PLOVDIV UNIVERSITY
“PAISII HILENDARSKI”

FACULTY OF PHYSICS AND TECHNOLOGY
DEPARTMENT OF ELECTRONICS, COMMUNICATIONS AND INFORMATION TECHNOLOGIES

MEng. Stanislav Mitkov Assenov

DESIGN, RESEARCH AND OPTIMIZATION OF LOW ENERGY WIRELESS SENSOR NODES

ABSTRACT

of a dissertation for obtaining an educational and scientific degree
"DOCTOR"

Doctoral program:
"Automation of areas of the intangible sphere
(medicine, education, science, administration, etc.) "

Supervisor:
Assoc. Prof. Dr. Eng. Dimitar Mihailov Tokmakov

Reviewers:
Assoc. Prof. Dr. Eng. Slavi Yasenov Lyubomirov
Assoc. Prof. Dr. Eng. Radoslava Nikolova Gabrova

Plovdiv, 2021

The dissertation has a volume of 165 pages, including 96 figures, 26 tables, formed in the introduction, 4 chapters, general conclusions, scientific and applied contributions, a list of terms and abbreviations used, a list of the author's publications. The list of cited literature includes 165 titles, all in English.

The designations of the formulas, figures and tables in the abstract coincide with those in the dissertation.

The dissertation was discussed and directed for defense at a meeting of the Department Council of the Department of “Electronics, communications and information technologies” at the PLOVDIV UNIVERSITY „PAISII HILENDARSKI“ at 30.06.2021 г., Protocol № 31.

The defense of the dissertation will take place on 24.09.2021 from 11:00 am in the hall "COMPASS" of the PLOVDIV UNIVERSITY “PAISII HILENDARSKI” at a meeting of the scientific jury.

The materials for the defense of the doctoral student are available to those interested in the office of the Faculty of Physics and Technology at the PLOVDIV UNIVERSITY "PAISII HILENDARSKI", room 214.

Scientific jury: Prof. Dr. Todor Stoyanov Jamiykov
Prof. Dr. Nedyalko Todorov Katrandzhiev
Assoc. Prof. Dr. Slavi Yasenov Lyubomirov
Assoc. Prof. Dr. Radoslava Nikolova Gabrova
Assoc. Prof. Dr. Nikolay Atanasov Shopov

Author: MEng. Stanislav Mitkov Assenov
Title: **DESIGN, RESEARCH AND OPTIMIZATION OF WIRELESS LOW ENERGY WIRELESS SENSOR NODES**

Circulation: 30 pcs.

GENERAL CHARACTERISTICS OF THE DISSERTATION WORK

Relevance of the problem

The topic of this dissertation is related to the design, research and optimization of wireless sensor nodes with low power consumption. It is specified on the methods and hardware for optimizing the energy consumed by the wireless sensor nodes.

Taking into account the relevance and significance of the problem, which necessitates the search for new methods and approaches related to in-depth experimental research, attention was paid to the peculiarities of the power supply of wireless sensor nodes and the energy consumed by them.

Wireless sensor networks (WSNs) are made up of a large number of terminal sensor nodes that collect information from the external environment with sensors, then process the information and communicate with other neighboring nodes in the network. Wireless sensor nodes usually run on low-battery batteries. As manual replacement or recharging of batteries is not an easy, desirable or always possible task, energy consumption is becoming a very important issue in the development of these networks.

The total power consumption of the wireless sensor nodes includes measurement, data processing and radio transmission. There are complex problems in the design and implementation of wireless sensor networks that need to be addressed in various areas of research. One of the main problems is to ensure high tolerance to damage to wireless sensor nodes.

The interruption of the network is possible due to failures of nodes and communication channels for several reasons, the main one being the limited power supply of the node.

The life of wireless sensor nodes is limited by the life of the power supply, which with very few exceptions is a chemical battery, and the task of reducing energy consumption becomes more important than ever and the effectiveness of its solution directly affects the further development of wireless sensor networks.

One of the main requirements for wireless sensor nodes is their autonomy, which can be met and satisfied by reducing the power consumption of the end nodes.

In recent years, there has been a desire to achieve higher quality in terms of supplies and services provided by wireless sensor networks and nodes. This is a prerequisite for the expansion and implementation of additional low-energy end sensor nodes to the networks.

