



**TECHNICAL UNIVERSITY OF GABROVO**

**Faculty of Electrical Engineering and Electronics**

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**DEVELOPMENT AND RESEARCH OF A LOW ENERGY WIRELESS  
COMMUNICATION PLATFORM FOR THE INTERNET OF THINGS**

## **A U T H O R ' s   A B S T R A C T**

Of a dissertation for awarding an educational  
and scientific degree Ph. Doctor

Field of high education: 5. Technical Sciences

Professional direction: 5.3. Communication and Computer Technology in Ph.

Doctoral program: "Communication Networks and Systems"

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Gabrovo 2023

The dissertation work has been discussed and directed for official defense at a meeting of the Extended Departmental Council of the Department of "Communication Techniques and Technologies" at the faculty "Electrical Engineering and Electronics" of Technical University - Gabrovo, held on 07.12.2023.

The dissertation contains 141 pages. The scientific content is presented in an introduction, four (4) chapters and, a conclusion, includes 78 figures and 6 tables. 88 literary sources and 42 Internet addresses are cited. The numbering of figures, tables and formulas in the abstract is consistent with those in the dissertation.

The research on the dissertation work was carried out in the Department of "Communication Techniques and Technologies" at the Faculty of "Electrical Engineering and Electronics" of the Technical University - Gabrovo and on the territory of the city of Gabrovo.

The official defense of the dissertation work will take place on 03/07/2024, from 1 p.m. in room 2215, Academic Building 2 (Bazhdar) of the Technical University - Gabrovo.

Materials are available for those interested in office 3209, building 3 of the Technical University - Gabrovo.

The reviews and opinions of the members of the scientific jury and the abstract are published on the university's website: [www.tugab.bg](http://www.tugab.bg).

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Title: Development and Research of a Low-Power Wireless Communications Platform for the Internet of Things

Circulation: 5 pcs. (English language)

Place of printing: University Publishing House "Vasil Aprilov" at TU - Gabrovo

## **I. GENERAL CHARACTERISTICS OF THE DISSERTATION**

### **Relevance of the issue:**

LoRa wide area networks with low energy consumption and LoRaWAN also called (LPWAN) enable an increasing number of solutions in the context of the Internet of Things (IoT), as well as applications with large geographical coverage, low but reliable data transmission rates and long life of battery power sources. These listed qualities lead to a number of challenges that are addressed and resolved in the current development. The main problems are the storage of data coming from different Internet networks, to which the radio frequency gateways are connected, as well as the visualization of the data, both in real time and in a certain time range. The main challenge is the correct geographical distribution of the gateways in the area where the network will be built. In more and more countries, the construction of such networks using the LoRaWAN protocol and standard has begun. In order for them to be maximally effective, the data flows from different networks must be united in a common platform both for the visualization of these data and for their subsequent use for the purpose of analyzes and optimization of processes and services, as in the Smart City concept ( Smart City ) and in the context of Industry 4.0 ( Industry 4.0). Radio frequency LoRaWAN networks are quite new in terms of development and have not yet found mass application in Bulgaria. The main beneficial effect of using LoRaWAN networks is the saving of both resources when two-way communication for monitoring and process control is built.

### **Research methods:**

**To achieve the goal and the tasks set in the research,** analytical, simulation and practical methods are applied. The software environments Radio Mobile and The Thinks Network Mapper were used as a tool for the simulation studies. The chosen research methodology is adequate.

### **News:**

Simulation models for low-energy wireless communications have been created, research has been conducted and contributions have been defined related to the effective use of frequency spectrum, type of modulation and channel coding in order to obtain more energy-efficient and constant quality of services in low-energy networks. Test setups were implemented and experimental evaluations of the radio coverage in different areas and points were made, graphical and tabular dependencies were presented giving information about the capabilities of the analytical model compared to real studies.

### **Aim and tasks of the research:**

*The purpose of the dissertation* is to develop and research a platform for low-power wireless communications in the context of the Internet of Things, using low-power hardware components with sufficient computing capacity, which use open-source software tools or with an end-to-end non-modifiable software product.

In order to realize the formulated goal, it is necessary to solve the following *general tasks*:

1. To identify risks for low-energy communications, through theoretical research and analysis of existing threats to information resources in these communications and platforms.
2. To analytically model data traffic under different conditions of the transmission environment (urban and non-urban) based on the existing theory and practice in the field of low-energy wireless networks.
3. To create a simulation model of wireless multi-data transmission in order to predict the network capacity and evaluate the performance of the low-power communication platform.

4. To synthesize and practically realize an exemplary low-energy platform on which to conduct experimental tests and research and to create recommendations for its application and construction in the context of the dissertation work.

**Subject and object of research of the dissertation work:**

*The subject* of research are the processes related to the processing, transmission and reception of data through a built communication channel based on LoRaWAN technology, its receivers and transmitters - modulation, channel coding, multiplexing, characteristics of the receiver/transmitter complex, synchronization and configuration of software and hardware modules building the platform. As criteria for determining the quality of service, various evaluation parameters and quality indicators were used, such as the equivalent isotropic radiated power ( EIRP), the field strength, the spectral and vector characteristics of the signal and the signal-to-noise ratio, with set criteria for the maximum permissible values of the width parameters bandwidth, received signal strength indicator ( RSSI) , etc.

**Dissertation approval:**

The main stages of the development of the dissertation work has been presented in six publications of international conferences and scientific publications, fully covering the minimum requirements regarding the considered criterion. Three of the scientific reports has been presented at the International Scientific Conference "Unitech", two at the national conference "TechCo" and one at the peer-reviewed international journal "JESTR", one of them is self-sufficing, and the other five being prepared in co-authorship with the scientific supervisor and author team. Publications have been published in peer-reviewed collections from the international scientific conference "Unitech", the national conference "TechCo" and the peer-reviewed international journal " JESTR" in the study period 2019-2022.

**II. BRIEF CONTENTS OF THE DISSERTATION**

**CHAPTER I. THEORETICAL OVERVIEW OF LOW ENERGY WIRELESS COMMUNICATIONS AND THE PROBLEMS IN THEM**

In the first chapter, a theoretical overview of the methods, means and communication protocols suitable for creating low-energy platforms when applied in IoT or IIoT is made. The mechanisms for ensuring information security, as well as the problems covering the low-energy LoRaWAN protocol, are considered.

**1.7 Conclusions to Chapter One**

1. Among the considered low-energy protocols, the LoRaWAN protocol proven algorithms are used to encrypt messages. The hopping method also contributes to data security. In this way, a smaller part of the bandwidth allocated for operation in the standard is used too.

2. In this low-energy protocol, the data is end-to-end encrypted, which is one of the factors for implementation of this protocol in the context of the Internet of Things and Industry 4.0.
3. In the most recent revision of the protocol (version 1.0.4), major security improvements have been made, namely the introduction of mandatory 32-bit frame counters and their retention in a permanent part of the memory. Frame counter removal on customization-enabled devices cannot be reset while the device is running.

## CHAPTER II. CREATING ANALYTICAL MODELING OF DATA TRAFFIC IN LOW ENERGY WIRELESS COMMUNICATIONS

### 2.1 Principles of analytical modeling

Solving the problem of wrong data acceptance requires a thorough and in-depth theoretical study of the problematic area. Based on the theoretical overview in Chapter One, conclusions are drawn regarding the shortcomings of some of the previous revisions of the low-energy LoRaWAN protocol, some of them being information security and receiving a data packet depending on the time of receipt.

### 2.2 Stages of analytical modeling

The purpose of the model is to characterize the behavior of a LoRaWAN network with a single GW that receives data packets from a set of end devices and must respond in one of two receiving windows (frequency channels specifically allocated for the purpose, with a certain frequency tape). Used when the end device requires confirmation. The system performance in terms of packet success probability is evaluated, following the approach used in [22] and extending it with a more accurate characterization of the GW behavior [A1]. This performance metric is an approximation of other key metrics, such as network throughput and capacity, that can be directly derived from it. In the reference scenario, the model assumptions, system parameters and their effects are described in item 2.2.1. Case-A, together with a brief presentation of the model structure and its main rationale; In item 2.2.1. Case-B some relevant quantities and parameters of the proposed model are described. Analytical formulation by separating the analysis of UL (Upload) traffic (item 2.2.1. Case-C and Case-D) and DL (Download) traffic.

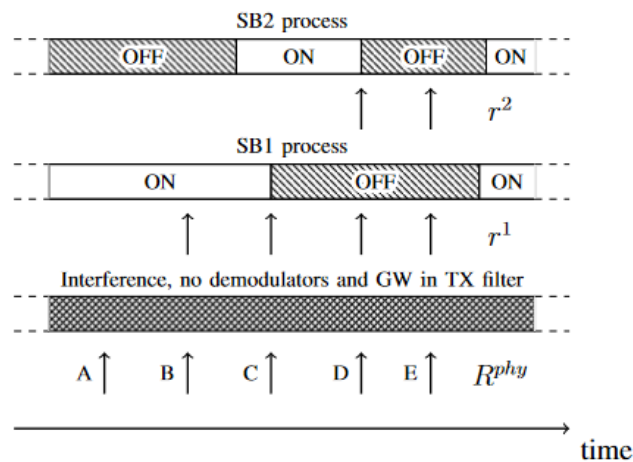


Fig. 2.1 Representation of the packet filtering structure of the model.  $R^{phy}$  is the rate of UL traffic, while  $r_1$  and  $r_2$  represent the rate of ACKs sent to SB1 and SB2, respectively

messages (2.2.1. Case-E) the formulas for the DL success probabilities in 2.2.1 are derived. Case -F . Finally 2.2.1. Case-G, describes various performance indicators and their calculation. The corresponding equation can be derived, in which case references are provided in the text.

### 2.2.1. Scenario suggestions when choosing architectural connectivity

Looking is a scenario where the end devices are any number and are uniformly distributed around one GW. Application layer packets are generated according to a Poisson process [93] with an aggregate packet generation rate  $\lambda$  [pck/s] , and the packets can be acknowledged or unacknowledged. To maximize the use of the analytical model, perfect orthogonality between different SFs is assumed, i.e. only packets using the same SF can collide. In this case, one of the two packets can survive if its received power is sufficiently higher than that of the colliding packet (collisions with more than two packets occur with negligible probability and are not taken into account).

### 2.2.2. Capabilities of the model

The model offers some adjustable parameters to increase its flexibility, allowing the evaluation of network performance in different configurations with minimal effort. The model parameters are:

- $SF = \{7, \dots, 12\}$  shows the set of all SF.
- $\alpha$ : fraction of application layer traffic requiring acknowledgment;
- $p_i^u, p_i^c$ - part of the devices generating unconfirmed and confirmed traffic with a specific SF,  $i \in SF$ , respectively  $\sum_{i \in SF} p_i^u = \sum_{i \in SF} p_i^c = 1$ ;
- $h$ : number of transmissions of an unconfirmed packet from the application layer;
- $m$ : maximum number of attempts to transmit confirmed packets;
- $\delta SB1$  and  $\delta SB2$ : the ratio between the silence time and the transmission time in SBk corresponding to a constraint set by the packet counter. For example, in Europe we have  $\delta SB1 = 99$  and  $\delta SB2 = 9$ , corresponding to

DC of 1% in SB1 and 10% in SB2. In general, when  $\delta SBk > 0$  the DC constraint applies to all devices transmitting in the SBk subchannel. Instead, it matches the setting  $\delta SBk = 0$  to a DC limit of 100%, which means there is no limit on the transmitted  $\text{вpeme}^3$ (this only applies for model purposes);

- $\tau_1$  and  $\tau_2$ : are prioritization flags. If  $\tau_k = 0$ , the GW prioritizes the receive transmission operations during the kth receive window, with  $k = 1, 2$ . In this case, the GW will reject any DL message that needs to be transmitted while UL receive is in progress . Instead of if TX is prioritized ( $\tau_k = 1$ ), the reception of any incoming packet will be interrupted because sending ACK is prioritized;

### 2.2.3. Calculation of the traffic speed of UpLink messages

The assumption of perfect orthogonality between the different SF factors makes it possible to split network traffic into different logical channels that do not interfere with each other. The traffic load for each SF  $i$  is evenly distributed over the given  $C$  frequency channels (since the end devices select a random UL frequency channel on each transmission attempt). Thus, the traffic generated at the application layer by end devices using authenticated and unauthenticated messages is given by:

$$R_i^{c,app} = \frac{p_i^c \cdot \lambda}{C} \cdot \alpha, \quad (2.1)$$

$$R_i^{u,app} = \frac{p_i^u \cdot \lambda}{C} \cdot (1 - \alpha) \quad (2.2)$$

Because ED's using unacknowledged traffic will perform  $h$  transmissions to each packet, PHY packet rate from these devices can be calculated as  $R_i^{u,phy} = R_i^{u,app} \cdot h$ ,  $h$  transmission of acknowledged messages by the end device Instead , the number of retransmitted packets depends on the success of both the UL transmission and the corresponding ACK. It is denoted as  $P_{i,j}^{DL}$  the probability that an acknowledged UL packet sent with SF  $i$  is successfully received and acknowledged on the  $j$ th transmission attempt, which will be obtained in (2.29) . Therefore the confirmed rate of

packets transmitted on SF  $i$ ,  $R_i^{c,phy}$ , is given by the product of the application-level rate,  $R_i^{c,app}$ , and the average number of transmissions per confirmed packet at the PHY level.

$$R_i^{u,phy} = R_i^{u,app} \left[ \sum_{j=1}^{m-1} j \cdot p_{i,j}^{DL} + m \left( 1 - \sum_{j=1}^{m-1} p_{i,j}^{DL} \right) \right]. \quad (2.3)$$

The first summation in the square brackets of ( 2. 3 ) takes into account the transmissions that were successfully received before the  $m$ th attempt, while the second term considers the case where the packet is transmitted  $m$  times (regardless of whether the last transmission was successful or not).

