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Ph.D. THESIS
SUMMARY

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OPTIMIZAREA SISTEMELOR AUTOMATE CARE FOLOSESC SENZORI

SENSORS-BASED AUTOMATIC SYSTEMS OPTIMISATION

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Introduction

Presentation of the field of the doctoral thesis

Sensors-based automatic systems cannot be separated from wireless sensor networks (WSN). Recently, starting with ad-hoc networks connecting vehicles for the purpose of their cooperation, with the integration of unamnned aerial vehicles (UAV) into IoT systems, flying ad-hoc networks were developed (FANET). Moreover, the principle of cooperation between vehicles has been taken over in maritime and other water-related applications, developing surface ad-hoc networks or aquatic ad-hoc networks, SANET.

Both FANET and SANET networks have been proposed to be integrated into the IoT landscape, but their performance in a common framework has not been studied so far. In terms of the perspective from which they are analyzed, it is worth mentioning that the paper will refer to the issues related to the propagation in such networks. This perspective is new. The literature abounds, however, with works approaching the concepts of routing in such networks. Thus, this paper aims to study and optimize the performance of a hybrid network WSN - SANET - FANET in the context of developing a multidisciplinary IoT platform that serves the following fields: agriculture precision, non-critical medical applications, environmental monitoring and disaster management.

Scope of the doctoral thesis

Next, this paper aims to answer the following question: *It is feasible to develop an IoT architecture based on hybrid sensor networks (WSN - FANET - SANET) and on the coexistence of LoRa technology with other communications technologies to replace wireless infrastructure on demand?*

This main question raises a number of research issues, highlighted by nine other derived questions listed in this section.

Content of the doctoral thesis

In order to be able to answer all the questions in the previous section, it is necessary to go through several stages illustrated by the structure of the paper itself.

Thus, the thesis begins with a theoretical chapter (Chapter 1) which presents the principles and components of wireless sensor networks, low power and wide area communication technologies, the IoT concept and architecture and a study concerning FANET (flying ad-hoc networks) and SANET (surface ad-hoc networks) and their integration in IoT architectures.

In Chapter 2, starting from the concepts described in Chapter 1 and adding many novel elements (WSN - FANET - SANET hybrid network, the communication technology selection method, the UAV and USV node position optimization algorithm), a new five-level IoT architecture is presented.

In Chapter 3, Device layer contributions are divided into two categories: non-critical Devices sub-layer contributions and critical Devices sub-layer contributions, the approach being both innovative and useful, considering the disadvantages of the current unitary approach where all data are treated with the same priority. A method of selecting the appropriate communication technology needed for a certain scenario was proposed, as currently the interval between two successive transmissions of the parameters data has a fixed value.

Chapter 4 presents the contributions to the development of the Connectivity layer using LoRa technology for IoMT applications and to increase the quality of life. Thus, the parameters of the LoRa technology necessary to have a communication coverage appropriate to a hospital scenario and, respectively, to a monitoring scenario at the patients' home are highlighted. Also, the last part of the chapter highlights the experimental results obtained after the implementation of the Connectivity level for a prototype alarm for the hearing impaired based on LoRa technology.

Chapter 5 is dedicated to the proposal of an algorithm that can run on a Cloud server for optimizing the positions of the mobile nodes UAV and USV so that they ensure the communication between a served WSN and a network gateway. In addition, the most important notions related to propagation were defined and the propagation models used in terrestrial, aerial and aquatic networks were detailed, such as: the two-ray model, the model proposed in the standards 3GPP, the model of propagation in free space. These are important for understanding the proposed IoT system optimization solution.

Chapter 6 ends the series of contributions at the Connectivity layer through a measurement campaign carried out to analyze the performance of LoRa technology and to compare it with the theoretical models proposed in Chapter 5. In addition to the previous chapter, notions related to the real gain of the antennas, the additional phenomena that appeared during the field measurements (attenuation from the vegetation, losses through reflection and diffraction, etc.) were highlighted. Based on the experimental results, experimental models characteristic of the area and the conditions in which the experiments were performed were proposed.

Finally, in Chapter 7 we summarized the personal contributions and the results of the research and experiments carried out and we highlighted the future directions of development of the topic. Thus, the paper deals extensively with personal contributions to the optimization and improvement of IoT platforms, but also with the challenges and difficulties encountered in this endeavor.

Chapter 1

Wireless sensor networks and Internet of Things

1.1 Wireless sensor networks: concept and applications

1.1.1 Introduction

Wireless sensor networks represents a link between the environment and the digital environment [1]. This type of network can be used for a wide range of applications, but this paper focuses on the use of sensor networks in agricultural crop parameter monitoring applications [2], [3], [4], environmental monitoring [5] and disaster management [6] and non-critical telemedicine applications [7], [8].

1.1.2 Principle of wireless sensor networks: features and architecture

Wireless sensor networks are infrastructures composed of connected sensor nodes so that they can cooperatively monitor an area [1]. They are able to acquire, process and transmit the acquired data from the sensors to a central system whose task is to collect, post-process and analyze data so that the events to which the central system must react are isolated [9].

1.1.3 Sensor nodes: components

A sensor node comprises the following components: sensors and signal conditioning circuits, acquisition and processing unit, wireless communication modules, power supply.

1.1.4 Wireless network: other components

The data received from the sensor nodes is collected by the central node. Some processing can be done at this node, but usually its resources are limited. Thus, new elements appear in the wireless sensor networks that participate in the aggregation and routing of data, the translation of protocols between different networks and the coordination of nodes [10]: routers, access points, gateways, base stations.

1.2 Internet of Things: Concept and architecture

Numerous proposals for IoT architecture have been described in the literature since 2005, when the first IoT-relevant architecture was proposed [11]. The reference model, however, is the one proposed by ITU (International Telecommunication Union) [12].

Starting from the standardized architecture and bringing together the Data Accumulation and Data Abstraction layers within the dedicated Cloud level, the doctoral thesis proposes an IoT architecture on the following five layers: Devices, Pseudo-Edge, Connectivity, Cloud, Application (Chapter 2) with multiple features and improvements compared to the one presented in this section.

1.3 New long-range wireless technologies for IoT systems: Low-power wide area networks

LPWAN technologies are a concept that includes technologies that allow wide-area, low-power, lower-cost communications with the requirement to transmit small amounts of data over long distances [13].

1.3.1 LoRa modulation and LoRaWAN protocol

LoRa technology is based on chirp-spread spectrum communication, CSS (Chirp Spread Spectrum) [14]. Operating in the 868 MHz band in Europe, 915 MHz in North America and 433 MHz in Asia, LoRa is characterized by a low data rate (27 kbps for $SF = 7$ and a channel bandwidth of 500 kHz and up to 50 kbps when using FSK modulation). According to Silva et al. [15], the transmission rate varies between 290 bps and 50 kbps. The latter is not necessarily a disadvantage if the LoRa technology is placed in the right context and in the right scenario. LoRa has a large coverage area (it can exceed 5 km in urban areas [7]; 15 km, [16] or, as in [15], 45 km in rural areas).

1.3.2 Sigfox

Sigfox was developed in Toulouse, France since 2010 [17]. In Europe, the maximum number of Sigfox messages per day is limited to 144. This number comes from a 1% limit on the duty cycle for this technology.

1.3.3 Narrowband-IoT (NB-IoT)

The technology is integrated into the LTE standard, being considered a new radio interface, as it eliminates many of the features of the LTE standard in order to improve battery life and minimize device cost [18].

1.3.4 LTE Cat M1 communications technology

LTE Cat M1 is developed in the LTE bands and occupies 1.4 MHz, coexisting with current traffic and operating across the LTE spectrum. Unlike NB-IoT, it can support handover and VoLTE.

1.3.5 Comparison of LPWAN technologies

In this section, a comparative analysis of the LPWAN technologies presented is performed. The most important parameters and the most important characteristics were highlighted.

1.4 Wi-Fi technology in the context of IoT development

Although Wi-Fi versions are multiple (Table 1.2), this section will cover the latest standards, 802.11ac, 802.11ah (Wi-Fi HaLow) and 802.11ax.

1.5 Aspects regarding the integration of the ad-hoc FANET and SANET networks in the IoT architecture

1.5.1 Introduction

Both aerial and aquatic ad-hoc networks are a newly developed concept based on the model of vehicle ad-hoc networks.

1.5.2 Ad-hoc aerial networks applications

Autonomous unmanned aerial vehicles and remotely-controlled air vehicles have been integrated into many applications such as those in Table 1.3.

Table 1.3 Applications in which unmanned or remotely piloted aerial vehicles are used

Risk area inspection	Search and rescue missions
Hazard detection (fire)	Patrol in border areas
Traffic monitoring	Monitoring the environment [19]
Redirect data to other entities (air vehicles become base stations [20])	Crop monitoring [3]
Inspection of power lines and other high-altitude equipment	Monitoring of glaciers and volcanic eruptions

1.5.3 Surface ad-hoc network applications

Unmanned water vehicles, respectively, autonomous water vehicle networks play a role in hydrographic monitoring, facilitate oceanographic research and maritime or river missions. There are two categories of unmanned water vehicles: underwater vehicles and surface vehicles, USV [21].

1.5.4 Principles of ad-hoc aerial and surface networks

In this section, the principles of ad-hoc air networks will be highlighted, with the mention that the issues related to mobility, topology and energy consumption are also valid for surface networks based on USV. Unlike FANETs, in SANET networks the relatively low antenna height is a disadvantage, reducing the likelihood of vehicles being in line-of-sight (LoS).

1.5.5 FANET and SANET architectures: Comparison with other types of architectures dedicated to unmanned aerial or surface vehicles communications

This section compares ad-hoc architecture with three other types of non-ad-hoc architectures: architecture based on direct communication of autonomous vehicles with a gound control center, architecture based on cellular networks, architecture based on satellite communications.

1.6 Conclusions

This chapter was dedicated to WSN and IoT concepts. In addition, the options for ensuring connectivity within the IoT platform proposed further in the paper were presented.