The overall theoretical and practical research reflected in the dissertation is aimed at the design and implementation of wireless sensor nodes with low power consumption. Various circuit solutions and ways to reduce the energy consumed by the wireless sensor nodes are proposed.

Purpose of the dissertation:

The aim of the dissertation is to design, research and optimize wireless sensor nodes by applying new approaches and technological solutions leading to a reduction in their energy consumption.

Tasks to achieve the goal:

1. Study of the existing methods and means for minimizing the energy consumption of the wireless sensor nodes.
2. Creation and research of an energy efficient model of LoRaWAN wireless sensor nodes with low energy consumption.
3. Design, research and optimization of wireless sensor nodes with low power consumption, hardware and software, including in its architecture modern powerful and low-energy microcontrollers.
4. Design and research of wireless sensor nodes with low energy consumption with harvester systems and battery-free power supplies.

Used research methods and tools:

The research methods used are from the scientific fields: theory of electronic - digital mixed circuits and microprocessor technology.

Implementation and practical applicability:

Innovative circuit solutions have been developed to reduce the energy consumption of the wireless sensor nodes and wireless sensor nodes with battery-free power supply have been implemented.

Publications on the topic:

The main results are published in: 6 issues in a collection of reports at National Conferences with international participation "Electronics 2020", "Electronics 2021", SEES, Sofia; ET 2019, ET 2020, SEES, Sozopol; TELECOM 2020, SEES, Sofia, 2 issues in collections of reports at the International Conference of Young Scientists, USB - Plovdiv. Seven of the publications are co-authored with the supervisor and one is independent.

Volume and structure of the dissertation:

The dissertation has a volume of 165 pages, including 96 figures, 26 tables, formed in the introduction, 4 chapters, general conclusions, scientific and applied contributions, a list of terms used and abbreviations, a list of the author's publications. The list of cited literature includes 165 titles, all in Latin

The designations of the formulas, figures and tables in the abstract coincide with those in the dissertation.

CONTENT OF THE DISSERTATION

Chapter 1. Literary review on the topic of the dissertation

Chapter One presents for discussion the design, research, and optimization of low-power wireless sensor assemblies. The results of the literature research on the existing technologies and modern methods for realization of wireless sensor nodes with low energy consumption are presented.

A study of the architectural features of wireless sensor nodes with low power consumption is presented.

A comparative analysis of the technologies for data transmission from wireless sensor nodes (LoRaWAN, Wi-Fi, Sigfox, BLE and others) is made.

A study of the power sources of wireless sensor nodes is presented.

The energy efficiency methods of wireless sensor nodes are classified.

Results of the literary research on the topic of the dissertation

The following problems can be defined from the conducted literature research:

1. Need for development of new methods and technological solutions, leading to reduction of the consumed energy from the final nodes.
2. The main problem is the limited power supply of the nodes, which creates a precondition for interruption or failure of the wireless network due to lack of power supply to the nodes.
3. The main requirement for wireless sensor nodes is their autonomy, which can be fulfilled by reducing the power consumption of the end nodes.
4. The battery supply is used as a source of energy for the final sensor nodes, which contradicts the requirement for their autonomy. Energy collection systems offer an alternative, although the problem cannot be completely avoided.

The object of the dissertation is designed and studied wireless sensor nodes with low energy consumption, and the subject of the dissertation is the optimization of the energy consumption of the wireless sensor nodes.

Chapter 2. Energy model of wireless sensor nodes with low power consumption

This chapter of the dissertation presents an energy model of wireless sensor nodes with low energy consumption. Emphasis is placed on the mathematical apparatus for determining the energy consumption of the individual components of wireless nodes. A new energy-efficient protocol for wireless sensor nodes has been proposed, reducing the power consumption of the nodes. An analysis of the energy consumption of a sensor node with low energy consumption was performed.

2.2. Energy model

Figure 2.2.1 illustrates the operating sequence of a wireless sensor node and allows to define the different operating modes that are controlled by the microcontroller of the sensor nodes.