Therefore, the total traffic for one frequency channel and for SF  $i$  is given by:

$$R_i^{phy} = R_i^{u,phy} + R_i^{c,phy} \quad (2.4)$$

In general, the distribution of spreading factors for transmitted packets at the PHY layer will differ from distribution of SF between devices,  $\{p_i^u, p_i^c\}$ , due to retransmissions. In this way, it is determined:

$$d_i = \frac{R_i^{phy}}{\sum_j R_j^{phy}} \quad (2.5)$$

as the ratio of PHY layer packets that are transmitted at SF  $i \in \text{SF}$ .

#### 2.2.4. Possible probabilities at the PHY layer

A UL packet is successfully received by the GW if all of the following conditions are met:

- ( i ) it does not overlap with other UL transmissions that use the same SF at the same frequency, or it overlaps with another UL packet but the received power is large enough, to allow correct decoding despite interference;
- ( ii ) not to overlap with GW and DL transmission in each channel;
- ( iii ) a free demodulator must be available;

These conditions are represented by the first filter in Fig. 2.1. Since packets are generated following a Poisson process, the probability of an event ( i ) is given by two components. The first is the probability that there are no other arrivals during a  $2T_i^{data}$  vulnerability period at the time the packet arrives. The second, considers a single packet collision and the fact that the receiver has successfully intercepted the frame (packet). The UL is considered to be the capture probability  $W^{GW}$  as calculated in (2.6). Since these two events are distinct, the probability of the surviving disturbance (event (i)) is given by the sum of the two components, which is given by:

$$S_i^{INT} = e^{-2T_i^{data} R_i^{phy}} + 2T_i^{data} R_i^{phy} e^{-2T_i^{data} R_i^{phy}} \cdot W^{GW} \quad (2.6)$$

#### 2.2.5. Acknowledgment transmission diagram for ACK messages

After an acknowledged packet is correctly received by the GW, an ACK must be sent back to the end device. (2.15) gives the probability of successful packet reception at the GW. Therefore, the rate of ACK messages that the GW will try to send in SB1 is:

$$r_i^1 = R_i^{c,phy} \cdot S_i^{UL} \quad (2.16)$$

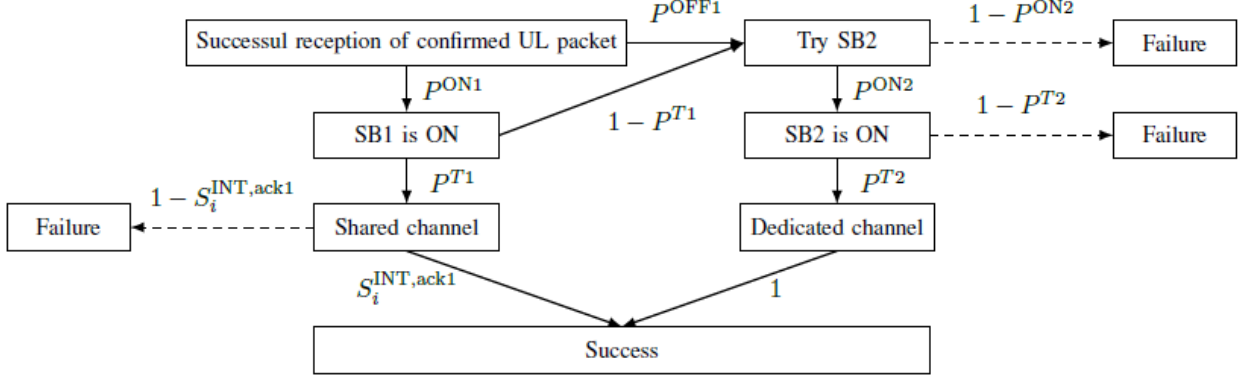


Fig. 2.2. Diagram showing the successful reception of an ACK request

### 2.2.6. An example of confirmed probability in a DL message

Given that an acknowledged UL packet sent with a certain SF  $i$  is successfully received by the GW, the probability that the corresponding ACK message is also successfully returned to the end device can be expressed as:

$$S_i^{DL} = S_i^{SB1} + S^{SB2}, \quad (2.25)$$

where  $S_i^{SB1}$  describes the probability of successful transmission of an ACK message in SB1 with SF  $i$ , while  $S^{SB2}$  considers the probability that SB1 is not available and the ACK message is successfully sent to SB2. These probabilities, in turn, can be expressed as follows:

$$S_i^{SB1} = P^{ON,1} \cdot P^{T,1} \cdot S_i^{INT,ack1}, \quad (2.26)$$

$$S^{SB2} = [P^{OFF,1} + P^{ON,1} \cdot (1 - P^{T,1})] \cdot P^{ON,2} \cdot P^{T,2}, \quad (2.27)$$

Fig. 2.2. can be used as a reference to calculate this quantity. Finally, the probability of success of transmissions  $m$  can be calculated. To simplify the expressions, the temporal correlation of retransmission of packets is neglected due to limitations imposed by the packet counter (the impact of this approximation will be analyzed through simulation).  $P_{i,j}^{UL}$  indicates the probability that a UL packet with SF  $i$  is successfully received at the GW in exactly the  $j$ th transmission attempt, which can be calculated as:

$$P_{i,j}^{UL} = S_i^{UL} (1 - S_i^{UL})^{j-1} \quad (2.28)$$

Then the end device ((ED)End Device) successfully receives the ACK exactly on the  $j$ th attempt if both UL and DL transmissions are successful. The probability  $P_{i,j}^{UL}$  of this event is given by:

$$P_{i,j}^{UL} = [1 - (S_i^{UL} S_i^{DL})]^{j-1} \cdot (S_i^{UL} S_i^{DL}) \quad (2.29)$$

After all the intermediate quantities have been calculated, the model can be summarized by two interdependent equations:

$$\begin{cases} S^{UL} = f(S^{UL}, S^{DL}), \\ S^{DL} = g(S^{UL}, S^{DL}), \end{cases} \quad (2.30)$$

### 2.2.7. Performance indicators for receiving and decoding data

To evaluate system performance, three classes of key performance indicators are considered, namely: reliability, delay and fairness /credibility indicators, which are discussed in more detail in the rest of this subsection together with the methodology for determining their value using the proposed model. Once a detailed parameter set and the model can be solved and the performance metrics can



be evaluated starting from  $S^{UL}$  and  $S^{DL}$ . Conversely, it is possible to use the model to optimize a given performance metric, finding the parameter setting that maximizes it, as discussed in Section 2.3.

1) Reliability indicators: Three Packet Delivery Rate ( PDR) indices are considered , namely:

- Unconfirmed Uplink (UU) PDR : fraction of unconfirmed packets (at the application level) that are successfully received by the GW;
- Confirmed Uplink PDR ( Confirmed Uplink (CU ) ): fraction of confirmed packets (at the application level) that were successfully received by the GW, regardless of whether an ACK message was sent to the end device;
- Confirmed Downlink PDR ( Confirmed Downlink(CD)): fraction of confirmed packets (at the application level) that are also successfully recognized by (Network Server(NS)) Network Server .

### 2.3 Model creation and simulation results

To validate the model, the performance estimates, obtained from a model are compared with those observed in more realistic simulations in which most from the simplifying assumptions of the model are removed. This point describes how to use the LoRaWAN ns-3 module described in [26] and how to validate the model. It should be noted that the more accurate modeling of LoRaWAN

SF	$T^{data}$ [s]	$T^{ack}$ [s]	$p_{equal}$	$p_{EXPLoRa}$
7	0.051	0.041	0.166	0.487
8	0.102	0.072	0.166	0.243
9	0.185	0.144	0.166	0.135
10	0.329	0.247	0.166	0.076
11	0.659	0.495	0.166	0.038
12	1.318	0.991	0.166	0.019

Table 2.1 Values of the distributions  $T_i^{data}$ ,  $T^{ack}$ ,  $p$  and SF. The payload of data packets is 10 bytes; ACKs have no payload.

the standard considered in the simulator requires more computation time to evaluate system performance. In fact, for the same set of parameters, the performance evaluation is instantaneous when using the theoretical model as it is run on every ns-3 simulation and takes time on the order of tens of seconds, with the execution time increasing rapidly with the traffic of load, the number of devices, and the number of randomized runs of the model required. The utility of the simulator is that it strives to be as realistic as possible while also taking into account some factors that are neglected by the model for tractability reasons. For example, the assumption of perfect orthogonality between transmitted packets using different SFs is removed, the simulator relies on the link-level model provided in [9] to determine the actual reception and probability in the case of overlapping transmissions, which is also accounted for by the capture effect. The parameters set in the simulator are the following:

- Traffic Load - The number of EDs is fixed at 1200 and the ED application layer is set to periodically generate packets to be transmitted by the MAC layer. The network traffic load is modified by changing the packet generation period. The periodic traffic generation model is more realistic than the assumed Poisson traffic in the model. Nevertheless, the good agreement

of the simulation and analysis results confirms that the assumption of the model is valid when the number of nodes is large enough.

- Distribution of channels - The typical frequency distribution sequence for Europe is considered, as they are described in the table. 2.2. Therefore, the number of different frequency channels for UL is  $C=3$ .
- Duty cycle - The simulator takes into account the limits set by the packet counter integrated in the server, and these limits are applied in all countries, depending on their frequency plan [12], which corresponds to the following values:  $\delta_{SB1} = 99$  and  $\delta_{SB2} = 9$  used in this model.
- Channel model - In contrast to the model, the simulated LoRaWAN end devices experience signal propagation loss over a logarithmic distance as in an outdoor scenario. Thus, the more distant devices have increased losses and their performance decreases with respect to the end devices that are close to the GW. Do not include rapidly decaying components that are assumed to be averaged by the LoRa modulation, nor the time-dependent variations in the channel, which remains constant throughout the simulation. Furthermore, the channel is assumed to be symmetrical and DL transmissions will suffer the same impairments as UL transmissions.
- SF distribution - the end devices are usually located around GW in a circular area with a radius of 2500 m, any end device falling within this area can send packets with any SF with negligible channel error probability (in the absence of interference). Instead, the positions of the EDs are chosen randomly at each simulation run. SF are assigned uniformly (see table 2.1.). In some scenarios, a different distribution of SF.
- Interference and Interference - To model interference, the simulator considers a collision matrix provided in [9] and the overlap time between packets as described in A [23]<sup>4</sup> packet is interfered by a signal modulated with the same SF if its power is at least  $CR_{db} = 6$  dB higher than that of the other incoming packet. To ensure \_ compared to this scenario, the analytical model uses the assumption of uniformly distributed EDs around the GW to calculate the packet intercept probabilities, as described in ( 2.6), leading to  $W^{GW} = 0.1796$ , and  $W^{ED} = 0.5682$ . It is noted that under different ED distributions around the GW can be modeled by adapting this derivation. Since the GW implementation in the simulator tries to emulate the behavior of a real device, the UL packet is successfully received when the following conditions:
  - 1) The package finds a free demodulator;
  - 2) Packet reception is not interrupted by DL transmissions;
  - 3) Once the reception is complete, the packet has not been damaged by interference.