Chapter 2

Proposed IoT architecture: Components and comparison with other architectures

2.1 Introduction

In this chapter, the IoT architecture proposed in the doctoral thesis is presented. Also, it is the result of a research effort that aimed to connect applications from perspectives such as: sustainable agriculture [4, 22, 23], IoMT [7], environmental monitoring, disaster prevention and management [6]. In this chapter, the components of each IoT layer proposed for integration into the platform were described. Later, in the following chapters, they were developed and validated.

2.2 Description of the proposed architecture

In Fig.2.1 the proposed IoT architecture is presented. It is structured on five proposed levels: Devices, Pseudo-Edge, Connectivity, Cloud and Application.

2.2.1 Devices layer

This level includes devices and acquisition units, such as sensors, development platforms, autonomous vehicles. To illustrate this level, use cases as precision agriculture and fire detection in homes or other environments were developed [5], [6].

2.2.2 Pseudo-Edge layer

The Pseudo-Edge layer (a microscopic projection of the original IoT Edge layer), based on current data (there are no previous samples available because this layer does not store data), generates a label based on a binary code that describes the current global event/state, for example: torrential rain and strong wind detected, or battery consumed and strong wind detected (UAV); low pH and very high turbidity (USV); liquefied petroleum gas release GPL (WSN). Based on the generated label, the selection of the appropriate communication technology for the scenario will be made. The method of selecting the communication technology is described in Chapter 3, Section 3.3 and has been customized for a critical events monitoring scenario, such as fires or flammable gases releases.

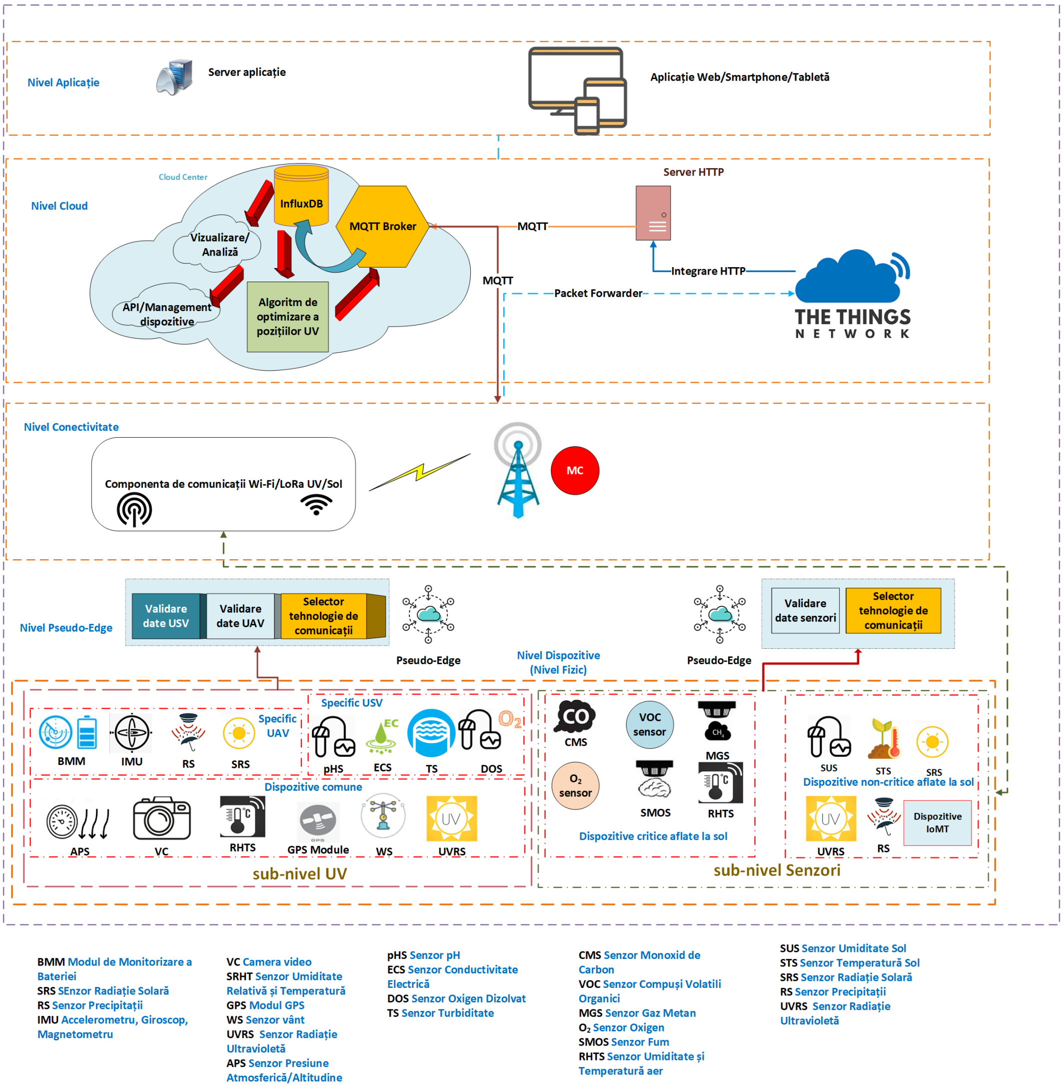

Fig. 2.1 The proposed Internet of Things architecture (adapted from [22–24])

2.2.3 Connectivity layer

The innovative component of this layer is the use of UVs as access points for WSNs that are not within the coverage of the gateway. This is possible using FANET and SANET infrastructures whose principles have been highlighted in Section 1.5.

Fig. 2.2 presents the sub-architecture highlighting the context of the development of an algorithm that provides the optimal position of unmanned vehicles (UV = UAV + USV) to connect a certain WSN terrestrial to an IoT platform.

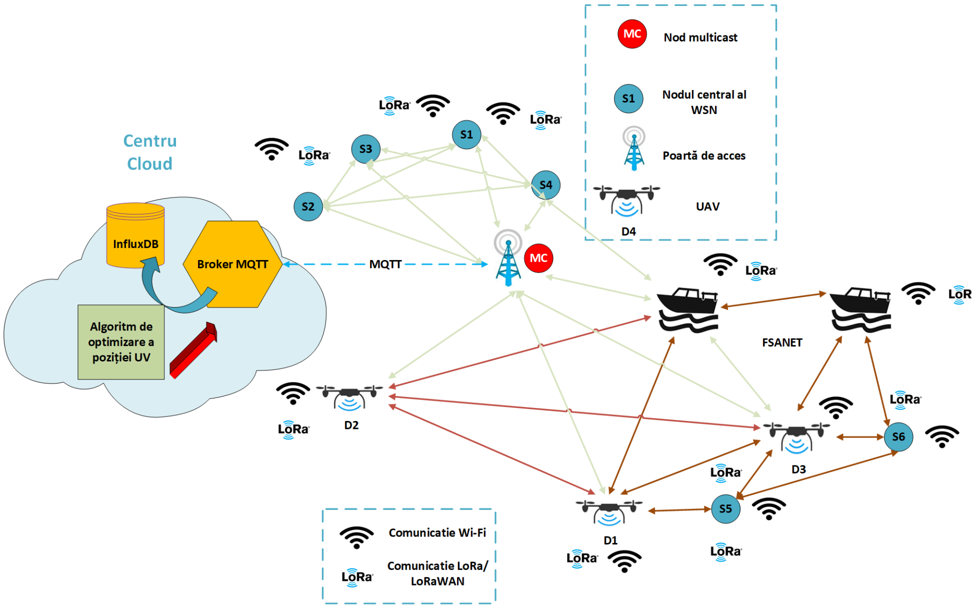

Fig. 2.2 WSN-FSANET network [24]

Contributions to the development of the Connectivity level using LoRa technology are presented in Chapter 4. The practical contributions to the development of the Connectivity level through the symbiosis between LoRa technology, Wi-Fi technology and aerial and surface networks are presented in Chapter 5.

2.2.4 Cloud Layer

From the gateway, data is sent to the Cloud Center via data protocols (HTTP, MQTT). The Cloud Center is responsible, among other things, for storing data in the database, to coordinate UV missions and to execute the algorithm for optimizing the position of UVs in the physical space proposed in Chapter 5.

2.2.5 Application Layer

The proposed IoT platform will include its own dashboard necessary not only for data visualization (this is already done through a Thingspeak application), but also for the end-user interaction with the entire system. In this way, the proposed platform will be a complete solution, covering all the essential levels.

2.2.6 Comparison with other architectures in the literature

This section presents a comparison of the proposed architecture with other architectures in the literature by fields of use.

2.3 Proposed use cases of IoT architecture using LoRa, LoRaWAN, Wi-Fi and hybrid networks

This section highlights some of the use cases for monitoring the environment employing IoT architecture proposed in Section 2.2: avoiding obstacles by boats, monitoring water quality and the environment, ensuring an ad-hoc connection for devices in the harsh regions of Danube Delta.

2.4 Conclusions on the proposed architecture

The proposed architecture follows the ITU [12] standard, encompassing the *Data accumulation* and *Data abstraction* levels in a single level validated in the literature as the Cloud level. Another difference from the ITU [12] architecture is the proposal and integration of a Pseudo-Edge layer that takes over the features of the original Edge layer and exploits them much closer to the central nodes of sensor or hybrid networks.

Chapter 3

Contributions to the development of the Device Layer and the Pseudo-Edge Layer

3.1 Introduction

In this chapter, we will present the improvements made to the IoT platform in terms of the first level of this architecture, called the Devices layer, and the results on the non-critical and critical sub-layers.

3.2 Non-Critical Devices sub-layer: Evaluation of parameters in precision agriculture

In order to assess the relevance of the parameters for precision agriculture, the Devices layer, with the Non-Critical Devices sub-layer, was developed, at the hardware level, based on the Libelium Smart Agriculture Xtreme [3] equipment that includes calibrated sensors. The experimental results highlight the relevance of the proposed parameters for the precision viticulture component of the proposed platform [2, 25].

3.3 Critical Device Sub-Layer and Pseudo-Edge Layer: Communication Technology Selection and Adapting the Interval between Two Consecutive Transmissions for Disaster Management Applications

3.3.1 Presentation of the context

The proposed IoT platform can support communities through its disaster management components. Critical sub-level devices can be installed in each neighborhood or community, and residents and rescue teams can be alerted when life, homes or other buildings are threatened [6].