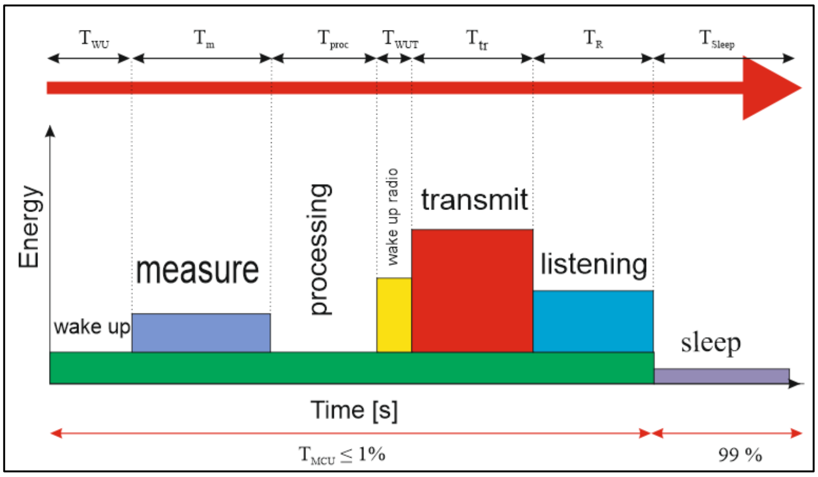

FIG. 2.2.1 Energy states and time intervals of sensor nodes

The presented energy model determines the different modes of operation of the communication sensor. The approach consists of considering all elements that are active during a certain time and inactive for the rest of the time cycle. Most of the time, the wireless sensor is set to low-power mode. The power consumed in this mode affects the power consumption of the sensor. All peripherals are supplied with the same voltage level equal to 3.0V

2.3. Energy efficient LoRaWAN protocol

It is concluded that sensor nodes that measure physical quantities in their environment (such as temperature, humidity, light, etc.) very often send the same data from their measurements for a certain period of time. This is due to the fact that physical quantities change with very small values at certain intervals. This transmission of the same measured values consumes too much energy to send this data, which shortens the battery life, and in fact this data is unnecessary.

Based on these conclusions, a new, more energy efficient protocol is proposed, aimed at reducing energy consumption by sensor nodes.

2.3.1. Energy model of the protocol

The energy model is based on the following scenario. The measured value from the sensor is processed by the microcontroller and sent by the transmitter, after which it switches to low energy mode. The next time it is activated, the microcontroller reads the data from the sensor and processes it. If the new read value is absolutely equivalent to the previous one, then the transmitter does not turn on and the microcontroller switches to low power mode again. In this scenario, the total Etotal energy of the duty cycle is:

$$E_{total} = E_{WU} + E_m + E_{proc} + E_{SLEEP}, \qquad (2.33)$$

In addition to optimizing the energy consumed by the sensor node, a method is proposed to reduce the data sent by the sensor. The number of bits sent is directly proportional to the energy consumed Etr, and hence to Etotal. In order to reduce the number of bits sent without changing the significant information, not the new measured value is sent, but only the difference from the previous one, expressed as a percentage difference. By using statistical tools to determine the confidence interval and the percentage change, the payload and therefore the total energy consumption can be reduced.

Send the percentage difference (Δ), which is calculated by formula (2.34):

$$\Delta i = [(X_i / X_{i-1}) - 1].100, \qquad (2.34)$$

Then the equation for the total energy consumption E_{total} is represented by a function of Δ:

$$E_{total}(\Delta) = E_{sleep} + E_{wu} + E_m + E_{proc} + \mu.(E_{wut} + E_{tr} + E_r), \qquad (2.35)$$

$$\mu = \mu(\Delta) = \begin{cases} 0, & \Delta = 0; \\ 1, & \Delta \neq 0; \end{cases}, \qquad (2.36)$$

where $\Delta = 0$ means that there is no difference in the successive measured values, and at $\Delta \neq 0$ it means that there is a difference and the new value must be sent.

2.3.2. The algorithm of the energy efficient protocol

The algorithm of operation of the energy efficient protocol is presented in Figure 2.3.1.

After the initialization, the microcontroller is woken up, and immediately after that the measured values are read by the sensor. The measured data is recorded in the variable "new_data", while the counter is incremented to count the first cycle.