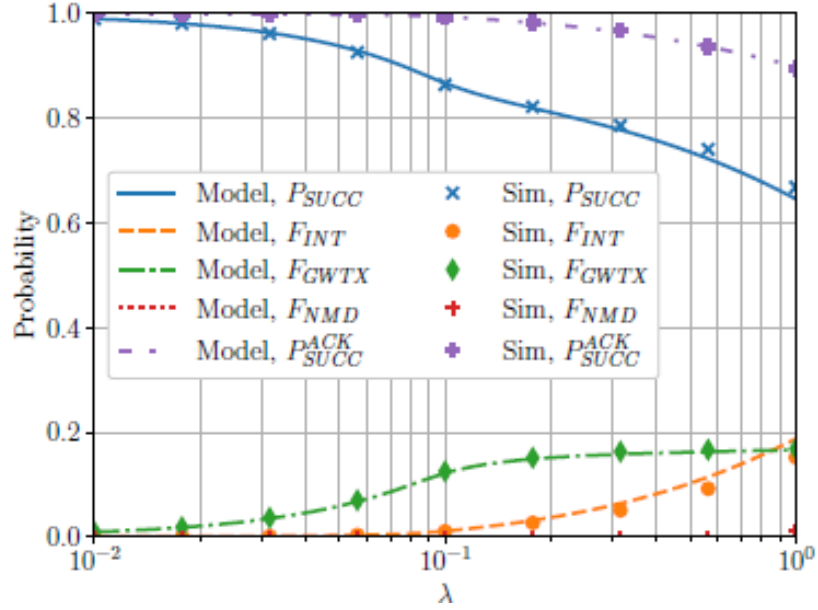
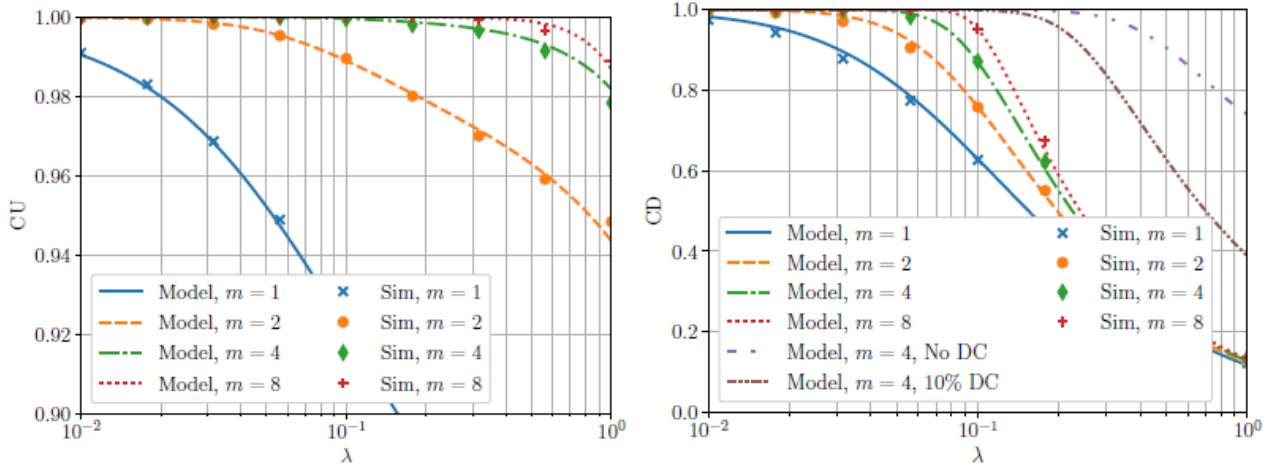


Fig. 2.3 PHY level performance with  $m = 8, \alpha = 1$ .

By using (2.6), (2.8) and (2.14), where  $E_i$  shows the expected distribution of the SF factors and  $S^{demod}$  the probability that in the simulations the packet can use an available demodulator. A real comparison between the performance estimated by the proposed model and by the ns-3 simulator is described. Results are presented for both the PHY and MAC layers, and the model assumptions are shown to be acceptable. Finally, some results show how the model can be used to gain insight into the behavior of LoRaWAN technology in a faster and easier way by analyzing the effects of different parameters on network performance. In the graphical dependences described at this point in the scientific paper, the analytical results are represented by lines, while the markers correspond to the simulation results. Fig. 2.3. shows the output packet probabilities at the PHY level in a network using acknowledged traffic. The fact that this performance loss is caused by the DC of the GW is confirmed by the lilac dashed line in Fig. 2.4.b: to obtain these results, the DC constraints have been removed by setting  $\delta_{SB1} = \delta_{SB2} = 0$  in the model, resulting in significantly better results compared to the corresponding green curve where DC is enabled.



(a) CU for different values of  $m, \alpha = 1$

(b) CD for different values of  $m, \alpha = 1$

Fig. 2.4 (a, b) Comparison of model and simulation results of CU and CD.

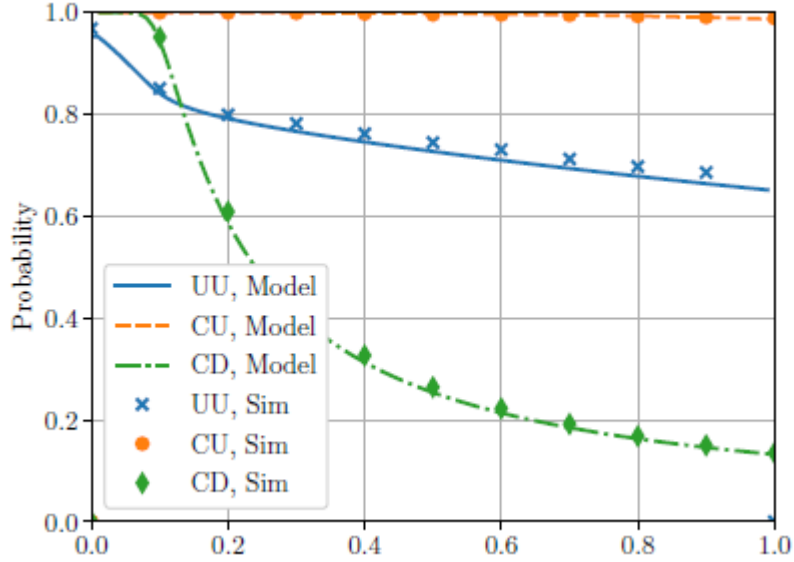


Fig. 2.5. Performance when changing part of confirmed traffic, with values  $\lambda = 1, m = 8, h = 1$

Another example of the model's flexibility, considering non-standard settings, is given by the solid dashed brown line, which represents the CD metric when  $\delta_{SB1} = \delta_{SB2} = 9$  i.e. when transmissions in both subbands are subject to a DC of 10%.

#### 2.4. Capabilities of the proposed analytical model

Example: what the analytical model can offer, which is presented in Fig. 2.8, which shows the fraction of traffic that achieves packet reception success after a certain number of retransmissions when attempting different traffic loads derived from  $P_{i,j}^{DL}$ .

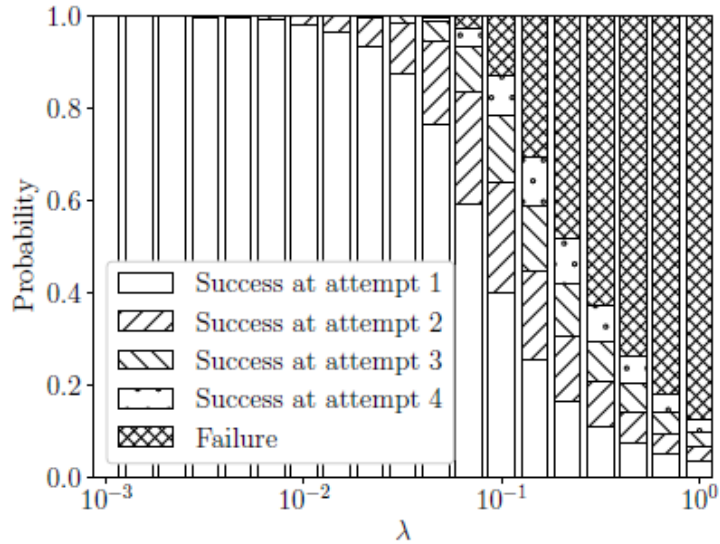


Fig. 2.8. Allocation in Retransmissions,  $m = 4, \alpha = 1$ .

This data is used to calculate the energy consumption of the end devices: at low traffic loads, the majority of packet transmissions at the MAC[91] level are successful with only one transmission attempt at the PHY level. As the traffic load increases, so does the proportion of devices that need multiples retransmissions to receive correct ACK responses. After a certain point, packet reception fails at such a high rate that most EDs must use the maximum number of transmissions and despite the high power consumption, still fail to receive an ACK[92] response from the GW.

#### 2.5. Software use of analytical model capabilities

For the purposes of the dissertation work, a software tool was created based on the analytical model discussed in chapter 2 of the dissertation development [96]. The model predicts the probability

of receiving a packet of information depending on the distribution environment (urban or non-urban). Several different models are built into the software, and more can be created or existing ones edited. Depending on the time from the transmission to the reception of a packet of information, different transmission times are set in the model, imitating the transmission of more or less information. A 4-state Markov matrix shown in Fig. is embedded in the model. 2.11. [46].

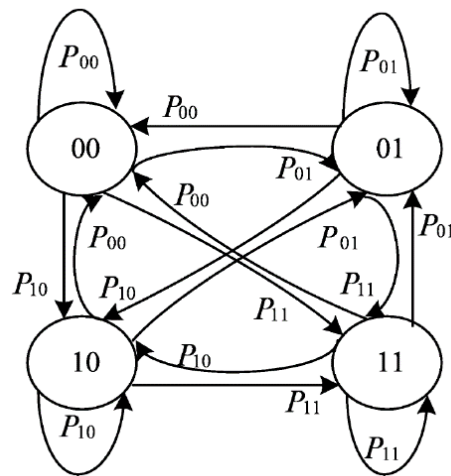


Fig. 2.11. A 4-state Markov matrix

The matrix used calculates the probability  $P(X_i)$ , i.e. the probability of containing  $X_i$  connectors between lines  $i$  and  $i+1$ . For each connector where  $i$  and  $i+1$  the condition  $i < n-1$  is satisfied, the 4-state Markov matrix can be fulfilled. States 00, 01, 10, and 11 represent logic values on both logic buses. The probability of transition from one state to another is:  $P_{00} = P_{01} = P_{10} = P_{11} = 0,25$ . Therefore the steady state probability is 0.25, see expression (2.39). The software tool is written using the Python programming language, more information about it can be seen here: <https://github.com/nikolaieniware/LoRaSim>. The software has a graphical interface for setting different simulation models shown in Fig. 2.12. From it, it can also be seen how the graphical interface of the software looks. The implemented software tool for traffic simulation using Markov chains was reinstalled on a Raspberry Pi 3 B+ single-board computer. After installing the software following the steps described in <https://github.com/nikolaieniware/LoRaSim> proceeds to launch the software. To start, run the LoRaSiM command in a command window , see Fig. 2.12.

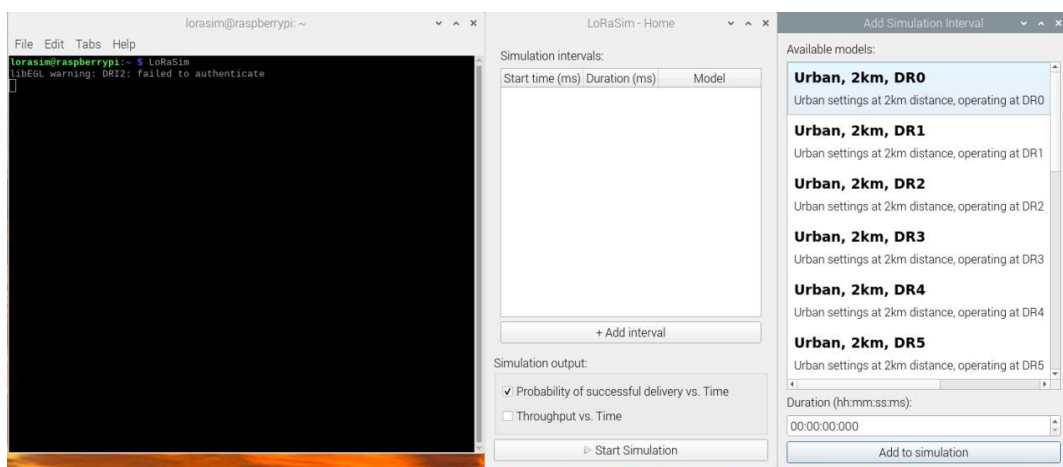


Fig. 2.12. Launch the LoRaSiM software

In the right part of Fig. 2.12. the terminal window is visible, in which the LoRaSim command is written , with which the software is started. A dialog window LoRaSim Home opens, from which

the so called “Simulation interval”. They represent fixed distances from the RF Gateway to the transmitter, at different data rates from DR0 to DR6, corresponding to different SF factors. The Duration field sets the time range for the transmitter to broadcast the information of this SF and the simulated distance to the receiver. In Fig. 2.13. you can see how an SF factor is set, the probability of receiving data by the RF Gateway, and on the graph next to it, the possible amount of information in bytes during this time.

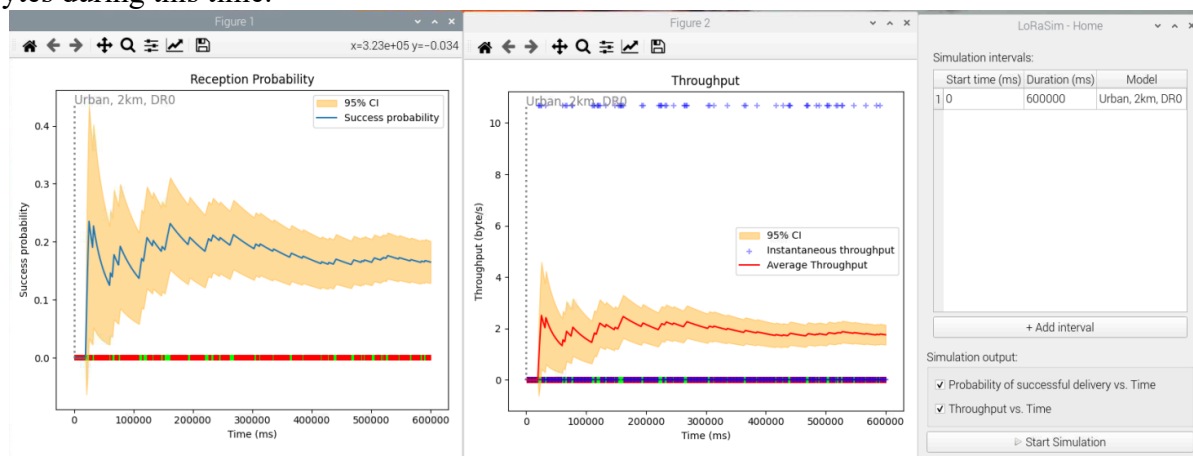


Fig. 2.13. Results of the conducted simulation of data transmission at DR0 ( information transmission time 1500 ms.