3.3.2 Tests performed and experimental results

In this section, the fire and release scenario GPL was investigated. Data from a domestic fire or fire in an industrial environment could not be captured, but various relevant experiments were performed.

3.3.3 Method for selecting the communication technology and adjusting the interval between consecutive sensor data transmissions

Based on the tests performed and the observations made on them (published in [6]), we can introduce the Pseudo-Edge level, which has the role of facilitating the processing of data from a central node. for the decision on the communication technology appropriate to the detected event, but also for the definition of a transmission rate adapted to this event. Thus, to each event it will be assigned a six-bit code at the center node (equivalent to the number of parameters considered for example), $C = b_1b_2b_3b_4b_5b_6$. As long as the event code is $C = 000000$, no event is detected, and LoRa transmission is used.

In Fig. 3.10, the comparison between the values of the Wi-Fi data transmission interval in three situations is illustrated.

In the first case, one proposed that the interval between two transmissions should be calculated based on Equation 3.2, taking into account only the event code.

$$T_t = \frac{T_z}{\sum_{n=1}^{p} 2^{p-n} \cdot b_n} \tag{3.2}$$

In the second case, the interval between two transmissions is calculated based on the Equation 3.3, taking into account both the event code and the number of sensors whose threshold values are exceeded. Unlike the first case, it can be seen that when we have

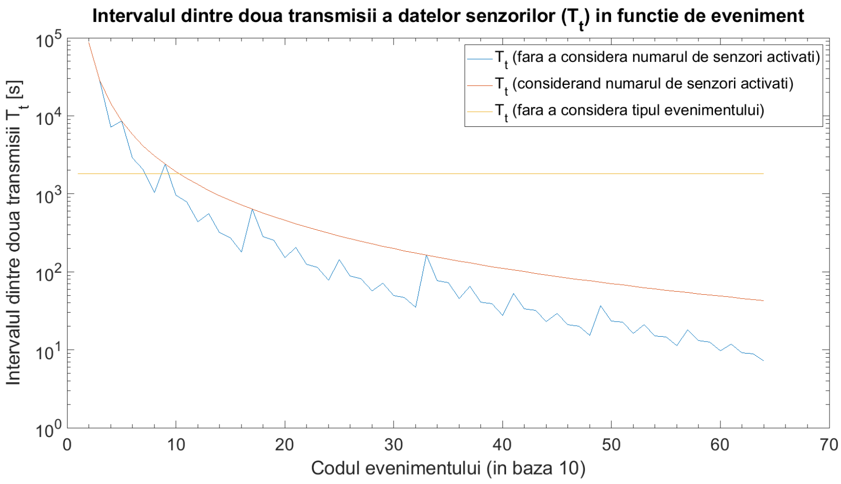

Fig. 3.10 Comparație între valorile intervalului dintre două transmisii a datelor senzorilor

more values of the exceeded thresholds, the interval between two transmissions decreases significantly, even if the importance of the parameters is not the highest. In this way, the impact of sudden changes and other more significant parameters (with a lower order of n) can be easily captured in a timely manner.

$$T_t = \frac{T_z}{\sum_{n=1}^{p} 2^{p-n} \cdot b_n \cdot \sum_{n=1}^{p} b_n} \tag{3.3}$$

Fig. 3.10 reveals both equations, where $p = 6$ (number of sensors). Both models can be applied for the case $C = 000000$, as $T_t \rightarrow \infty$ for $b_n = 0, \forall\ 1 \leq n \leq p$, and the interval between two Wi-Fi transmissions will be ∞ (in this case the transmission will be made only by LoRa technology). For both cases, $T_z = 86400$ s, the equivalent of 24 hours.

In the third case, the interval between two transmissions is the one used in most telemetry applications, 30 minutes. From the graphical representation, it can be seen that this range is not suitable for critical scenarios or those that can generate false-positive alarms, due to abnormal variations of parameters over short periods of time.

3.4 Conclusions on the contributions to the development of the Devices Layer

In this chapter, aspects such as the evaluation of the precision agriculture sensors and the parameters determined with their help were highlighted. The hardware and software resources used for testing in scenarios such as flammable gases and fires were also presented, and a method for selecting the appropriate communication technology for a particular scenario (Wi-Fi or LoRa) was defined. An equation has also been proposed to determine the time interval between successive transmissions depending on the detected event.

Chapter 4

Contributions to the development of the Connectivity Layer using LoRa technology

4.1 LoRa communication performance analysis in IoMT

As with other IoT applications, there are Internet of Medical Things (IoMT) devices that do not require high transmission rate communication technologies. However, it is necessary for these devices to have as much autonomy as possible and for the complexity of the network they belong to be kept to a minimum. The section will present the tests performed to determine the LoRa communication parameters in the IoMT platforms for certain use cases [7].

4.1.1 Implementation of the experimental prototype

Two Lopy v1 development platforms (1) equipped with the LoRa Semtech SX1272 transceiver, two 868 MHz LoRa antennas (2), two 900 MHz antennas (3), two expansion boards for programming and power supply (4) and an infrared temperature sensor (5) were used for the prototype.

Suggested experimental locations are in Bucharest, Romania: 1. Bucharest University Emergency Hospital (SUUB) (base station), 2. Bucharest Faculty of Medicine and Pharmacy (FMFB) (final device), 3. Cotroceni Avenue (final device), 4. Politehnica subway station (final device), 5. Păcii subway station (final device).

To exemplify the use case in the hospital environment, the connection was made between the base station located at SUUB and a final device placed at FMFB (1-2), and for home use, the following locations were connected: 1-3, 1-4, 1-5.

4.1.2 Experimental results

For the hospital-specific architecture proposed in the thesis [7], the monopole antenna (2) was used for frequencies between 824 and 960 MHz. The required spreading factor (SF) was 12, although a lower spreading factor would be sufficient to obtain a higher transmission rate and a relatively low coverage area (SF = 9, for antenna (3)). As observed, the characteristics of the monopole antenna determine the use of a higher spreading factor.

In the case of the telemonitoring scenario of patients at home [7], for all experiments the dipole antenna on 868/915 MHz frequency was used, one testing different values for the spreading factor to make possible the communication with the established final devices.

In Table 4.3 the results of the experiment are summarized.

Table 4.3 Maximum coverage and required SF value

Scenario	Connected locations	Distance	TX Power	Necessary SF	Antenna
Hospital IoMT	1-2	217,12 m	14 dBm	12	Monopole
Home IoMT	1-3	735,63 m		7	Dipole
Home IoMT	1-4	1360 m		9	Dipole
Home IoMT	1-5	5240 m		12	Dipole

4.1.3 Conclusions and future directions for the use of LoRa technology in IoMT platforms

In this section, we have proposed a communication solution for applications in dedicated IoMT platforms.

The packets containing the data of a temperature sensor were sent from the University Emergency Hospital to the mobile terminal nodes. The widest coverage area (5.24 km) was obtained for the maximum spreading factor, but packet losses were observed [7].

Deploying a LoRa network reduces deployment costs (fewer nodes are required, resulting in a high coverage area), as well as simplification of network and node maintenance procedures.

4.2 Use of LoRa in systems dedicated to people with disabilities

4.2.1 Presentation of the context

In [8], an alarm clock system based on vibration motors, ultrasonic sensors, BLE and LoRa technologies has been proposed to wake the user and to automatically update the electronic clock of the system (RTC, Real-Time Clock) used by the system. To address the time-related issues due to a power outage, the system time can be automatically adjusted by connecting to the LoRa server.

4.2.2 Workflow and description of the proposed system

In this section the workflow of the proposed system is described and graphically represented. The alarm clock can operate autonomously or depending on the user's smartphone.

4.2.3 Updating the RTC using the LoRa time server

RTC will be updated as follows (Figure 4.3): the system component named LoRaTimeServer receives Coordinated Universal Time (UTC) from the GPS module connected to the LoRa server and adjusts the time zone according to the location of the server. Time data is sent to the LoRa sync block using LoRa communication. Due to the limitations of the transmission technology (very low data rate and latency), the LoRa synchronization block estimates the propagation delay and adjusts the time accordingly. The UpdateRTC block allows the RTC module to be automatically updated based on the output of the LoRa sync block.

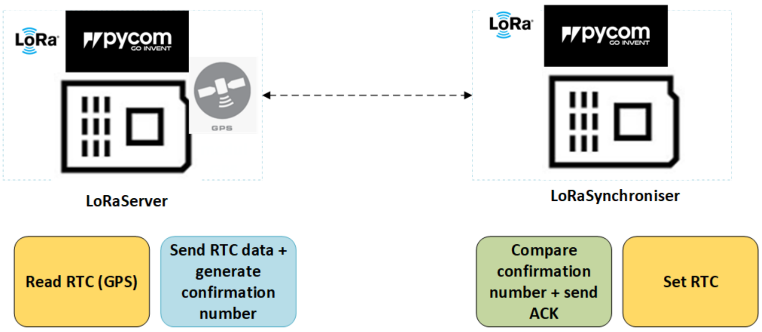

Fig. 4.3 LoRa subsystem used to analyze the performance of LoRa technology [8]

4.2.4 LoRa hardware components

The proposed LoRa communication hardware modules are Semtech SX1272 (868 MHz), with a sensitivity range between -111 dBm and -148 dBm. The Pytrack board will be used to track the GPS position of the mobile node.

4.2.5 Measurement campaign for LoRa devices

In order to determine the performance of the LoRa server and the LoRa synchronizer, as well as the corresponding time lag between them, four scenarios were proposed and several tests were performed. The antenna height has been changed according to the scenarios in Table 4.4. The size Δh is the difference between the antenna height of the LoRa server and the antenna height of the portable device.