The algorithm continues by checking that the data stored in the variables of the sensor are the same. In the first execution of the cycle, the data are not the same, whereby “data” is equated to the value measured by the sensor, the counter is reset, as the data will be sent. Calculate the percentage change, which is coded with a corresponding value (number and letter A for a positive value or B for a negative value). The data is sent to the application server, where it is decoded. After the transmission is completed, the sensor node waits for the two Rx message slots in the downward direction (DL). After the regulated message time has elapsed, the device is set to low power mode.

When the set time for "sleep" has elapsed, the microcontroller wakes up again and starts the execution of the next cycle.

If during the verification of the data from the previous measurement and the newly measured data, no differences are found, then the transceiver is not turned on and no data is transmitted.

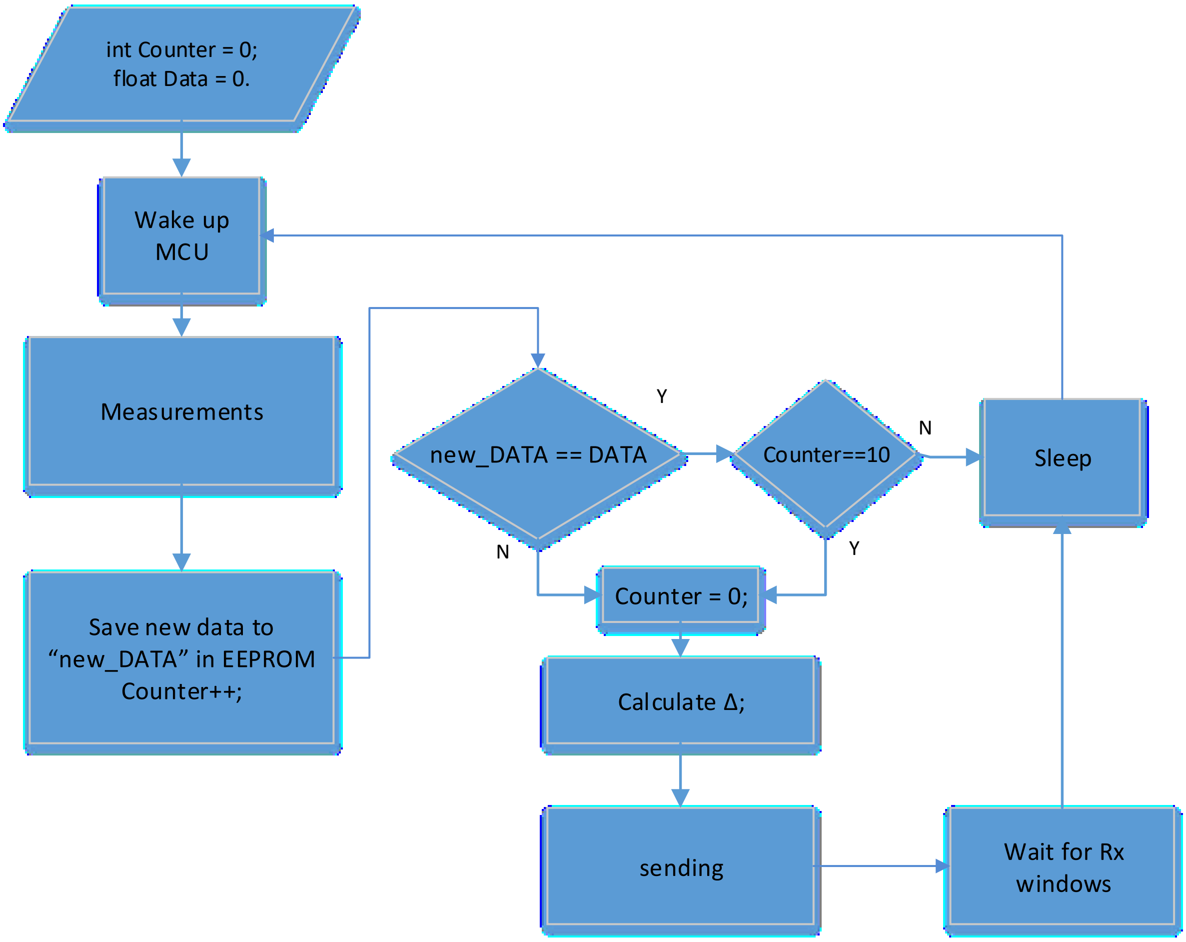

FIG. 2.3.1. Energy efficient protocol algorithm

2.3.3. Experimental results

To prepare the energy profile of the presented algorithm, a final LoRaWAN wireless sensor node powered by 3V batteries (2 x AA) was designed and manufactured. It is designed as a sensor node of class A. The current consumption and the time for execution of the different energy states of the sensor node - measurement, transmission, listening and falling asleep of the device are measured. Experimental results and tests were performed using Siglent SDS 1052 DL +. The sensor node measures the light in the workroom and sends the data to the LoRaWAN router. A total of 300 illuminance measurements were performed in the workroom.