In Fig. 2.14. a similar graphical dependence is visible at the same distance of 2 km, but with DR1 at a time for transmitting the information of 760 ms.

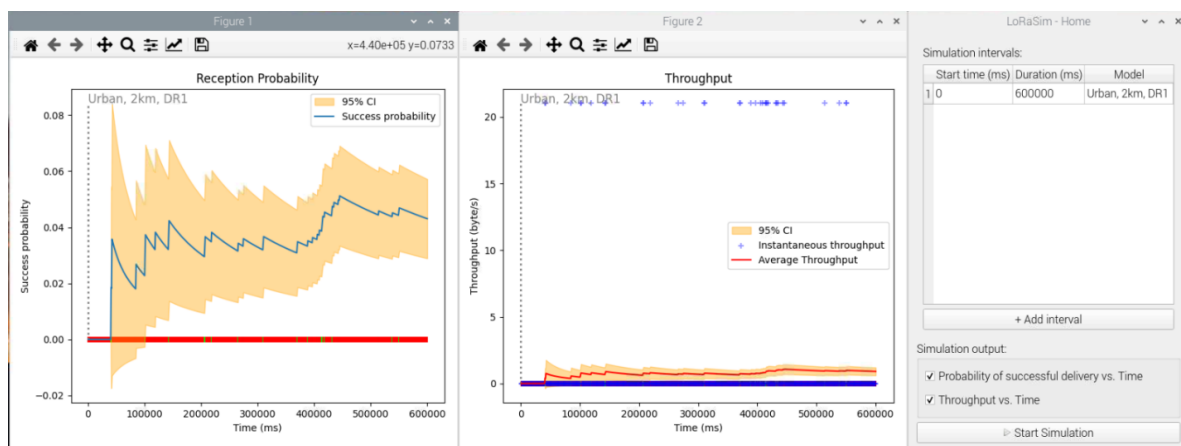


Fig. 2.14. Results of the conducted simulation of data transmission at DR 1 ( information transmission time 760 ms.

A comparison between the two figures shows that for the shorter sending time, the probability of receiving a data packet is less 0.08, while for a sending speed of 1500 ms, the probability is 0.4, which is a much more acceptable result. For the remaining values of the distance to the RF Gateway and a different DR coefficient, no comparisons were made and they were not included in the dissertation note.

## 2.6.Conclusions to Chapter Two

Based on the considered model and the possibilities of traffic simulation in a LoRaWAN network, it can be concluded that the technology and the wireless standard make it possible to transmit information over long distances, albeit at a low speed, but only if the configuration and setting of the end devices and the network server are configured correctly.

In the traffic simulation in item 2.2.7. are formulated and defined the performance indicators, which are distinguished into three groups - reliability, latency and credibility.

The model is embedded in the ns-3 simulator and enables the calculation of the probability of packet loss in the absence of demodulators using a certain mathematical dependence.

In point 2.4 are presented the capabilities of the model used in several different scenarios are shown in table. 2.2., and in Fig. 2.9 graphical dependences of different performances for different network configurations are shown.

In point 2.5, the software use of the probability model for data reception and transmission at different distances in an urban environment using a 4-state Markov matrix is set. Based on this method, a software tool was also created for simulating data traffic at different data transfer rates DR. The tool has the ability to overlay several different DR factors for different times and monitor the amount of information transmitted over that time.

## CHAPTER III. PLANNING, BUILDING AND RESEARCHING WIRELESS DATA TRANSFER CAPABILITIES IN THE LOW ENERGY PLATFORM

### 3.1. Scheme of the experimental setup

For the purposes of experimental research and analysis of data transmission through the constructed low-energy LoRaWAN network is presented, the block diagram experimental setup of Fig. 3.1.

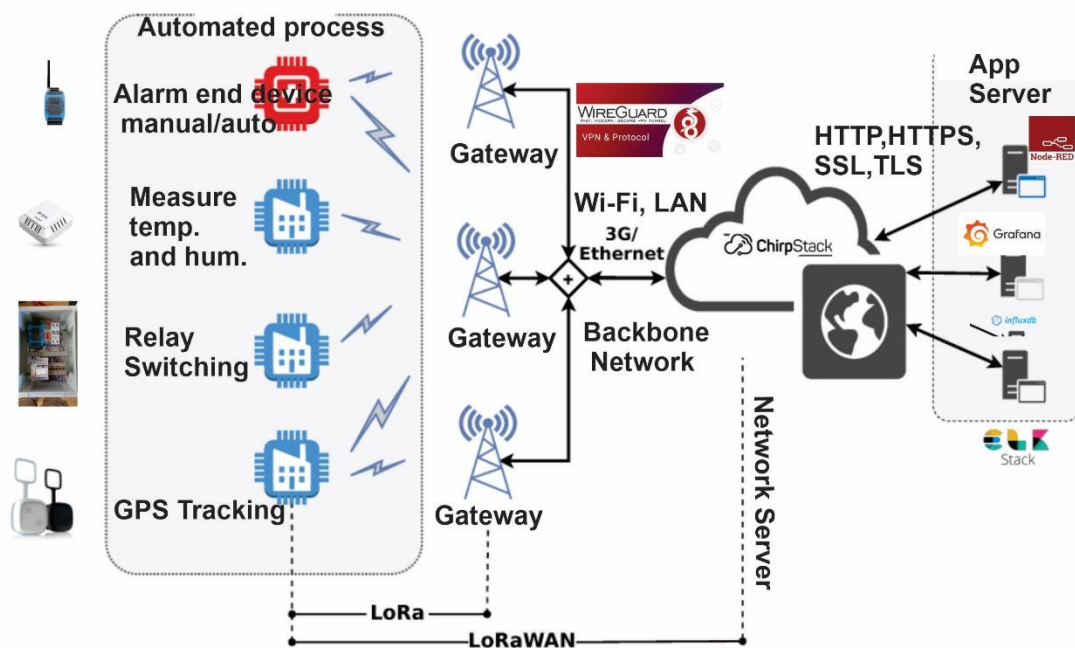


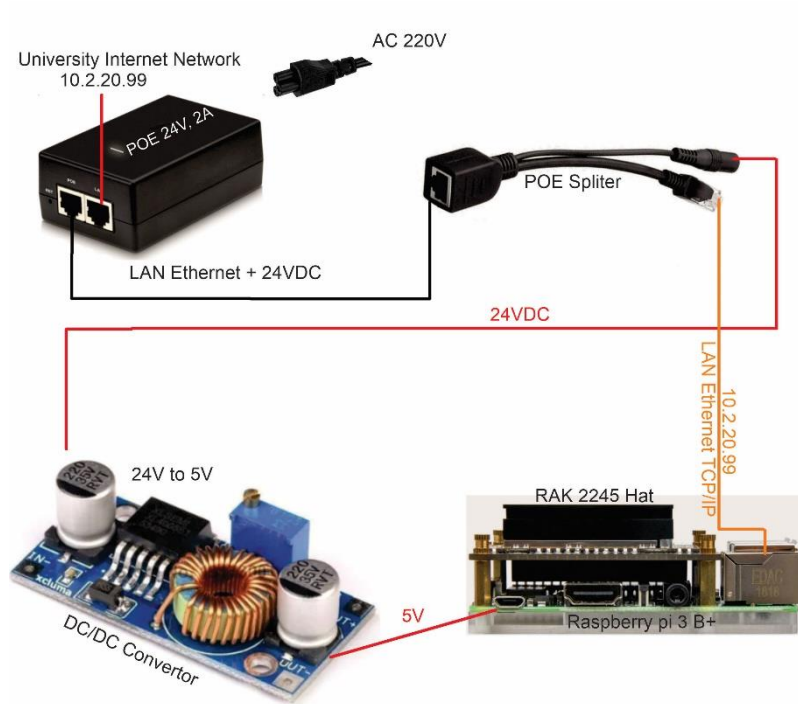
Fig. 3.1. Conceptual block diagram for conducting the experimental studies

### 3.2. Design and assembly of RF Gateway

RF Gateway also called LoRaWAN Gateway is composed of two hardware modules:

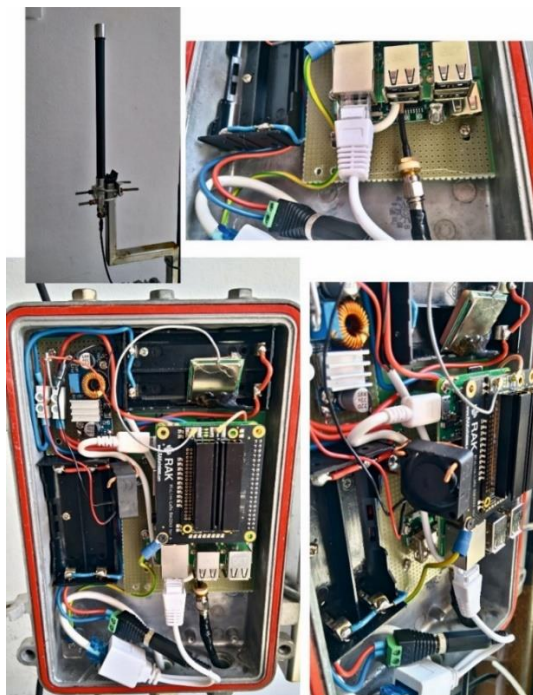
- Raspberry pi 3B+ single board computer
- LoRaWAN hub RAK2245

The two modules are housed in a hermetic aluminum box with suitable mounting elements. The power supply of the two modules is 5 V, 3 A as required (at long distances there are large losses on the wires). This challenge is solved by using a POE (Power Over Ethernet) power supply unit with a 24 volt supply voltage value. A converter ( DC/DC Converter) is also placed in the box, with the help of which the voltage is adjusted to the desired 5V needed to power the modules [A4]. The implementation of the power supply is shown in Fig.3.2.



*Fig. 3.2. Implementation of the power supply of the RF Gateway*

In Fig.3.3. the battery sockets are shown as well as the battery charge controller.



*Fig.3.3 Component modules of the RF Gateway*



### 3.3. Algorithm and methodology of synthesizing an experimental setup and conducting the research

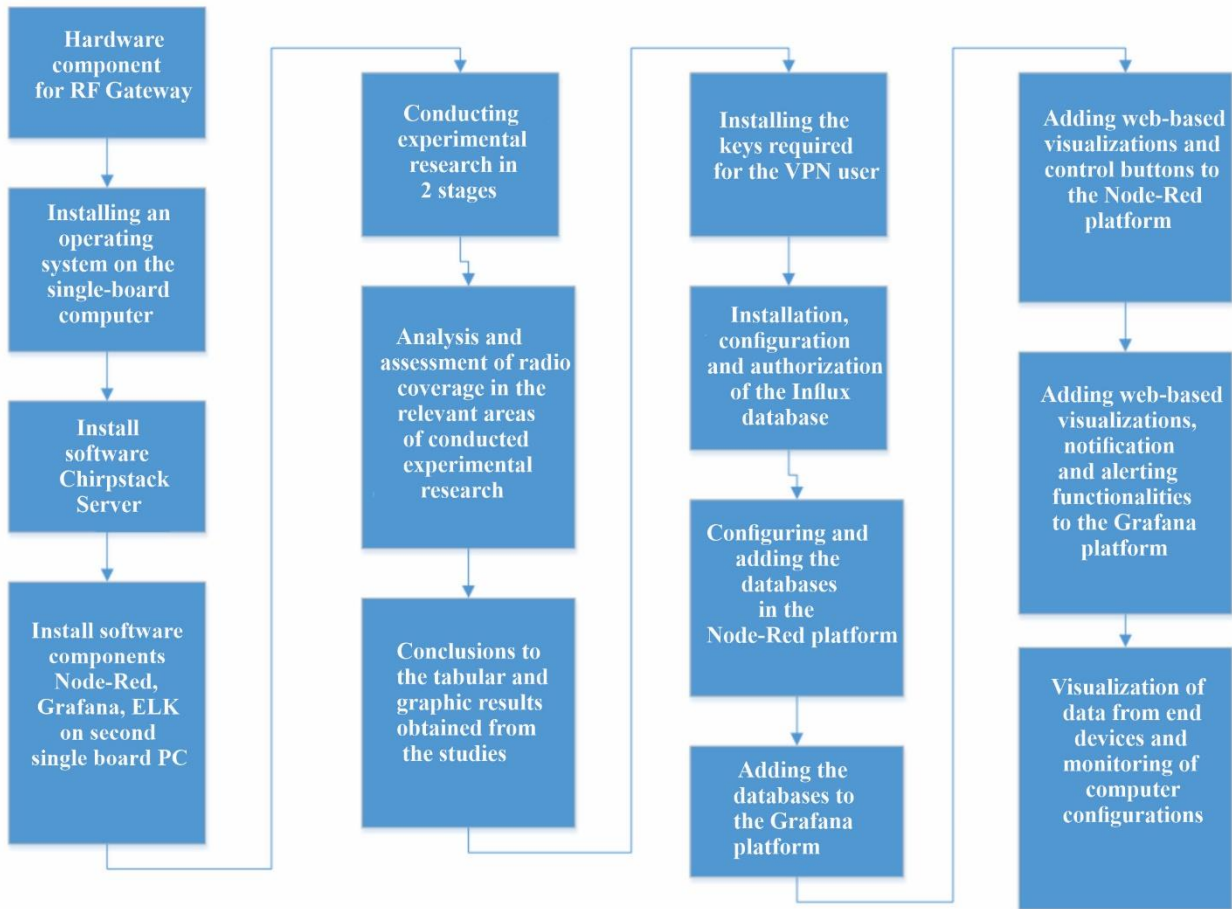


Fig. 3.4. Methodology Algorithm for Platform Design

### 3.4. Installation and configuration of Chirpstack LoRaWAN server

The overall installation of the server is divided into several stages, or more precisely, into 3 modules that are installed separately on the single-board computer.