Table 4.4 Description of the scenarios [8]

Scenario	**Mobility**	**Distance T-R**	**Δh**	**SF**	P_{tx}
I	No	1,5 m	0 m	7	14 dBm
II	Yes	1,5 m-100 m	0-7,14 m	7	
III	Yes	1,5 m-350 m	<1 m	12	
IV	Yes	1,5 m-650 m	3 m	12	

In all four scenarios, LoRaTimeServer will send time coordinates based on UTC time and the time difference according to the time zone. For all tests, for each received packet that includes the received time coordinates, relevant parameters for LoRa communication and target scenarios, such as the received signal strength indicator RSSI, SNR, are purchased and stored at the server level, the transmission power (P_{tx}) and the number of retransmissions, but also the GPS coordinates which will be used to determine the maximum coverage of the communication. For this purpose, two methods will be used:

1. Determine the maximum coverage area (radius) using the Google Earth Pro tool;
2. Determination of the maximum coverage area (radius) based on the Haversine equation [26] (Equations 4.1–4.3 in the doctoral thesis).

4.2.6 Non-mobility scenario (I) and LoS mobility scenario (II)

In this section, the distributions of the values RSSI in relation to the received packets, for the scenario without mobility and for the first scenario with mobility (maximum distance less than 100 m) are represented graphically and analyzed.

4.2.7 NLoS mobility scenarios (III, IV)

In Scenario III, in the worst case scenario, the Δh difference is less than 0.5 m. The maximum distance obtained is 0.398 km, with the lowest RSSI value of -136 dBm.

In Scenario IV, the height of the transmitting antenna has been increased so that Δh becomes approximately 3 m. In the section, the RSSI feature and the distance to the server for each packet received by the mobile node are represented. The coverage radius increases to 615,98 m.

4.2.8 Conclusions on the use of LoRa in the proposed system

With regard to the proposed system for updating the alarm clock based on LoRa technology, the proposed framework, designed on the basis of energy-efficient devices and LPWAN technologies, such as LoRa, is the main aspect that differentiates it from of the other existing solutions.

Chapter 5

Contributions to the development of the Connectivity Layer using LoRa / LoRaWAN, Wi-Fi and FANET and SANET networks

5.1 Introducere

In Chapter 2, Section 2.2.3 we presented the architecture of a hybrid network consisting of wireless sensor networks, aerial and surface networks that ensure the transmission of data from isolated environments to a gateway connected to Internet. This hybrid network is the novelty of the Connectivity level, and the current chapter presents an innovative approach to determine the optimal positions of mobile nodes (UAV, USV) to ensure the data link between the isolated wireless sensor network and the gateway based on the relay links provided by these vehicles.

5.2 UV position optimization algorithm

5.2.1 Context

This section aims to present the framework and the simplified IoT architecture in which such an algorithm is needed.

5.2.2 Concepts related to propagation, graph of propagation losses and graph of communication links

To ensure communication between the nodes of a terrestrial wireless network, it is necessary to have communication links between all the nodes acting as transceivers that are at a certain distance from each other and under certain environmental conditions. The scenario becomes much more complex when it comes to integrating aerial or surface vehicles into the wireless network. Thus, it is necessary to determine the optimal 3D coordinates for their placement in space. Theoretical aspects related to the propagation of wireless signals were taken into account, such as: communication parameters, propagation environment, propagation channels and propagation models.

Numerous simulations have been performed for two-ray, 3GPP and free space path loss propagation models. A very important task of the algorithm proposed in this chapter resides in the estimation of the optimal set of values (d, h_t, h_r) which will be translated to the set of values $(\phi_i, \lambda_i, \phi_j, \lambda_j, \varepsilon_i, \varepsilon_j)$ to minimize propagation loss and avoid signal loss due to destructive signal composition.

5.2.3 Integration of the communication optimization component

In the thesis, before the development of the UV nodes position optimization algorithm, another intermediate algorithm was introduced. It has the role of reducing the search space for the optimal solution. The problem of optimal placement is a non-deterministic polynomial problem, very consuming from the point of view of computational resources and usually backtracking algorithms are applied. The preliminary algorithm uses the notion of orthodrome - the shortest path between two nodes on a sphere. This concept is widely used in navigation, but it is proposed for the first time to reduce the search space for the optimal placement solution. Algorithm 1 is used to determine the actual UV nodes (*rn*) that are the closest to the virtual nodes (*vn*), so as to minimize the distance traveled from the actual nodes to the final positions.

Based on the characteristics of the propagation channels, the antenna heights and the propagation losses, Algorithm 2 calculates the latitude, longitude and elevation of the optimal positions. Thus, the communication link is ensured at a minimum cost in terms of horizontal and/or vertical UV movement. The purpose of the algorithm is to minimize the cost function $f_0(\Delta, \chi)$.

$$\begin{aligned} &\underset{\Delta_j, \chi_j}{\text{minimise}} \qquad && f_0(\Delta, \chi) = \sum_{j=1}^{vn} a_j \Delta_j + b_j \chi_j, \\ &\text{given } w_{j,j+1} < 1 + \zeta && \end{aligned} \tag{5.43}$$

where $j \in \{1, .., N_{vn}\}$, $\Delta = [\Delta_j]$ is the distance travelled by rn_j, and $\chi = [\chi_j] = \mid [h_f] - [h_i] \mid$ is the height offset, where h_f and h_i are the final and the initial height, respectively, of rn_j (just UAV can change their altitude). a_j and b_j are the weight of the distance and the weight of the height, respectively.

The optimization problem involves a linear optimization function with nonlinear constraints. Consequently, it is a non-linear programming (NLP) problem.

Algorithm 1 The algorithm for the nearest real UV nodes [24]

```
Input: $N_{vn}, N_{rn} = n_{UAV} + n_{USV}$; GPS coordinates;
Output: CN (the vector of the nearest real nodes), CD (the distances between the nodes
    closest to the virtual nodes and the virtual nodes themselves)
Determine the distances between each virtual node $vn_i$ and each real node $rn_j$,
    $D = \left[d_{i,j}\right]\ i \leq N_{vn},\ j \leq N_{rn}$
Redefine the matrix $D$ ca $BD_{1\times(N_{vn}\cdot N_{rn})}$
Arrange $BD$ in ascending order as $BD_1$
Find the vector $bd$ (index positions for $BD_1$ in $BD$)
Initialize the vector of the nearest real nodes $CN_k = 0 \forall k \leq N_{vn}$
Initialize the vector of the actual nodes visited $AT = \emptyset$
for $i \leftarrow 1,\ N_{rn}$ do
    $c \leftarrow \lfloor bd_i / N_{vn} \rfloor$
    $r \leftarrow bd_i \% N_{vn}$
    if $r > 0$ then
        $n \leftarrow c + 1$
    else
        $r \leftarrow N_{rn}$
        $n \leftarrow c$
    end if
    if $CN_n = 0\ \&\ r \notin AT$ then
        $CN_n \leftarrow r$
        $AT \leftarrow AT \cup \{r\}$
        $CD_n \leftarrow d_{n,r}$
    end if
end for
```

Table 5.9 The results of the path division algorithm and the determination of the real nodes closest to the virtual ones: the execution time depending on the distance between GW and WSN and the number of UVs [24]

$n_{UAV} + n_{USV}$	d [km]	t [s]
3	1,0	0,0348
	1,5	0.0325
	2,0	0.0343
10	1,5	0,0323
	2,0	0,0404
	5,0	0,0295
	8,0	0,0325
20	2,0	0,0377
	5,0	0,0295
	8,0	0,0322
52	2,0	0,0493
	5,0	0,0427
100	2,0	0,1152
	5,0	0,1165

Algorithm 2 Placement loss algorithm based on propagation losses [24]

```
Input: $n_{UAV}$, $n_{USV}$, $N_{vn}$, $N_{rn}$ GPS Coordinates; served WSN; $h_{th}$ {Maximum allowable altitude of UAVs}; $h_{FSPL}$ {Minimum altitude of UAVs to be able to apply the FSPL model}; $\delta h$ {Height step} LB {Link budget}, $\delta d$ {Distance step for $PL < LB - \Delta_{LB}$}, $\Delta d$ {Adaptive distance step for $PL > LB$}, $\rho$ {The coefficient for the adaptive step of the distance $\Delta d$}.
Output: Optimal latitude $\phi_{opt,n_i}$, optimal longitude $\lambda_{opt,n_i}$, optimal elevation $\varepsilon_{opt,n_i}$ for each UV
1: Calculate the initial 2D and 3D distances between each two nodes, $d_{i,j}^{2D}$, $d_{i,j}^{3D}$
2: Steps 2-108 (please see [24] or the doctoral thesis)
```

5.2.4 Evaluation of the positioning algorithm and results

Table 5.10 presents the evaluation of the algorithm for different parameter values.

First, the implemented code was profiled. In order to highlight the improvements made after profiling in terms of the execution time specific to each function or instruction, the execution time before profiling (t_1) and after improvements (t_2) were included in Table 5.10 . The σ performance indicator is the sum of all subunit weights of the edges that compose the path between the WSN and the gateway, based on the total number of path edges in the communication graph ($\sigma = \frac{s}{n_{vn}+1}$, where s is calculated based on Equation 5.45). When a connection is successfully established between the gateway and the WSN served, $s \to n_{vn} + 1$ and thus $\sigma \to 1$. The significance of the very low values of σ and $\sum_{i=0}^{n_{vn}} c_i = n_{vn} + 1$ would be that there are more close UVs that behave like relays than necessary, leading to interference and inefficient placement or ineffective choice of UV, which is not the case for the evaluated scenarios.

$$s = \sum_{i=0}^{n_{vn}} \frac{c_i PL_{CN[i],CN[i+1]}}{LB} \tag{5.45}$$

where $CN[0]$ represents the gateway, $CN[n_{vn} + 1]$ represents the WSN served, and

$$c_i = \begin{cases} 1 & PL_{CN[i],CN[i+1]} \leq LB \\ 0 & PL_{CN[i],CN[i+1]} > LB \end{cases} \tag{5.46}$$

Analyzing Table 5.10, we notice that the best results for this scenario (maximum σ) are obtained for $\rho = 0.1$ and for execution time $t_2 = 14,347$. However, a good compromise is $\rho = 0.2$ in which the execution time decreases to 8,982 s.

