vladeanu and I. Marghescu, "Aerial Drone Defense System based on Software Defined Radio Platforms," 2022 14th International Conference on Communications (COMM), Bucharest, Romania, 2022, pp. 1-4, doi: 10.1109/COMM54429.2022.9817314.

[234] Omer Mohammed Khodayer Al-Dulaimi, Florin-Lucian Chiper, Călin Vladeanu and Alexandru Martian Triple-Threshold Energy Detection With Adaptive Intermediate Threshold for Cooperative Spectrum Sensing to 2022 14th International Conference on Communications (COMM) doi: 10.1109/COMM54429.2022.9817314.

[235] Vlădeanu, C.; Nastase, C.; Martian, A. Energy Detection Algorithm for Spectrum Sensing Using Three Consecutive Sensing Events. IEEE Wirel. Commun. Lett. 2016, 5, 284-287.

[236] Martian, A.; Al Sammarraie, M.J.A.; Vlădeanu, C.; Popescu, D.C. Three-Event Energy Detection with Adaptive Threshold for Spectrum Sensing in Cognitive Radio Systems. Sensors 2020, 20, 3614. https://doi.org/10.3390/s20133614.

[237] Urkowitz, H. Energy Detection of Unknown Deterministic Signals. Proc. IEEE 1967, 55, 523-531.

[238] Ettus Research USRP X310. Available online: https://www.ettus.com/all-products/x310-kit/ (accessed on 12 January 2022).

[239] Ettus Research Twin-RX RF Daughterboard. Available online: https://www.ettus.com/all-products/twinrx/ (accessed on 12 January 2022).

[240] DJI Mavic Air Drone. Available online: https://www.dji.com/mavic-air (accessed on 12 January 2022).

[241] DJI Phantom 4 Pro v2.0 Drone. Available online: https://store.dji.com/product/phantom-4-pro-v2/ (accessed on 12 January 2022).

[242] DJI Mini 2 Drone. Available online: https://store.dji.com/product/mini-2 (accessed on 12 January 2022).

[243] Mini-Circuits ZN4PD1-63HP-S+ 4 Ways DC Pass Power Splitter. Available online: https://www.minicircuits.com/WebStore/dashboard.html?model=ZN4PD1-63HP-S%2B (accessed on 12 January 2022).

[244] Ettus Research VERT2450 Antenna. Available online: https://www.ettus.com/all-products/vert2450/ (accessed on 12 January 2022).

[245] Ettus Research B200mini SDR Platform. Available online: https://www.ettus.com/all-products/usrp-b200mini/ (accessed on 12 January 2022).

[246] Mini-Circuits ZHL-2W-63-S+ Power Amplifier. Available online: https://www.minicircuits.com/WebStore/dashboard.html?model=ZHL-2W-63-S%2B (accessed on 12 January 2022).

[247] Ubiquiti UMA-D Antenna. Available online: https://dl.ubnt.com/datasheets/unifi/UMA-D_DS.pdf (accessed on 12 January 2022).

[248] Ettus Research USRP E312 SDR platform. Available online: https://www.ettus.com/allproducts/usrp-e312/ (accessed 02 April 2022).

[249] Ettus Research VERT2450 antenna. Available online: https://www.ettus.com/allproducts/vert2450/ (accessed 22 March 2022).

[250] DJI Mavic Air Drone. Available online: https://www.dji.com/mavic-air (accessed on 22 March 2022).