**Module 1:** Gateway Bridge. ChirpStack Gateway Bridge is a service that converts LoRa packets into a common ChirpStack Network Server [data format \(JSON and Protobuf\)](#). This component is part of the ChirpStack open source LoRaWAN<sup>®</sup> Network Server stack.

The following commands are used for its installation:

```

1: sudo apt-key adv --keyserver keyserver.ubuntu.com --recv-keys
1CE2AFD36DBCCA00
2: sudo echo "deb
https://artifacts.chirpstack.io/packages/3.x/deb stable main" |
sudo tee /etc/apt/sources.list.d/chirpstack.list
3: sudo apt update
4: sudo apt install chirpstack-gateway-bridge
5: sudo systemctl [ start | stop | restart | status ] chirpstack-
gateway-bridge
  
```

- **Module 2 :** Network Server . ChirpStack Network Server is an open source implementation of LoRaWAN Network Server. This component is part of the ChirpStack stack. The responsibility

of the network server component is the deduplication of the received LoRaWAN frames from the LoRa gateways and for the collected frames processing:

- Authentication
- LoRaWAN mac-layer (and mac-commands)
- Communication with [the ChirpStack application server](#)
- Scheduling frames for sending data

The following commands are used for its installation:

```
1: sudo -u postgres psql
2: Create base and base role:
-- create the chirpstack_ns user with password 'dbpassword'
create role chirpstack_ns with login password 'dbpassword' ;
-- create the chirpstack_ns database
create database chirpstack_ns with owner chirpstack_ns;
-- exit the prompt
\ q
3: Checking base and user for correct setup:
psql -h localhost -U chirpstack_ns -W chirpstack_ns
4: Download the installation file for Chirpstack Network Server:
sudo apt-key adv --keyserver keyserver.ubuntu.com --recv-
keys 1CE2AFD36DBCCA00
sudo echo "deb
https://artifacts.chirpstack.io/packages/3.x/deb stable main" |
sudo tee /etc/apt/sources.list.d/chirpstack.list
sudo apt update
5: Installing Chirpstack Network Server
sudo apt install chirpstack-network-server
6: To start the process automatically
sudo systemctl [ start | stop | restart | status ] chirpstack-
network-server
```

- **Module 3:** ChirpStack Application Server. It is responsible for the device "inventory" part of the LoRaWAN infrastructure, connection request processing, and application payload (data) processing and encryption. The server is owned by web interface where users, organizations, applications and devices can be managed. For integration with external services, it offers gRPC and RESTful API.

Device data can be [sent and/or received](#) via MQTT, HTTP and written directly to an InfluxDB database .

The following commands are used for its installation:

```
1: Create a user and database with the command: sudo -u postgres psql
2: Additional database settings:
-- create the chirpstack_as user
```

```

create role chirpstack_as with login password 'dbpassword' ;
-- create the chirpstack_as database
create database chirpstack_as with owner chirpstack_as;
-- enable the trigram and hstore extensions
\ c chirpstack_as
create extension pg_trgm;
create extension hstore;
-- exit the prompt
\ q

```

3: To verify the user and database: `psql -h localhost -U chirpstack_as -W chirpstack_as`

4: Download the installation file for Chirpstack Application Server:

```

sudo apt-key adv --keyserver keyserver.ubuntu.com --recv-keys
1CE2AFD36DBCCA00
sudo echo "deb https://artifacts.chirpstack.io/packages/3.x/deb
stable main" | sudo tee /etc/apt/sources.list.d/chirpstack.list
sudo apt-get update

```

5: Installation of Chirpstack Application Server: `sudo apt-get install chirpstack-application-server`

6: Automated service start: `sudo systemctl [start | stop | restart | status ] chirpstack-application-server`

7: Accessing the Application Server: Web Interface: <https://localhost:8080/>

With this step, the Chirpstack server installation is complete and you can proceed to add device and application to the server.

### 3.5.1. Creating applications in Chirpstack LoRaWAN Server

To create an application in the Chirpstack LoRaWAN server, navigate to the web interface of the server, enter the user login data using the IP address and network port 8080 of the installation:

User: admin

Password: admin

Then navigate to the Applications menu (1), and then click the + CREATE button (2), see Fig. 3.8. In Fig. 3.8. It can be seen that two applications have already been created that are involved in the dissertation development.

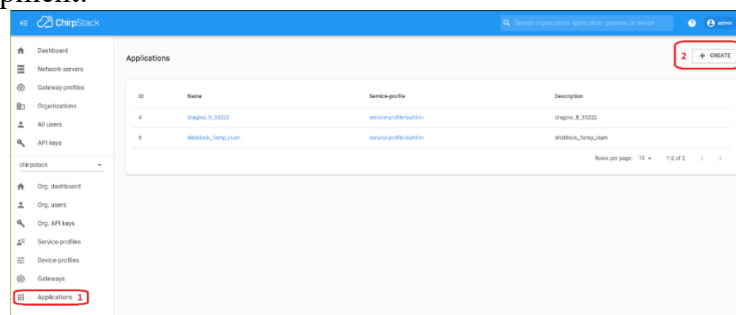


Fig. 3.8. Creating an application on the Chirpstack LoRaWAN server

### 3.6.1. Installing and configuring Node-Red

Node-RED[25] is a software tool for programming and connecting hardware devices, APIs and online services in new and interesting ways. It provides an online-based editor that makes it easy to connect streams using the wide range of nodes in the Capability Palette, which can be deployed at runtime with a single click. For the purposes of the thesis development, Node-Red and Grafana were installed on a Raspberry Pi 3 B+ single-board computer, as mentioned earlier in this chapter on a second computer configuration, with both Node-Red and Grafana software tools installed. Before proceeding with the installation sequence we need to make sure that we are using Raspberry Pi OS[41]. Installation steps:

1. Run the following command in a terminal window: **bash <(curl -sL https://raw.githubusercontent.com/node-red/linux-installers/master/deb/update-nodejs-and-nodered)**
2. To ensure automatic start when loading the operating system, the command is executed: **sudo systemctl enable nodered.service**
3. To start the automated authorization the command is executed: **sudo systemctl start nodered.service**

### 3.7.1. Experimental studies in a closed room

The experimental studies in a closed room were carried out in the Building 2 "Bajdar" of TU-Gabrovo, and a large number of measurements were made at each control point in order to achieve a real arithmetic mean coefficient of the signal parameters. The parameters that are investigated in the dissertation development are:

- RSSI
- LoRaSNR

A total of about thirty control points in the building, on all floors, were visited.

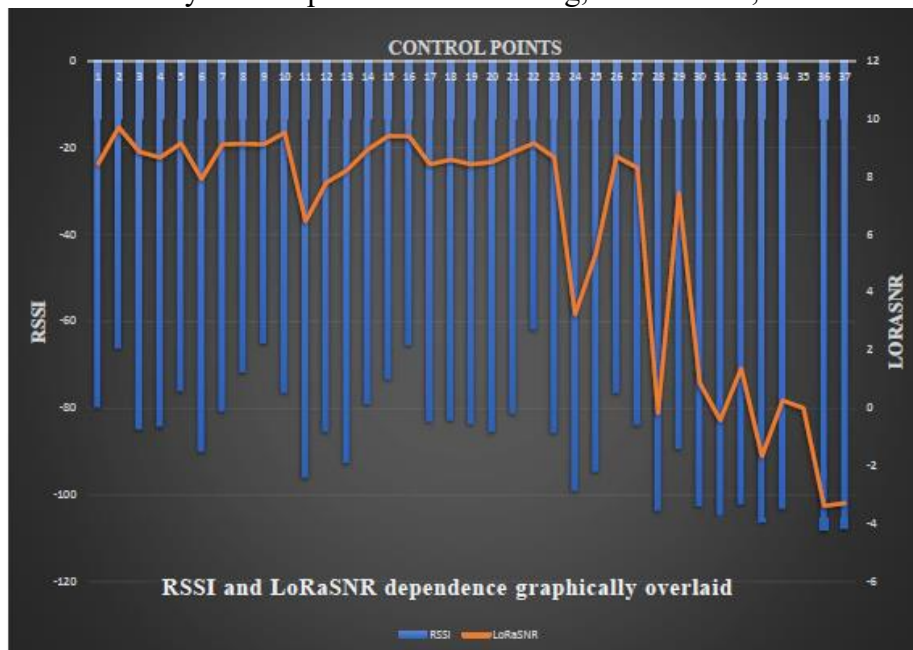


Fig. 3.30. Graphical dependence between RSSI and LoRaSNR parameters against measurement control points

### 3.7.2. Experimental studies in an open area

The research on the quality of the radio coverage in an open area was carried out on the territory of the town of Pavel Banya, with most control points being covered by bicycle, and the final transmitting device was carried in a backpack on the back [A6].