The cases in which σ is marked with * are for the failed link $\sum_{i=0}^{n_{vn}} c_i \neq n_{vn} + 1$.

Table 5.10 Algorithm results: execution time (before and after improvement) and performance indicator σ ($\delta h = 7$ m, $nt = 3$, $LB = 92$ dB, $d = 7.2209$ km) [24]

n_{UAV}	n_{USV}	n_{vn}	d [km]	ρ	δd [m]	t_1 [s]	t_2 [s]	σ
19	2	19	7,2209	0,05	20	149,29	24,073	0,9859
				0,1	20	113,649	14,347	**0,9871**
				0,12*	20	126,498	14,424	0,9347*
				0,13	20	115,96	12,913	0,9836
				0,14	20	110,018	12,008	0,9813
				0,15	20	120,43	11,118	0,9815
				0,2	20	116,178	**8,982**	0,9830

5.2.5 Discussion

This section discusses important issues related to (1) the possibility of using the algorithm for real-time and non-real-time applications, and (2) the mobility states between the initial and final positions.

5.3 Conclusions on the proposed optimization algorithm

Along the doctoral thesis, the impact of UAV and USV networks on Internet of Things ecosystem was highlighted and the concept of the Internet of Autonomous Vehicles was explored, as an extrapolation of the narrower concept of the Internet of Drones (or Internet of Unmanned Aerial Vehicles). In addition, an IoT architecture based on a hybrid network of WSNs, UAVs and USVs (UVs) was proposed, having two main roles: (1) ensuring the communication between a WSN served and a gateway and (2) performing tasks assigned by a Cloud Center (CC).

5.3.1 Comparison with other works

In this section, a comparison between the approach proposed in the chapter and other papers in the field was outlined.

5.3.2 Open challenges and future directions

As highlighted in this chapter, the propagation models in the literature, researched and used in the simulations presented in the thesis, have limitations, which make them not applicable in all real-life scenarios. As a result, new channel models may be explored in the future to cross the limits of the propagation models used so far.

Chapter 6

WSN-UAV-USV measurement campaign for LoRa technology

6.1 Introduction

In this chapter, the propagation models introduced in Chapter 5 (3GPP model, two-ray model) will be compared with the results of real measurements for LoRa technology and improvements will be proposed to adapt them to the real environment. Furthermore, the results of a field measurement campaign are presented below. On its basis, realistic models of the received signal strength can be defined.

6.2 Implementation of the measurement platform and proposed scenarios

A Mavic 2 Enterprise Advanced [30] aircraft, hereinafter referred to as the UAV, and a Double Horse 7004 1:12 RTR [31] surface vehicle, hereinafter referred to as USV, were used to implement the measurement platform.

Both vehicles are equipped with Lopy v4 development platforms with Semtech SX1272 communication module and ESP32 microcontroller, Expansion Board v3 expansion board to power the development platforms and expand their capabilities (e.g. SD slot equipment), Pytrack expansion board v1 for powering development platforms and tracking GPS coordinates and $\lambda/2$ sleeve LoRa antennas optimized for 868 MHz. Next, the measurements made for LoRa technology for the following scenarios in Table 6.3 will be presented.

Fig. 6.2 shows the measurement platform built upon the UAV, Lopy v4 modules and the Pytrack expansion board for monitoring GPS coordinates (1, 3, 5-6, 8).

Table 6.3 Scenarios for conducting the measurement campaign

Communication type	Link	Comparison
Unidirectional	UAV-USV	two-ray model
	UAV-WSN	3GPP model
	USV-WSN	two-ray model

Fig. 6.2 UAV-based measurement platform, Lopy modules and Pytrack expansion board for GPS coordinate monitoring

6.3 Experimental results obtained for LoRa technology and interpretation

The link between the transmitting power, the receiving power and the propagation losses was stated in Equation 5.1 and is resumed, with slight changes, in this chapter (Equation 6.3).

$$P_{rx}[dBm] = P_{tx}[dBm] + G_{tx}[dB] + G_{rx}[dB] - PL[dB] \tag{6.3}$$

The transmission power is 14 dBm. Antenna gains are determined based on the elevation angle θ and on the directivity calculated using Equation 6.1 specific to $\lambda/2$ dipole.

For all scenarios, measurements were made for the spreading factor value of 7. The bandwidth $BW = 125$ kHz was chosen so as not to greatly affect the sensitivity of the receiver and to have a satisfactory bit rate. Also, since the measurements were performed in a location with low interference, the code rate $CR = 4/5$ was chosen. This configuration corresponds to a bit rate of 5.469 kbps.

6.3.1 Scenario 1: UAV-USV LoRa communication

To perform the measurements in this scenario, the horizontal positions of the UAV and USV and the vertical position of the UAV were varied ($h_{UAV} = 30$ m, respectively, 80 m, $h_{TX,UAV} = 29$ m and 79 m, respectively, $h_{RX,USV} = 0.05$ m, $d_{UAV-USV} = 0 - 500$ m).

In Fig. 6.5 the geometric representation of the scenario is provided when $h_{UAV} = 30$ m. Based on the geometric model, the elevation angles were calculated and plotted along with the corresponding antenna gains. The gain of the receiving antenna may drop to about -23 dB for longer distances. We also determined the angle ϕ, between the reflected wave and the surface of the ground.

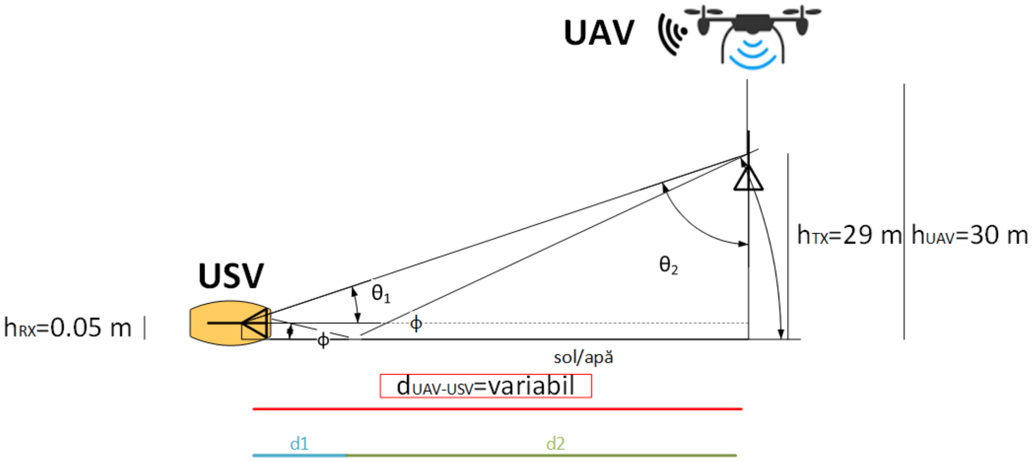

Fig. 6.5 Geometrical representation of the scenario for h_{UAV}=30 m and $d_{UAV-USV}$ in the range 0-500 m

For the theoretical comparison, the simplified two-ray theoretical propagation model from Equation 5.24 was initially chosen, but it does not completely characterise the propagation losses specific to the environment in which the measurements were made, approximating the reflection coefficient to the value $R_0 \approx -1$. Therefore, the two-ray model has been improved to take into account the influence of environmental conditions (PL_{2-ray+}). Thus, the new theoretical propagation losses were determined based on the two-ray model and the electrical characteristics of the surface of the water and the Earth, based on ITU-R P.527-6 recommendation [32] and on ITU 1008-1 report [33]. The strength of the received signal determined experimentally was compared with the received signal power determined on the basis of the improved two-ray model (Fig. 6.7).

Fig. 6.7 Comparison between the experimental received signal power for h_{UAV}=30 m and $d_{UAV-USV}$ in the range 35-500 m and enhanced two-ray model (2-ray+)

In Fig. 6.8 the difference between the theoretical model and the experimental results as a function of distance was represented, as well as the histogram of this difference.

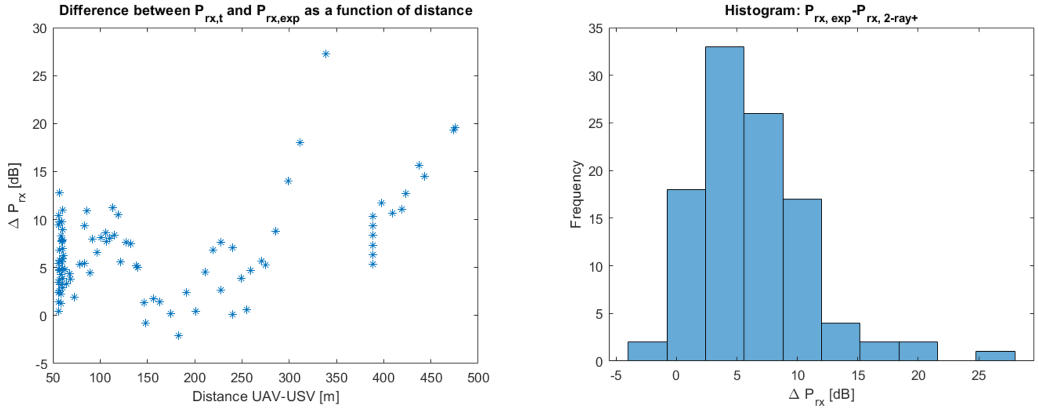

Fig. 6.8 Difference between experimental and theoretical received signal power (two-ray+ model) for h_{UAV}=30 m and $d_{UAV-USV}$ in the range 0-500 m

It can be seen that the differences are mainly in the range of 0-10 dB and that they increase over long distances (packets 188, 202-203). Also, the results on the mean, maximum, minimum and standard deviation of the difference between the theoretical model and the experimental results were represented in tabular form. Due to the specificity of the area in which the experiments were performed, additional propagation losses that the theoretical models cannot include may occur. The differences can be:

- due to the fact that the two-ray model has isolated minima at certain tuples $(h_{TX}, h_{RX}, d_{UAV-USV})$ as shown in Chapter 5. Since the distance was calculated on the basis of GPS coordinates, and their accuracy may affect the calculated value of the distance, it is possible that these minima were actually avoided;

- as a consequence of ignoring the attenuation phenomenon caused by vegetation. From the graphical representation of this attenuation depending on the elevation angle θ_1 for different lengths of the vegetation segment, it was found that a length of the vegetation segment of only 20 m introduces an attenuation between 7.87 and 9.18 dB. At a value of 100 m in the length of the vegetation segment, the attenuation can reach 13.73 dB;
- as a result of the attenuation of the wood fiber of the trees. The attenuation introduced was found to be approximately 5.05 dB.