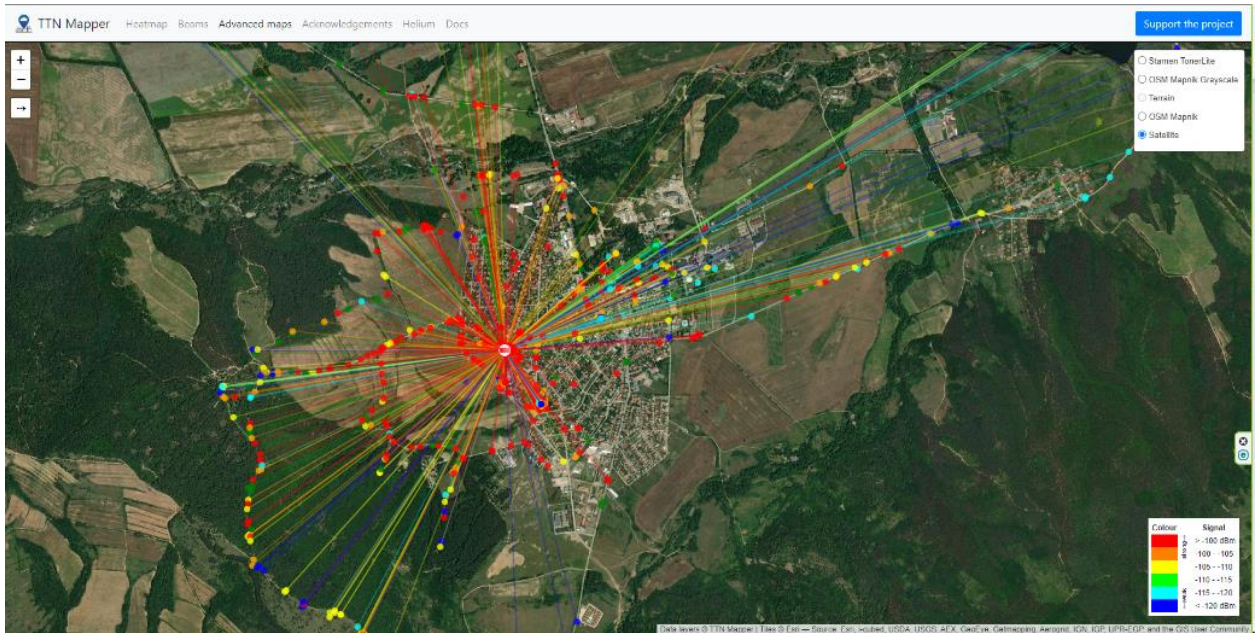


Fig. 3.37. Signal strength at different control points

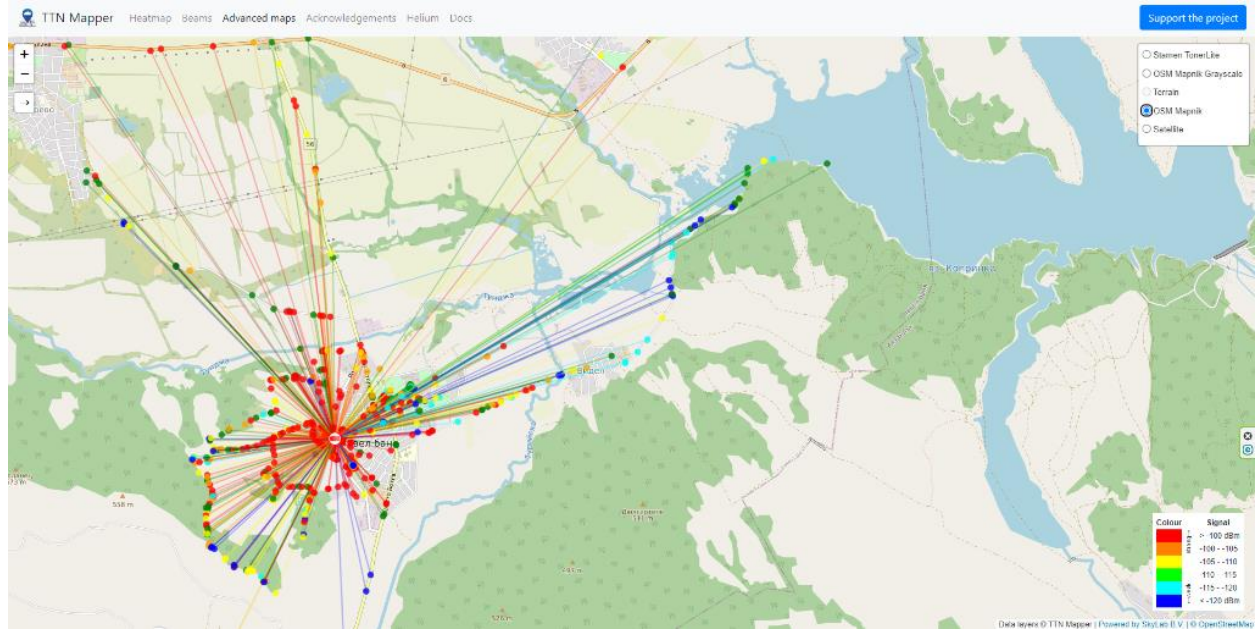


Fig. 3.38. Control points on the bank of the Koprinka Dam

The results of the radio coverage simulations are presented in Fig. 3.39A and Fig. 3.39B.

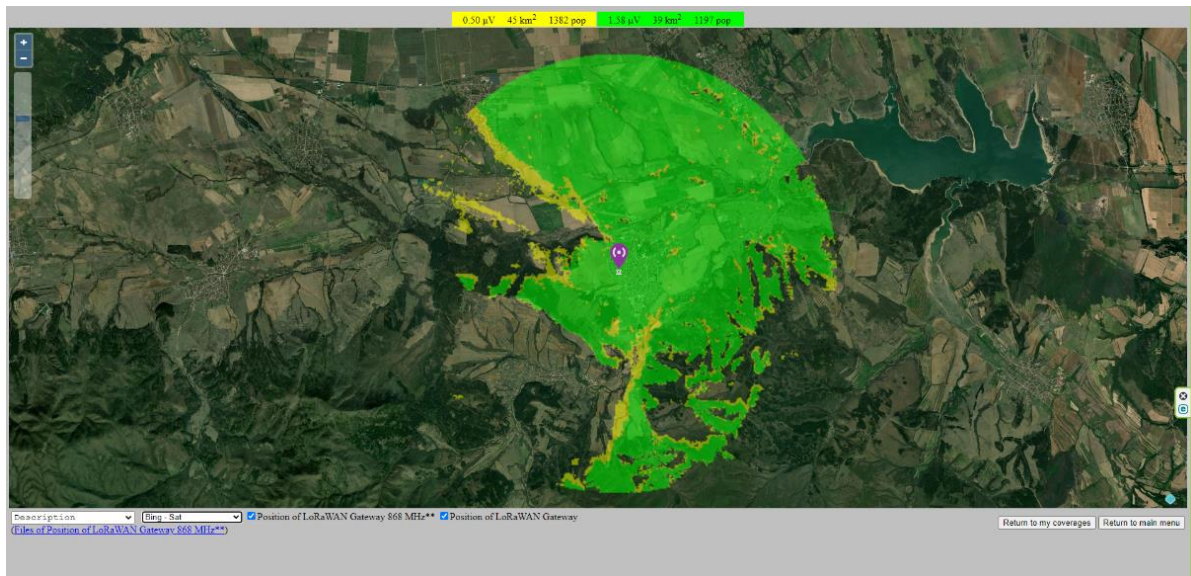


Fig. 3.39A. Radio coverage simulation results (satellite view)

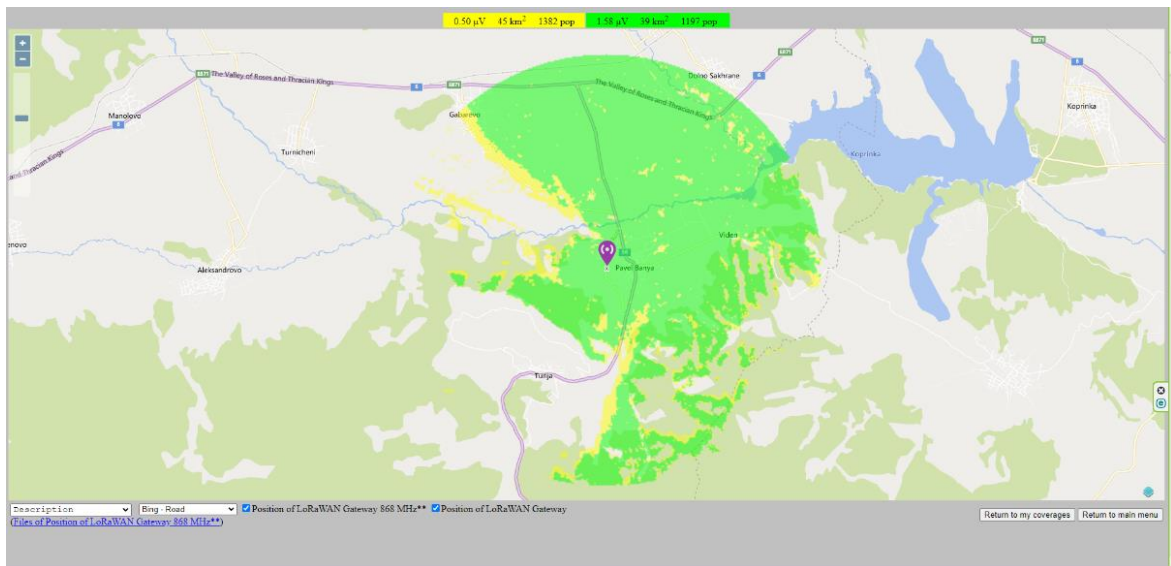


Fig. 3.39B. Radio coverage simulation results (topographical view)

### 3.8. Conclusions to Chapter Three

From the built RF Gateway and the experimental research done with it in a closed area, it can be summarized that the LoRaWAN technology can also operate in closed spaces, of course up to a certain distance, depending on the materials from which the building is built, their attenuation (absorption and reflection), which also determines the quality of radio coverage in this area. Research conducted in building 2 "Bajdar" of TU-Gabrovo proves that the radio waves manage to overcome the thick walls and slabs of concrete of the building in all control points of the measurements, with the RF Gateway located in all scenarios on floor 2 in the middle of the corridor.

The research carried out in an open area around the town of Pavel Banya was also successful and proved the technology's workability in urban and non-urban areas. The results are proven with practical studies compared with simulation studies in the same area of radio coverage with parameters of the end device and the RF Gateway, attenuation in the coaxial line, etc. taken into account .

The software tools used form a platform for low-energy wireless communications, which is flexible and universal in terms of different devices that can be integrated into it .

The use of LoRa modulation has been proven, with robustness and error-free data transmission, both in indoor and outdoor spaces, further research can also explore the modulation qualities in mobile devices, which will expand the spectrum of use of the technology.

## **CHAPTER IV. INVESTIGATING THE PERFORMANCE OF THE DATA TRANSMISSION PLATFORM IN LOW ENERGY WIRELESS COMMUNICATIONS**

### **4.1 Low-Energy Communications Platform Performance Analysis**

In future low-power wireless networks, there will be an ever-growing need to provide more capacity to accommodate the growing traffic demanded by consumers, industry, and academia. At the moment, network operators in Bulgaria have little interest in this type of network, but some of them have launched an NB-IoT network with paid mobile cards in 2020. The wireless technology discussed in the second and third chapters of the dissertation makes it possible to build a private network for data transmission, while it does not exceed the antenna power standards and health norms. The technology is suitable for start-up companies with an eye on the future and energy-efficient methods of transferring data over long distances. The other major plus that LoRaWAN technology has is the ability to build a Mesh transmission network and cover a larger range of services and devices. The affordability of the technology makes it suitable for building a network of RF Gateways using this technology by technically literate people, enabling them to become competitive in the service market, both in the "smart city" concept and in industrial automation and scientific research. The low-energy platform includes, a number of sub-units.

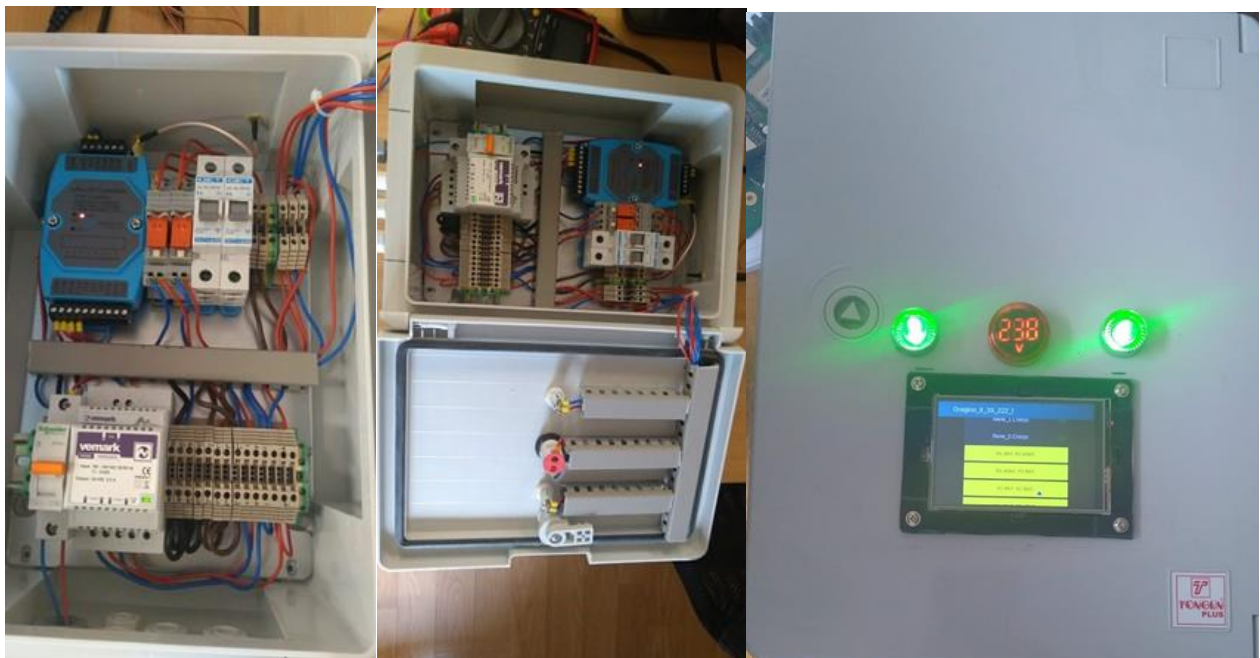
### **4.2. Exploration of the performance of low-energy end devices making up the low-energy platform**

The first of several low-power wireless devices that were created for the purposes of the thesis development is a Relay Switching Device with Feedback on the state of the contacts in the relays. The final device is built from the LoRaWAN module Dragino LT-33222, and two relay contacts with a maximum switching current of 5A at 240 V AC power supply. The module specification is described in [48]. The management of the relay contacts can be performed in two ways: automatically or manually. The idea behind the creation of the final device is automated and remote control of a circuit of urban street lighting. By measuring the current consumption of the loop, possible defective luminaires can be predicted according to the current consumption. The automatic execution logic for incl. and off of the relay contacts is controlled by the Node-Red environment, where on and off time configurations are set. The system has the option of adding a light sensor, which also controls the on and off time of the relay contacts. In this way, the efficiency of the platform is increased, as well as the optimal lighting time of the illuminator. In Fig. 4.1. the external view of the Dragino LT-33222 module can be seen .



*Fig. 4.1. LoRaWAN module for control and monitoring IO's.*

The module is housed in an electrical panel together with relay contacts, a power supply unit, and a single-board computer with a display that serves to visualize the web-based interface launched by Node-Red. Each button and field reads data from the device in real time and is visualized on the interface [A5]. The overall finished appearance of the final device can be seen in Fig. 4.2.



*Fig. 4.2. End device with 2 relay switches*

In Fig. 4.3. the web- based interface for controlling and monitoring data from the device can be seen.