In addition, an experimental model was formulated to determine the experimental model of the received signal power. The general model determined based on the experimental results for frequency f=868 MHz, $h_t = 30$ m, $h_r = 0,05$ m is given by the Equation 6.19.

$$P_{rx,UAV-USV}[dBm] = a \cdot log_{10}(d[m] + d_1) + b \tag{6.19}$$

where a_{opt} =-20,91, b_{opt} = -65,4 dBm, $d_{1,opt}$ =-25,48 m. For optimal values, the Root Mean Square Error (RMSE) of the estimate is reduced to 2,655 dBm. The same metrics (mean, maximum, minimum, standard deviation) are used to compare the experimental model and the improved two-ray model.

Finally, based on the experimental model and on the receiver sensitivity values provided in the catalog sheet of the Lopy v4 development platform and the SX1272 communication module, the coverage ranage was approximated for the spreading factor values in the range 7-12 for $h_{UAV} = 30$ m, $h_r = 0,05$ m, in the UAV-USV scenario. The following methodology for estimating the coverage is applied:

1. Based on the value of the receiver's sensitivity, estimate the value of the minimum received signal power for which a packet is correctly received ($\hat{P}_{rx,max} = S_{rx}$);
2. Find the intersection between $y = \hat{P}_{rx,max}$ and the graph of the modeled received signal power and determine the value of the maximum propagation distance corresponding to this intersection.

From Table 6.9 it is observed that for SF = 7, the estimated range based on the experimental model is approximately 100 m longer than the distance for which the experiments were performed, which is also validated by the value of the received signal strength for packets transmitted from a distance of 480 m (-120 dBm, over the receiver sensitivity threshold).

Further, we will briefly describe the two other scenarios. It is worth mentioning that the thesis exhaustively describes the three scenarios and the corresponding sub-scenarios, in total six sub-scenarios.

Table 6.9 Coverage range estimation for UAV-USV communication, SF=7-12, BW=125 kHz, $h_{UAV} = 30$ m, $h_r = 0,05$ m

SF	S_{RX} [dBm]	$R_{max,est}$ [km]
7	-124	0,587
8	-128	0,992
9	-131	1,385
10	-134	1,952
11	-136	2,419
12	-137	2,706

6.3.2 Scenario 2: UAV-WSN LoRa communication

In this scenario, the horizontal position and the vertical position of the UAV varied, respectively. In Scenario 2, the measurements were performed for the UAV-WSN communication, where the UAV was also at a height of 30 m. The WSN antenna was placed at a height of 1.5 m from the ground. The elevation angles were determined on the basis of the same relations. A packet success rate of 91.09 % was found to be higher than in the case of UAV-USV communication, which was 80.07 %. Also, the antenna gains were represented and we noticed that the receiving antenna has a minimum gain of about -22 dB. The maximum coverage radius is 437.15 m. Packages could not be received beyond this distance.

The theoretical received signal strength was compared with the experimentally determined one and a similar pattern is noticed again, with differences determined by the appearance of the diffraction phenomenon due to the existence of an obstacle with a relative height from the direct path of 9 m, at a distance $d_1 = 6$ m from WSN, which obstructs Fresnel areas. The mean and standard deviation in this scenario are higher than in the previous scenario, as demonstrated by the histogram. In this scenario, the values are concentrated in the range (-15, 5) dB.

The equation of the experimental model is similar to the previous scenario, but the optimal parameters are different. For this model, the average has a very small value, of order 10^{-4}, and the standard deviation has dropped to 6 dB. Again, the maximum coverage radius was determined and a radius of 881 m was found for the UAV height of 30 m and $SF = 12$.

6.3.3 Scenario 3: USV-WSN LoRa Communication

To perform the measurements in this scenario, due to the constraints related to the positioning of the USV (battery, remote control signal–LoRa interference signal) the

USV moved at a distance of 50 m from the lake shore and one varied the horizontal and vertical position of the WSN with respect to USV.

The height of the WSN with respect to ground was 1 m, but the elevation of the ground is between 638.1-678.8 m, and the distance for which the measurements were made is between 5 and 315.58 m. Tthe latter does not represent the maximum coverage radius, though, as there is still a 10 dB margin of receiver sensitivity that could extend the distance to which the experiments are performed. An average difference of only 0.66 dB was found between the theoretical model and the experimental results, while the histogram concentrated the values between -10 and 0 dB. In this scenario, due to the presence of an obstacle at a distance $d_1 = 6$ m from TX, having an approximate height with respect to the direct path of $h = 2$ m, there were also losses caused by diffraction of about 9 dB.

6.4 Conclusions on the measurement campaign

6.4.1 Results obtained

In this chapter, there were presented the experimental results obtained following a measurement campaign in the vicinity of the Paltinu weir, Valea Doftanei, Prahova. Initially, one wanted to carry out measurement campaigns in the Danube Delta area, but this was not possible due to the pandemic conditions. The following communication scenarios were analyzed:

1. UAV-USV communication. In this case, the influence of the distance between UAV and USV and of the UAV horizontal speed on the received signal strength was studied. Two sub-scenarios were evaluated (h_{UAV} = 30 m and h_{UAV} = 80 m/s) and five different cases were compared for travel speed ($v = 1.5$ m/s, $v = 2.9$ m / s for h_{UAV} = 30 m, respectively $v = 2.74$ m/s, $v = 3.3$ m/s, $v = 9$ m/s for h_{UAV} = 80 m). Significant packet loss was found when the UAV's speed was doubled when it was at a height of 30 m, and the reception rate was only 36.58% in this case. When h_{UAV} = 80 m, even for a speed of 9 m/s, the reception rate is 64.1 %. The experimental results were compared with the improved two-ray theoretical model based on the experimental conditions, taking into account the actual value of the ground and water reflection coefficient and the antenna gains. It was found that the experimental power of the received signal differs, on average, by 6.45 dB from that determined by the two-ray model for $h_{UAV} = 30$ m and by 4.311 dB, respectively, when $h_{UAV} = 80$ m.
2. UAV-WSN communication. In the case of this type of communication, two sub-scenarios were also studied: (1) h_{UAV} - constant, $d_{UAV-WSN}$ - variable, (2) h_{UAV} -variable, $d_{UAV-WSN}$ - constant. For both sub-scenarios, comparisons were made

with the theoretical 3GPP model. For the first sub-scenario, a UAV height of 30 m was chosen, the distance between the nodes varying in the range of 0-500 m. The comparison with the 3GPP propagation model showed an average difference of -6.37 dB. The second sub-scenario was performed in two stages, for approximately the same range of UAV height values (13-120 m, 20-120 m), but for two completely different values of $d_{UAV-WSN}$, respectively 5 m and 120 m. For the case of $d_{UAV-WSN}$ = 5 m, it was found that the received signal strength calculated on the basis of the 3GPP model differs on average by -6.05 dB from the experimental ones. Thus, the 3GPP model is a good enough candidate for this scenario. For the case $d_{UAV-WSN}$ = 120 m, it was noted that the theoretical received signal strength modeled according to the 3GPP standard differs, on average, by 1.73 dB from the experimental one.

3. USV-WSN communication. In this scenario, the elevation of the antenna of the central node of the WSN network varied in the range of 638.1-678.8 m, while the heights of the USV and WSN antennas, respectively, were 1 m and 0.05 m, respectively (as due to the size of the ship model). The distance between USV and WSN varied in the range of 5-315.58 m. For the theoretical modeling, the reflection coefficients and the real antenna gains, determined on the basis of the scenario geometry, were considered. Also, the diffraction phenomenon was taken into account and it was pointed out that the strength of the received signal determined experimentally varies on average by 0.66 dB compared to that determined based on the improved two-ray theoretical model.

Also, for all scenarios, the coverage radius values were estimated for different values of the spreading factor ($SF = 7$-12) based on the mathematical models resulting from the experiments and the value of the receiver sensitivity provided in the catalog sheet of the SX1272 communication module. The coverage radius can also be approximated for other bandwidth values (other than BW = 125 kHz).

In the future, the scenarios will be resumed for other communication technologies.

6.4.2 Challenges encountered

Prior to or during the experiments, numerous challenges could be identified by placing the development platform with the LoRa communication module in the immediate vicinity of the boat's electronic components or by recharging the drone's battery, which led to continuous experiments (without interruptions that would lead to better discrimination of scenarios and no landing of UAVs until the battery runs out). Therefore, there is a possibility that the package-scenario mapping may not be 100 % accurate (there may be a gap of several packages between the different types of sub-scenarios). Further details on the challenges encountered are provided in the doctoral thesis.

Chapter 7

Conclusions and future research directions

7.1 Summary of the results obtained

In this thesis, the research conducted by the author was presented, with the aim of optimizing the sensors-based automatic systems.

First of all, regarding the theoretical study, in the first part of the Chapter 1, the technology of wireless sensor networks was presented, and the LPWAN and Wi-Fi communication technologies used in wireless sensor networks and IoT platforms have been highlighted. As the thesis exploits the benefits of LoRa Low Power and Wide Range communication technology, special attention has been paid to this technology, often presenting it in comparison to other technologies (Wi-Fi, NB-IoT, LTE-Cat M1). The second part of Chapter 1 was dedicated to the presentation of the standardized IoT architecture ITU. Also in this chapter, the principles of ad-hoc air and surface networks were highlighted, as well as a comparison with other approaches (cellular, satellite, centralized networks).