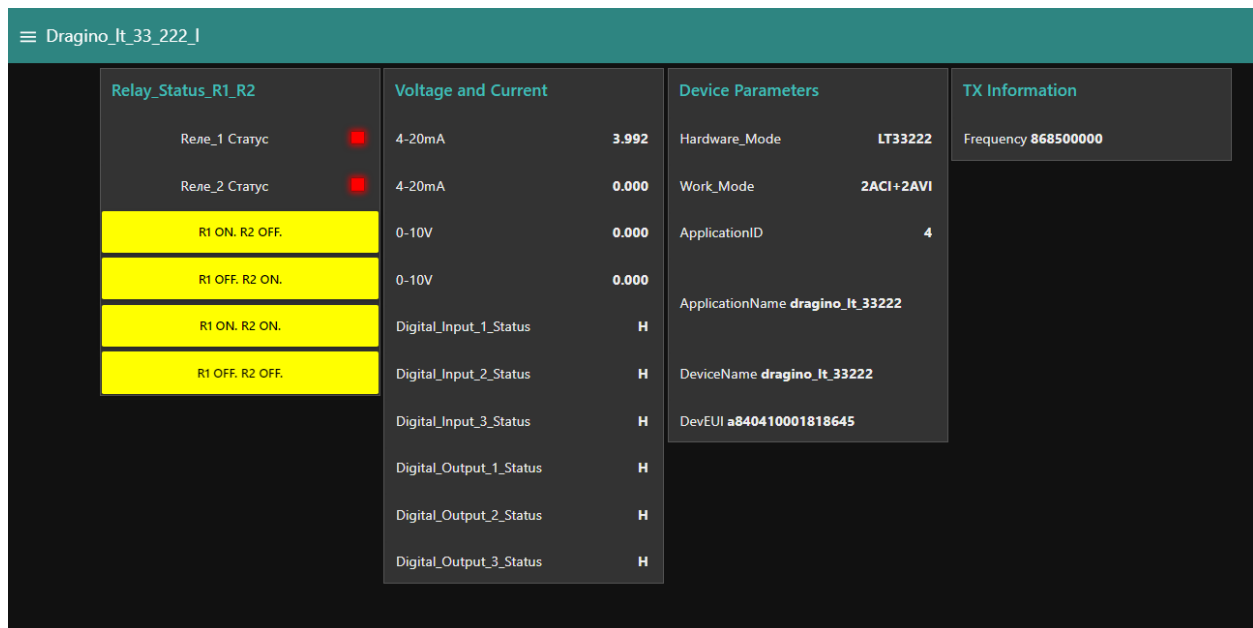


Fig. 4.3. Web- based interface for management and monitoring of end device

The following end device was recreated for the purposes of the dissertation development in order to automatically and autonomously control ventilation and aeration in a greenhouse installation. The device is powered by a battery source and the battery cells are charged by a solar panel that can be moved outside the greenhouse. The communication wireless device is MKRWAN1300[49] having LoRaWAN communication interface, it has a number of possibilities for connecting to it different types of sensors and measuring different values , which will serve to automate a certain process in the case of automated opening and closing of the greenhouse skylights at a certain temperature and humidity. A sensor for measuring soil moisture can be connected to the same controller, and an irrigation installation can be controlled using this information. The finished appearance of the final device can be seen in Fig. 4.4.

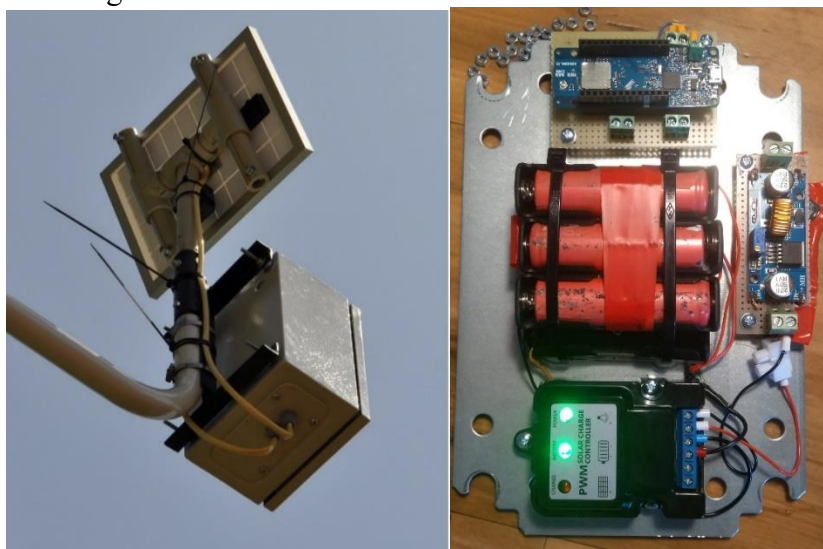


Fig. 4.4. An end device with a solar panel measuring the temperature and humidity of the air.

The data from this device is visualized in the Grafana software environment, and it can be visualized over a long period of time for the purpose of statistics and prediction of happening events. In Fig. 4.5. a period of preview data from the device can be seen.

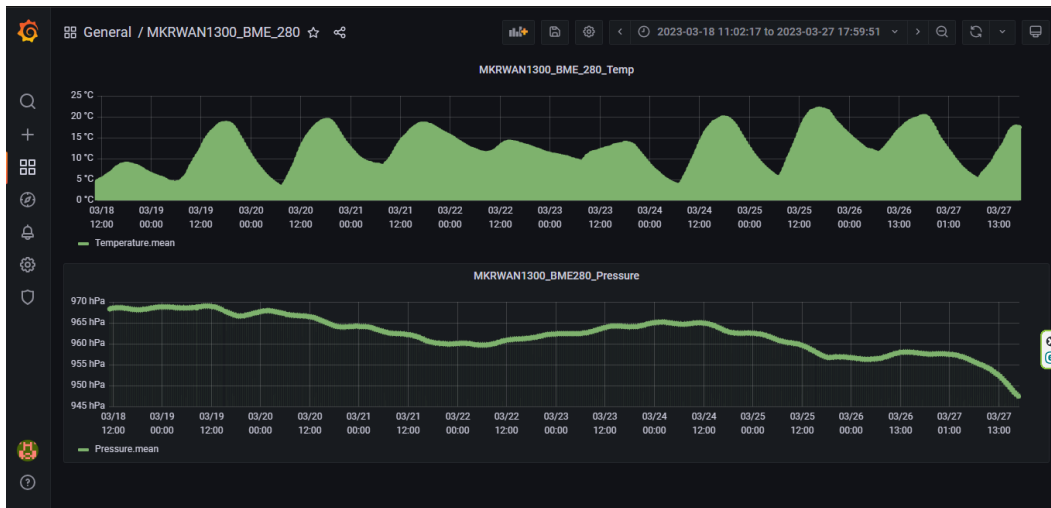


Fig. 4.5. Visualized data from the solar end device

The efficiency of the device is expressed in the fact that it is autonomously powered by a solar energy source, and the battery cells are provided with a greater capacity, due to possible changeable or cloudy weather, in order to ensure uninterrupted measurement of temperature and humidity. Its current consumption in the mode when no message is transmitted is 1.6 mA at 3.3 V DC power supply. Roughly speaking, this is a power worth 5.28 mW. This result has been achieved by using software libraries to "sleep" hardware components from the controller, at certain time intervals the device wakes up, takes a measurement and then sends the data, this moment happens for about 25 ms[53], and then again the hardware shuts down for a specified time. For a test load on the device, a pause time interval between transmissions of 15 minutes is set, i.e. the device sends information every 15 minutes in order to consume more energy in a 24 hour period and to determine if the battery cells are optimally calculated.

The last end device used in the wireless low-energy platform is intended for building automation, namely air conditioning control and automated shutter movement. It measures temperature and humidity again, but indoors. The device is made up of several modules connected together, and they are: RAK5005 [50] is a main board on which additional modular measuring or switching modules are included, the RAK11300 [51] is a communication module compatible with the LoRaWAN communication protocol, and the RAK1901 [52] temperature and humidity measurement module. The LoRaWAN antenna used is a patch antenna (low profile antenna) and is connected with an IPX connector via a thin coaxial cable to the main board. The device can also be placed in a suitable case manufactured specifically for the device, but for the purposes of the thesis development one was not purchased. The control of these air conditioners and blinds is performed by other devices that are not included in the thesis. The logical operations of monitoring the temperature, switching the air conditioner on and off or sending commands via an infrared module are performed in the Node-Red environment program. Fig. 4.6 depicts what the final device looks like with the modules plugged into the main board.

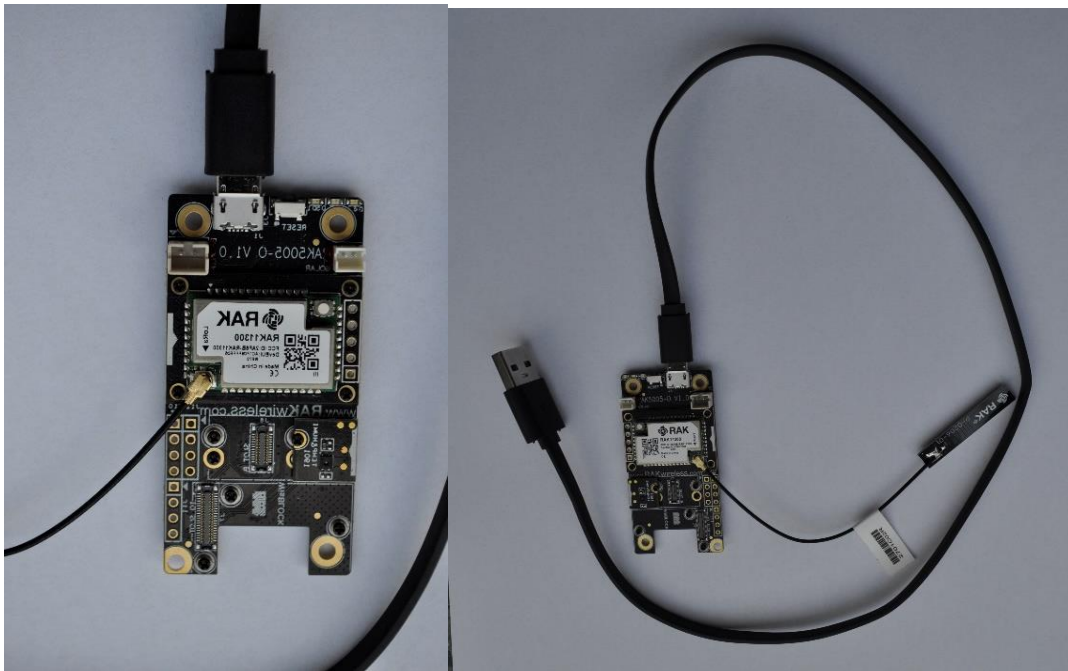


Fig. 4.6. End device RAK 5005 with communication module RAK 11300 and temperature and humidity sensor RAK 1901

The device is designed to be powered by a battery source of voltage and current, with the option of connecting to a solar panel to charge the batteries. The charge controller is integrated and soldered onto the printed circuit board. The MicroUSB interface is intended for configuration of the device, as well as for its power supply if battery cells will not be included. The device is modular, i.e. different types of sensors or measuring modules can be connected to the main board. The programming environments with which the device is configured are Arduino IDE[54] and PlatformIO [55], and for each sensor or measuring module there are software libraries created by the manufacturer.

#### **4.3. Exploration of network connectivity between different low-energy wireless networks**

When building several low-energy wireless networks in different buildings, areas, settlements or different Internet networks, it is good to store the data generated by the end devices in one main place, necessarily with copying of the data (backup). For this possibility and for the purposes of the dissertation work, network connectivity between different Internet networks using VPN tunneling was built. For convenience, the WireGuard [56] tunneling software product was used, as it can be installed manually on a number of operating systems, or as used in the case of the dissertation development, as a software package from the operating system of a MikroTik1100 router[57]. The concept of the VPN tunnel includes a server and users, in the case described in the dissertation development the MikroTik1100 is configured to be the server and the MikroTik3011[47] is configured to be the client. For detailed information on how to configure the two routers, see [58]. After this configuration between the two routers, the two networks can exchange information with each other. The only condition for this to be possible is that both routers have a public private static IP address so that they can be accessed from outside the local network. The two networks are located in two different cities in Bulgaria - Gabrovo and Pavel Banya. In Fig. 4.7. the Internet connectivity between the two low-energy networks is shown graphically.