In Chapter 2, the proposed IoT architecture, based on wireless sensor networks, LoRa/LoRaWAN and Wi-Fi technologies, as well as FSANET hybrid network, was presented. The latter were used to connect autonomous air and surface vehicles (UAVs, USVs) and WSNs. The developed architecture comprised four of the seven usual IoT levels: Devices, Network, Cloud and Application, indispensable for a complete IoT system. Between the Devices layer and the Network layer, one proposed to introduce a layer called Pseudo-Edge. Before the data is actually transmitted to the gateway, the Pseudo-Edge layer performs intermediate processing, necessary to properly select the communication technology used by the central nodes of the WSN or FSANET networks. The benefits of the proposed architecture were highlighted in all these contexts, and several use cases in which the WSN-FSANET-based IoT architecture could be used effectively were also proposed.

Chapter 3 presents the improvements made to the IoT platform in terms of evaluating the relevant parameters for a particular use case (precision viticulture). At the same time, the disaster management component was presented, customized for the scenario of potential flammable gas releases or fires. Following the testing of this component of the IoT architecture, one proposed the implementation of a method for selecting the communication technology used and adjusting the time interval between two successive transmissions, according to the detected event.

In Chapter 4, contributions to the development of the Connectivity level of the IoT architecture using LoRa technology were included. The performance of LoRa technology was highlighted in two use cases, specific to the Internet of Medical Things and, respectively, the increase of the quality of life. They can be extended, based on experimental results, to other uses.

Other contributions to the development of the Connectivity Layer have been made in Chapter 5 using LoRa/LoRaWAN, Wi-Fi and FANET and SANET networks. The chapter presents an innovative approach for computing the optimal positions of aerial and surface mobile nodes to ensure a data link between the isolated wireless sensor network and the gateway based on the intermediate links provided by these vehicles. To reduce the time required to transmit data through UAV and USV nodes, Wi-Fi technology is used, while LoRa technology is used for the long-distance transmission (between mobile nodes and the gateway) of the geographical coordinates of each node collected at the moment of their interrogation by the gateway. An architecture and positioning algorithm based on communication parameters related to propagation losses and allowing the positioning of UVs so as to develop an entire network infrastructure based on UAVs and USVs have been proposed. The developed algorithm uses all types of UAV channels (A2A, A2G equivalent to G2A) and USV channels (OW, S2S, A2S). UAV propagation models adapted to real case scenarios were used. The approach proposed in this chapter is unique and could be a starting point for many collaborations between specialists in different layers of the Internet of Things architecture, so as to develop a strong ecosystem of the Internet of Unmanned Vehicles, whether air, land or surface.

Chapter 6 presents the results of a WSN-UAV-USV field measurement campaign for LoRa technology. Three communication scenarios were proposed: 1. UAV-USV; 2. UAV-WSN; 3. USV-WSN. Based on the results, realistic models of propagation losses were defined. Real antenna gains and additional propagation losses due to vegetation and phenomena such as reflection and diffraction were considered.

7.2 Personal contributions

In the following, the personal contributions to this thesis will be highlighted.

1. Comparison of LPWAN communication technologies and analysis of the influence of physical level parameters of LoRa technology (spreading factor, bandwidth, transmission rate);
2. Analysis of the characteristics of the standardized IoT (ITU) architecture and of the SANET and FANET networks in order to integrate them in the IoT architecture;
3. Proposing an innovative IoT architecture that exploits the mobility benefits of unmanned aerial (UAV) and surface (USV) vehicles;
4. Discrimination between critical and non-critical devices and differentiated approach to data transmission by proposing the Pseudo-Edge level and a method of selection of communication technology;
5. Proposing and implementing a method of adjusting the duration between successive transmissions of sensor data to respond differently to critical and non-critical scenarios;
6. Analysis and selection of communication parameters to ensure connectivity in the data transmission scenario between the different wards of a hospital or from patient to hospital using LoRa technology;
7. Proposing, implementing and analyzing the performance of a synchronization system for devices connected by LoRa technology and customization for systems dedicated to the hearing impaired;
8. Proposing a FSANET architecture and analyzing theoretical propagation models appropriate to the channels and scenarios specific to this architecture;
9. Defining, implementing and analyzing the performance of optimal UAV and USV positioning algorithms within a hybrid WSN-FSANET network to ensure the communication link between a targeted WSN and a gateway (based on the analyzed theoretical propagation models);
10. Implementation of a prototype for LoRa technology performance evaluation within the WSN-FSANET hybrid network;
11. Proposing appropriate scenarios for evaluating LoRa technology;
12. Carrying out a measurement campaign for LoRa technology using the evaluation prototype;
13. Carrying out a comparison between the theoretical models analyzed and the experimental results obtained in the measurement campaign;

7.3 List of published works

During the doctoral studies and the research carried out, 35 articles resulted (out of which 31 articles in WoS conferences and journals - 7 Q1 / Q2 articles). Of these, 28 articles have been published in the field of doctoral thesis or in related fields. Thus, 25 articles are published in WoS conferences and journals: 4 articles in Q1 journals (one article Q1 as first author), 3 articles in Q2 journals, 1 article in Q3 journal.

Next, the two categories of publications will be presented (in the field of thesis, respectively, in related fields), the latter being summarized.

List of papers published in the field of doctoral thesis

Articles [Cf1], [Cf2], [Cf3] are used as a basis for Section 4.2. Contributions from articles [Cf4], [Cf5], [Cf6] have been included in Sections 3.1-3.2. The results of Article [Cf7] have been included in Section 3.3. The results of Article [R1] have been included in Section 4.1. The contributions in Article [R2] have been integrated in sections 2.1 and 3.1. The results and contributions in Article [R2] have been included in Section 3.2. The results and contributions of the article [Cf8] have been included in section 4.2. Contributions from article [Cf9] have been included in sections 3.1-3.2. Contributions from articles [Cf10], [R4] have been included in section 2.2. Contributions from articles [Cf11], [Cf12] have been included in sections 1.2 and 2.1. Contributions from article [R5] have been included in section 4.1. Contributions from article [R6] have been included in sections 1.5, 2.1, 2.3 and Chapter 5.

Patent Applications

[AB1] Ioana Marcu, Octavian Fratu, Simona Halunga, Alexandru Vulpe, Carmen Florea, Alexandru Vulpe, **Ana-Maria Drăgulinescu**, George Suciu, Gheorghe Suciu, Cristina Bălăceanu, Alexandru Drosu, Romulus Chevereșan, Daniel Miu, Smart Agro (Telemetry system for precision agriculture), OSIM Patent Application No. A/00442/27.07.2020.

Journal articles

[R1] **Ana Maria Claudia Drăgulinescu**, Adrian Florin Manea, Octavian Fratu, and Andrei Drăgulinescu. LoRa-Based Medical IoT System Architecture and Testbed. *Wireless Personal Communications*, mar 2020. (**ISI, Q3, IF:1.671, WOS: 000521919100001**).

[R2] Ioana Marcu, George Suciu, Cristina Bălăceanu, Alexandru Vulpe, and **Ana-Maria Claudia Drăgulinescu**. Arrowhead technology for digitalization and automation solution: Smart cities and smart agriculture. *Sensors*, 20(5):1464, Mar 2020. (**ISI, Q1, IF: 3.576, WOS: 000525271500226**).

[R3] Ioana Marcu, **Ana-Maria Drăgulinescu**, Carmen Florea, Cristina Bălăceanu, Marius Alexandru Dobrea, and George Suciu. Agricultural data fusion for

SmartAgro telemetry system. *Advances in Science, Technology and Engineering Systems Journal*, 5(5):1266–1272, October 2020.

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[Cf1] **Ana-Maria Claudia Drăgulinescu**, Ioana Marcu, Simona Halunga, and Octavian Fratu. Sensors system design for discrimination between humans and animals. In Marian Vlădescu, Răzvan Tamaș, and Ionică Cristea, editors, *Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies VIII*. SPIE, December 2016. (**ISI, WOS: 000391359600038**).

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[Cf5] George Suciu, Hussain Ijaz, Ionel Zatreanu, and **Ana-Maria Claudia Drăgulinescu**. Real Time Analysis of Weather Parameters and Smart Agriculture Using IoT. In *Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering*, pages 181–194. Springer International Publishing, 2019. (**ISI, WOS: 000552334400018**).

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[Cf7] **Ana-Maria Claudia Drăgulinescu**, Andrei Dragulinescu, Ciprian Zamfirescu, Simona Halunga, and George Suciu Jr. Smart Neighbourhood: LoRa-based environmental monitoring and emergency management collaborative IoT platform. In *2019 22nd International Symposium on Wireless Personal Multimedia Communications (WPMC)*, pages 1–6, 2019. (**ISI, WOS: 000587757300073**).

[Cf8] Cătălina Mărculescu, **Ana-Maria Claudia Drăgulinescu**, Alina Machedon, Ioana Marcu, and Ciprian Zamfirescu. LoRa and Bluetooth-based IoT alarm clock device for hearing-impaired people. In *2020 IEEE 26th International Symposium for Design and Technology in Electronic Packaging (SIITME)*, pages 140–143, 2020. **(ISI, WOS: 000651085100028)**.

[Cf9] Cristina Bălăceanu, Alexandru Negoiţă, **Ana-Maria Claudia Drăgulinescu**, Roxana Roşcăneanu, Veronica Sanda Chedea, and George Suciu. The use of IoT technology in Smart Viticulture. In *2021 23rd International Conference on Control Systems and Computer Science (CSCS)*, pages 362–369, 2021.

[Cf10] Denisa Pastea, Daniela-Marina Draghici, George Suciu, Mihaela Balanescu, George-Valentin Iordache, Andreea-Geanina Vintila, Alexandru Vulpe, Marius Vochin, **Ana-Maria Drăgulinescu**, and Catalina Dana Popa. Decision support platform for intelligent and sustainable farming. In *Advances in Intelligent Systems and Computing*, pages 401–410. Springer International Publishing, 2021.

[Cf11] **Ana-Maria Drăgulinescu**, Filip Constantin, Oana Orza, Sabina Bosoc, Robert Streche, Alexandru Negoita, Filip Osiac, Cristina Balaceanu, and George Suciu. Smart Watering System Security Technologies using Blockchain. In *2021 13th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*, pages 1–4, 2021.

[Cf12] **Ana-Maria Claudia Drăgulinescu**, Cristina Bălăceanu, Filip Osiac, Roxana Roșcăneanu, Veronica Sanda Chedea, George Suciu Jr., Mirel Ciprian Păun, and Ștefania Bucuci. IoT-Based Smart Water Management Systems. In *2021 IEEE*

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List of papers published in related fields

Books

[C1] I. M. Marcu, I. Pirnog, A. Vulpe, L. Dogariu, **A.-M. Drăgulinescu**, Electronic Measurements. Theory and Applications, Politehnica Press, 2021 (ISBN:978-606-515-987-7)

Journal articles

[R1] Octavian Fratu, Maria-Mădălina Andronache, **Ana-Maria Claudia Drăgulinescu**, Carmen Voicu, and Alexandru Vulpe. Cooperation scenarios in multi-agent water monitoring platform. *Periodicals of Engineering and Natural Sciences (PEN)*, 7(1):261, April 2019. (BDI).

[R2] Andrei Drăgulinescu, **Ana-Maria Drăgulinescu**, Gabriela Zincă, Doina Bucur, Valentin Feieș, and Dumitru-Marius Neagu. Smart Socks and In-Shoe Systems: State-of-the-Art for Two Popular Technologies for Foot Motion Analysis, Sports, and Medical Applications. *Sensors*, 20(15):4316, Aug 2020. (**ISI, Q1, IF:3.576, WOS: 000559029300001**).

[R3] Razvan Alexandru Popa, Dana Catalina Popa, Gheorghe Emil Mărginean, George Suciu, Mihaela Bălănescu, Denisa Paștea, Alexandru Vulpe, Marius Vochin, and **Ana-Maria Claudia Drăgulinescu**. Hybrid Platform for Assessing Air Pollutants Released from Animal Husbandry Activities for Sustainable Livestock Agriculture. *Sustainability*, 13(17), 2021. (**ISI, Q2, IF:3.251, WOS:000694541300001**).

[R4] Eugen Borcoci, **Ana-Maria Drăgulinescu**, Frank Li, Marius Vochin, and Kjetil Kjellstadli. An overview of 5G slicing operational business models for Internet of Vehicles, maritime IoT applications and connectivity solutions. *IEEE Access*, 2021. (**ISI, Q2, IF: 3.367, WOS:000724471600001**).

Six conference articles (listed in the doctoral thesis) were also published in related fields.

7.4 Awards and lectures

1. **A. M. C Drăgulinescu**, “Cyber-Physical Systems 2018” Summer School (CPS2018), July 16-20, 2018, Toulouse, France
   Distinctions Poster presented at CPS2018 Summer School, “Cellular and Long

Rang Wide Area Wireless Technologies for the Internet of Things ”, was evaluated and awarded during the poster session.

2. S-Chance Team (**A. M. C. Drăgulinescu**, Gabriela Zincă, Techallenge National Competition 2019, organized by UPB and Honeywell, Bucharest, May 9, 2019
Distinctions The project on the assistance system for people who need motor rehabilitation or who work in environments with a high risk of accidents presented in the Techallenge competition received the special prize Eliza Leonida Zamfirescu.
3. **A. M. C Drăgulinescu**, ICTurkey2019, Turkey in H2020, July 5, 2019, Istanbul, Turkey

   Distinctions The presentation sent to the organizers was selected for a travel grant and for support in the Smart Health and Care Workshop.
4. **A. M. C Drăgulinescu** and others, “IoT meets AI” Summer School, September 2-5, 2019, Munich, Germany

   Distinctions At the "IoT meets AI" Summer School, September 2-5, 2019, following the hackaton organized by Siemens and Munich Technical University and the successful implementation of the challenge proposed by coordinators (Using the SIMATIC open controller to control a robotic arm which gets the target position by an AI component combined with a vision sensor), along with the team, I received the Best Challenge Implementation Award.
5. **A. M. C Drăgulinescu**, O. Fratu, CTIF Global Capsule Workshop, October 14-17, 2019, Herning, Denmark

   Presentation: "Safety and Security in Smart Community"
6. O. Fratu, **A. M. C Drăgulinescu**, CTIF Global Capsule, October 14-17, 2019, Herning, Denmark

   Presentation: "Challenges in LPWAN-based IoT applications"

7.5 Participation in research projects in the field of thesis

The author has participated in two national projects in the field of thesis, which are being completed, and is currently a member of two national projects and four international ongoing projects.

1. 2018-2020, Research Assistant, MultiMonD2 Project, “Platform of multi-agent intelligent systems for water quality monitoring on the Romanian sector of the Danube and Danube Delta”, contract no. 33PCCDI / 2018 (UPB project manager Prof. Octavian Fratu)
2. 2018-2020, Technical-Scientific Respondent, SmartAgro Project: “Telemetry System for Smart Agriculture (SmartAgro)”, subsidiary contract no. 8592 / 08.05.2018

within the project “Ecosystem of research, innovation and development of ICT products and services for a company connected to the Internet of Things - NETIO”, contract no. 53 / 05.09.2016 (Project Manager UPB: Assoc. Prof. Ioana Marcu)

3. October 2020-present, Research Assistant, SmartDelta Project: “Increasing the innovative competitiveness of SC AdNet Market Media through initial innovation investments, in order to achieve a SmartDelta technology platform, within a newly established unit for collaborative CD activities effective "(UPB Project Manager: Assoc. Prof. Șerban Obreja)
4. November 2020-present, Research Assistant, NGI-UAV-AGRO Project, "Next Generation Internet Platform based on 5G and UAVs for precision agriculture" (UPB Project Manager: Assoc. Prof. Ioana Marcu)
5. January 2021-present, Research Assistant, SOLID-B5G Project, "Massive MIMO-based IoT platform with network slicing for IoV / V2X and maritime services in networks beyond 5G" (UPB Project Manager: Assoc. Prof. Marius Vochin)
6. December 2020-present, Research Engineer, FarmSustainBl Project, "Intelligent technologies in the field of animal husbandry for environmental sustainability using Blockchain" (Beam Innovation Project Manager: Assoc. Prof. Alexandru Vulpe)
7. November 2021-present, Communications Research Engineer, HUBCAP Project, Business Intelligence Enhanced Venue-agnostic Threat Management Platform for Citizens’ Safety and Venue Resilience (BIE-T4S), Beam Innovation Project Manager: Assoc. Prof. Alexandru Vulpe)
8. December 2020-present, Research Engineer, DISAVIT Project, "Intelligent system for substantiating decisions in the viticultural field" (Beia Consult International Project Manager: Dr. Eng. George Suciu)

7.6 Participation in research projects outside the field of the thesis

The author participated in six projects outside the scope of the thesis, all of which were completed.

1. 2017, Research Assistant, FractOFDM Project, “OFDM system based on the use of FFT with incomplete argument (FractOFDM)” - PN3 contract type "PED" no. 213PED/2017 (UPB project manager Prof. Simona Halunga)
2. 2017-2020, Research Assistant „Integrated Software Platform for Terminal Malware Analysis mobile (ToR-SIM) ”- PN3 contract type“ Solutions ”no. 5Sol/2017 (Project manager Prof. Octavian Fratu)

3. 2018-2020, Research Assistant, "Integrated Information System for Business Management (SIIMA)" - PN3 contract type "Solutions" no. 8Sol/2018 (UPB project manager Prof. Octavian Fratu)
4. 2017-2018, PhD student, GEX-2017 Project, "Modeling small-scale road traffic" (Project manager: Lect. Radu Badea)
5. 2017-2018, PhD student, GEX-2017 Project Modulation $\Sigma\Delta$ in 5G systems (ModΣs) ", contract no. 43/25.09.2017 (Project director: Assoc. Prof. Ioana Marcu)
6. 2019-2020, Member of the target group, "Developing the entrepreneurial skills of PhD students and postdoctoral fellowship - the key to career success (A-Succes)", ID 125125, based on the financing contract no. 51675 / 09.07.2019 (Project Manager Prof. Horia Iovu)

7.7 The impact of research and results

This paper is a starting point for building IoT platforms where devices can extrapolate their goals. Taken as a whole, the thesis presents the elements of IoT architecture dedicated to smart communities in which areas such as environmental monitoring, precision agriculture and telemedicine can be approached congruently or not, depending on the applications developed at higher levels of architecture.

The research conducted and presented most often differentiated, modular, by levels, in the thesis, are useful in understanding the opportunities that the Internet of Things offers, and the components described can be further integrated into other systems or IoT platforms.

The development of the unmanned vehicles positioning algorithm is also useful in the case of the Internet of Vehicles, where the criteria and constraints of optimization can be customized for applications with higher transmission rate, in a denser environment. As implemented, this algorithm focuses on the idea of reconfigurability (other criteria/constraints) and the multifunctionality of nodes (the possibility of assigning tasks to vehicles depending on their final location and trajectory), and in the future new sub-algorithms can be implemented to adapt the algorithm to new scenarios.

Through the evolution of the last years of the doctoral studies and through the activities carried out within the research projects, it has been shown that the research and the obtained results find their applicability in emerging fields, with important possibilities of extension and collaboration connected by keywords such as: LPWAN and mixed networks, Internet of Things (sensors, vehicles and other smart devices), ad-hoc terrestrial, air and surface networks.

7.8 Future research directions

As future research directions, regarding the positioning algorithm of the nodes in the FSANET network: new channel models will be explored, in order to exceed the limits of the propagation models used so far and more elaborate propagation models will be implemented. The algorithm will be improved, taking into account the impact of the interference experienced by UAVs at low altitude and a disadvantage of the algorithm will be eliminated, which consists of the long execution time for the technical solutions that involve a high budget of the connection.

Since the goal resided in the implementation of a complete platform, in the future a graphical interface will be created for the users of the IoT platform. The results of the measurement campaign and the analysis of the performance of the server designed to take over the data of the LoRa / LoRaWAN network through the gateway will also be presented in new scientific articles.

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