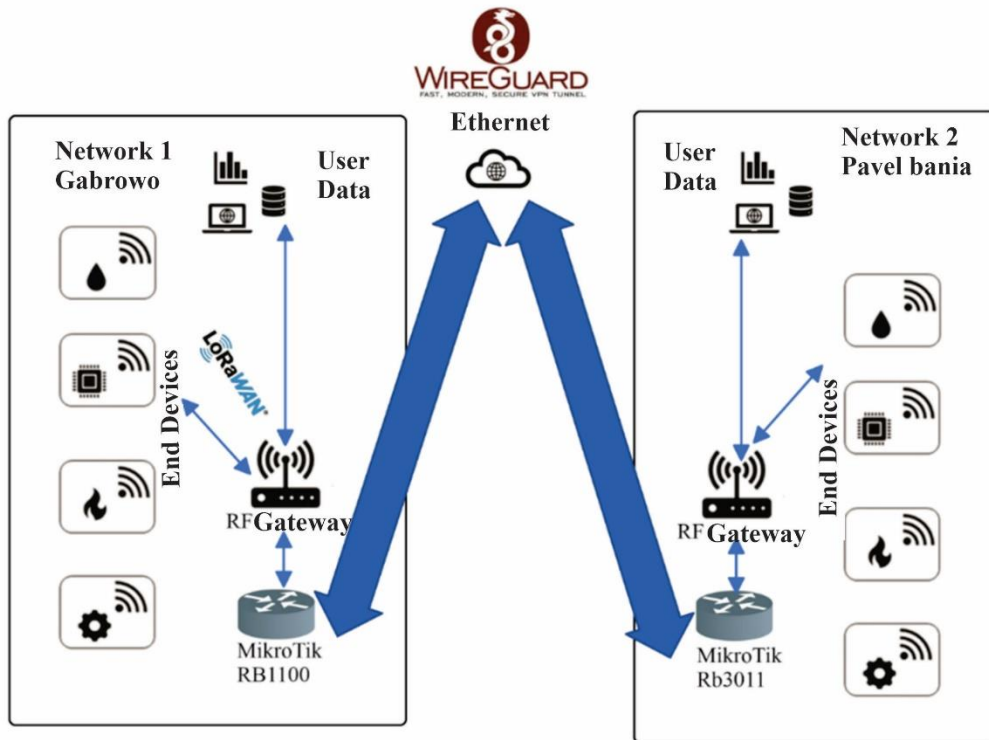


Fig. 4.7. Network connectivity between two low-power networks via WireGuard VPN

The common server for saving the two low-power networks data is located in Network 2 with a public static IP address with added protection elements for network security, and the RB1100 router is connected to it through the VPN tunnel see. Fig. 4.7.

#### 4.2.1. Configuration of tunnel connectivity between routers

##### WireGuard interface configuration

First, the WireGuard interfaces must be configured on both routers to allow automatic private and public key generation. The command is the same for both routers (entered separately in each router):

```
/interface/wireguard
add listen-port =13231 name = wireguard1
```

Now, when the interface details are printed, both the private and public keys must be visible to allow the exchange of TCP/UDP packets.

! No private key will ever be needed on the remote device - hence the name private.

### The configuration of router 1 RB1100 :

```
/interface/wireguard print
Flags: X - disabled; R - running
  0 R name = "wireguard1" mtu = 1420 listen-port =13231 private-key =
"yKt9NJ4e5qlaSgh48WnPCDCEkDmq+VsBTT/DDEBwfEo="
      public-key = "u7gYAg5tkioJDcm3hyS7pm79eADKPs/ZUGON6="
```

### The configuration of router 2 RB 3011:

```
/interface/wireguard/ print
Flags: X - disabled; R - running
  0 R name = "wireguard1" mtu = 1420 listen-port =13231 private-key =
"KMwxqe/iXAU8Jn9dd1o5pPdHep2blGxNWm9I944/I24="
      public-key = "v/oIzPyFm1FPHrqhytZgsKjU7mUToQHLrW+="
```

In order to be able to access information traffic from end devices from one network to another and vice versa, it is necessary to configure partner devices that determine who can use the WireGuard interface and what kind of traffic can be sent through it. To identify the remote peer, its public key must be specified along with the created WireGuard interface.

### The network 1 end device configuration is:

```
/interface/wireguard/peers
add allowed-address = 192.168.14.100 /24 endpoint-address = 37.143.223.
xxx endpoint-port =13231 interface = wireguard1 \
    public-key = "v/oIzPyFm1FPHrqhytZgsKjU7mUToQHLrW+="
```

! Routers on both networks must have a real public static IP address provisioned. In the case of the dissertation development, one router resides in the provider's network of Internet services Bulsatcom, and the other in the network of the provider Unics.

### 4.3.2. Testing tunnel communication between routers

To check tunnel connectivity between routers, the client application Wireguard [56] is used, its installation package is developed for different operating systems. After its installation, it is necessary to create or attach a configuration file describing which network the computer configuration should connect to and which addresses it can access. The installed and configured application can be seen in Fig. 4.8.

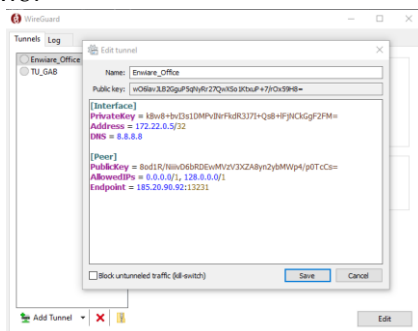


Fig. 4.8. Configuration file to connect to the VPN server

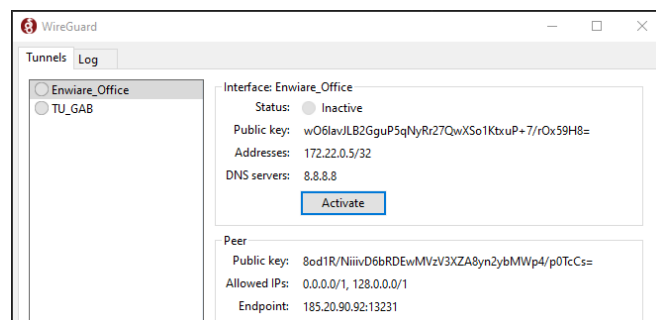


Fig. 4.9. Activation of VPN connectivity

After pressing Save and then the "Activate" button, the connection is established see. Fig. 4.9.

The connection can be tested by running the " ipconfig" command in a terminal window to check the communication of the network interfaces of the machine see Fig. 4.10.

```

Command Prompt
C:\Users\nicks\ipconfig

Windows IP Configuration

Unknown adapter Enwiare_Office:

    Connection-specific DNS Suffix  . : 
    IPv4 Address. . . . . : 172.22.0.5
    Subnet Mask . . . . . : 255.255.255.255
    Default Gateway . . . . . : 

Wireless LAN adapter Local Area Connection* 1:

    Media State . . . . . : Media disconnected
    Connection-specific DNS Suffix  . : 

Wireless LAN adapter Local Area Connection* 2:

    Media State . . . . . : Media disconnected
    Connection-specific DNS Suffix  . : 

Wireless LAN adapter Local Area Connection* 11:

    Media State . . . . . : Media disconnected
    Connection-specific DNS Suffix  . : 

Ethernet adapter Ethernet:

    Connection-specific DNS Suffix  . : 
    IPv4 Address. . . . . : 10.2.20.16
    Subnet Mask . . . . . : 255.255.0.0
    Default Gateway . . . . . : 10.2.0.1

Wireless LAN adapter Wi-Fi:

    Media State . . . . . : Media disconnected
    Connection-specific DNS Suffix  . : 

Ethernet adapter Bluetooth Network Connection:

    Media State . . . . . : Media disconnected
    Connection-specific DNS Suffix  . : 

```

Fig. 4.10. Checking established communication with the VPN network

### III. CONCLUSION

#### *Summary conclusions*

The search and experimentation with new low-energy communication protocols and improvement of channel coding, the use of new modulation methods and expansion of the frequency spectrum lead to interesting results related to the improvement of the efficiency and range of wireless coverage. The choice of the LoRaWAN protocol with high energy efficiency would allow monitoring important parameters or managing processes in remote locations in order to improve the quality of life. This, in turn, leads to an increase in the traffic of information in the communication channel.

The dissertation examines possibilities for data transmission over long distances using low-energy communication protocols. It is built a software platform for visualization, notification and alarming when a parameter changes. The presented topic leads to the creation of methodologies of procedures related to the creation of a low-energy communication platform in the context of the IoT concept.

#### *Publications related to the dissertation*

Regarding the reflection of the results of the dissertation work, six publications at international conferences and scientific publications, fully covering the minimum requirements regarding the considered criterion, have been presented. Three of the papers were presented at the International Scientific Conference "Unitech", two at the national conference "TechCo" and one at the peer-reviewed international journal "JESTR", one of them being independent, and the other five being prepared in co-authorship with the scientific supervisor and author team. Publications have been published in peer-reviewed collections from the international scientific conference "Unitech", the national conference "TechCo" and the peer-reviewed international journal "JESTR" in the study period 2019-2022, actually representing nearly 2/3 of the content of the dissertation.

## **IV. CONTRIBUTIONS TO THE DISSERTATION**

### **Scientific and applied contributions:**

❖ Proven message encryption algorithms using the low-energy LoRaWAN protocol have been established and researched to ensure the security and reliability of the transmitted data. The use of the linearly varying frequency (Chirp) method has been proposed, which contributes to greater data security by using a narrower frequency band applied in the wireless communications.

❖ An approach to determine the coverage efficiency of the low-energy wireless networks in a city environment has been proposed, based on determined indicators divided into three groups: reliability, protection and authenticity.

❖ An algorithm is proposed, presenting a practical approach for the implementation of an RF gateway and a sequence in conducting the experimental studies in an indoor and outdoor area.

❖ The influence of the signal-to-noise ratio on the quality of wireless coverage in a specific open area is investigated. A comparative assessment was made between the practically obtained results and the simulation results in the same radio coverage area, as the object of research are the parameters of the final device, the RF gateway, the attenuation in the coaxial line, etc.

### **Applied Contributions:**

❖ For the purposes of the dissertation work, an endmost device of a communication system has been practically implemented using the low-energy LoRaWAN protocol for wireless communications with remote control of electrical contacts with contacts status feedback.

❖ An endmost device with solar power has been practically realized, which has been tested over a period of 3 years under different weather conditions. Its economy has been achieved through the newly created software library for optimization of end device consumption during non-transmission of data.

❖ An opportunity of VPN connectivity of several routers with the implemented low-energy communication system using the LoRaWAN protocol has been proposed and was implemented, in order to store the data in a certain place. In such a case, the need to purchase additional hardware for data saving is eliminated, as potentiality for data processing, analyzing, visualizing and researching from one centralized point are provided too.

## **V. LIST OF DISSERTATION PUBLICATIONS**

A1. Angelov K., **N. Manchev** , P. Kogias and S. Sadinov, Design and Development of a Platform for Test Applications in LoRa/LoRaWAN, Journal of Engineering Science and Technology Review (JESTR), Kavala Institute of Technology ISSN: 1791-9320 , E-ISSN:1791-2377, 2019, pp. 17-21 (Scopus, SJR 0.189)

A2. Angelov K., **Manchev N.** , Sadinov S., Ivanov T., Planning and research of radio coverage area in LoRaWAN communication network, International scientific conference UNITECH 2020, November 20-21, 2020, Gabrovo, Volume I, p. I-263-268, 2020, ISSN: 1313-230X.

A3. Tashev P., K. Angelov, **N. Manchev** , Research and analysis of the performance of IoT communication protocols, Proceedings of the scientific conference TechCo– Lovech 2021, pp. 71 – 76, 2021 (ISSN: 2535-079X).

A4. Tashev P., K. Angelov, **N. Manchev**, Comparative performance analysis of LoRa modulation for IoT applications. UNITECH 2021 International Scientific Conference, November 19, 2021, Gabrovo, Bulgaria, vol. 1, pp. I-163-168, 2021 (ISSN: 1313-230X).

A5. P. Tashev, **N. Manchev** , K. Angelov, Research and comparative analysis of the performance of LoRa end devices for street lighting monitoring, TechCo 2022, p. 47 – 52 (ISSN 2535-079X).

A6. **N. Manchev**, Planning and research of a wireless coverage area in a LoRaWAN communication network. UNITECH 2022 International Scientific Conference, November 18-19, 2022, Gabrovo, Bulgaria, Volume 1, Pages I-196-201, 2022 (ISSN: 2603-378X)



**TITLE: „DEVELOPMENT AND RESEARCH OF A LOW ENERGY WIRELESS COMMUNICATION PLATFORM FOR THE INTERNET OF THINGS“**

**Author: Dipl. Eng. Nikolay Petkov Manchev**

**ABSTRACT:**

The dissertation deals with simulation models for low-power communications based on an analytical mathematical model describing the LoRaWAN communication protocol are presented, research is carried out and contributions related to the efficient use of the frequency spectrum, modulation type and channel coding are defined in order to achieve higher quality of service in low-power communication channels. Test setups have been implemented, experiments have been performed to evaluate the RF coverage and the success rate of the communication protocol in indoor and outdoor environments, and graphical relationships are presented giving information about the capabilities of the analytical model compared with results from the NS-3 simulation software.

The processing, transmission and reception of low-energy signals in low-energy transmitters and receivers has been studied concerning modulation, channel coding, multiplexing, synchronization, configuration, tuning and coordination of transceiving equipment. Different evaluation parameters and quality metrics such as equivalent isotropic radiated power (RSSI), field strength and signal-to-noise ratio are used as criteria to determine the quality of service, and the maximum allowable values of the SF spectrum broadening factors depending on the distance to the receiver are used in the criteria.

**Keywords:** Low Power Wide Area Network, LoRa, LoRaWAN, FSK, DSSS, CSS, SNR, RSSI, Dragino LT-33222, MKRWAN1300, Chirpstack, The Things Network