Three sensor node operating scenarios have been developed to determine the energy consumption of each.

The first scenario uses the conventional algorithm of action, without any optimizations. The second scenario uses the method of reducing the bits sent by the transmitter, sending only the percentage difference "Δ". The third scenario uses the energy-enhanced algorithm presented in Figure 2.3.1. It uses both the method of reducing the number of bits sent and the method of switching off the transmitter at unambiguously measured sequential values ($\Delta = 0$).

In the representative sample of 300 illuminance measurements, 87 measurements are reported, in which the previous measured values are the same as the newly measured ones, therefore $\Delta = 0$. The diagram in Figure 2.3.4 summarizes the results of the total energy consumption of the sensor node from all 300 measurements in all three scenarios.

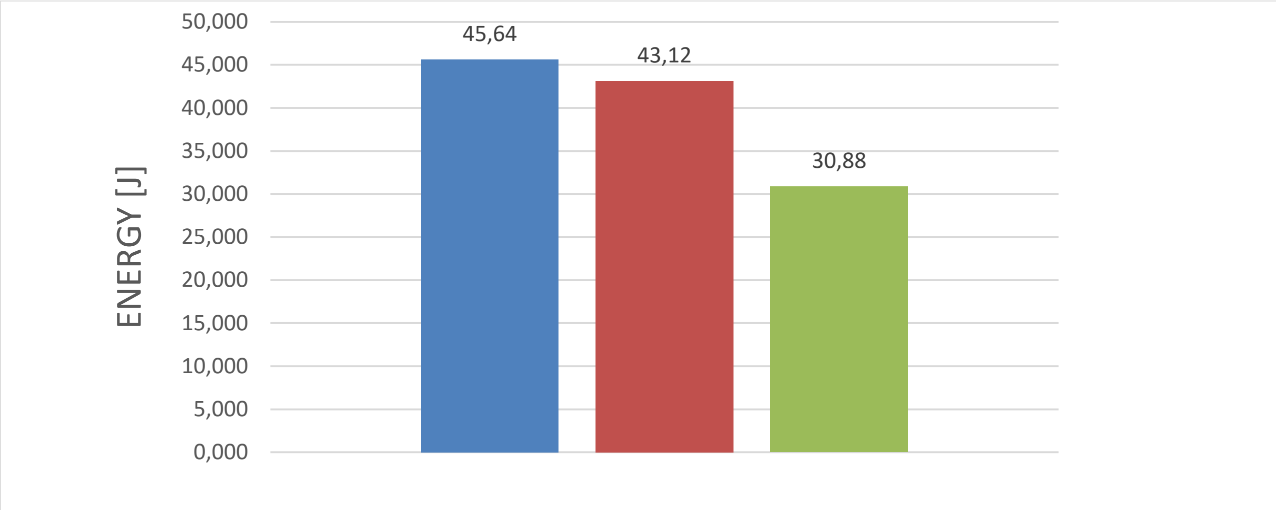

FIG. 2.3.4. Results of total energy consumption

As can be seen from the diagram, in the second scenario the total energy consumed decreased by 5.5% in contrast to the first scenario.

The difference between the first and third scenarios is significant. The reduced consumption is 32%. This significant reduction in power consumption also significantly increases the battery life of the sensor node.

The battery life of the sensor node in the different operating scenarios, as well as depending on the frequency of measurements that are performed for one day is visualized in Figure 2.3.6.

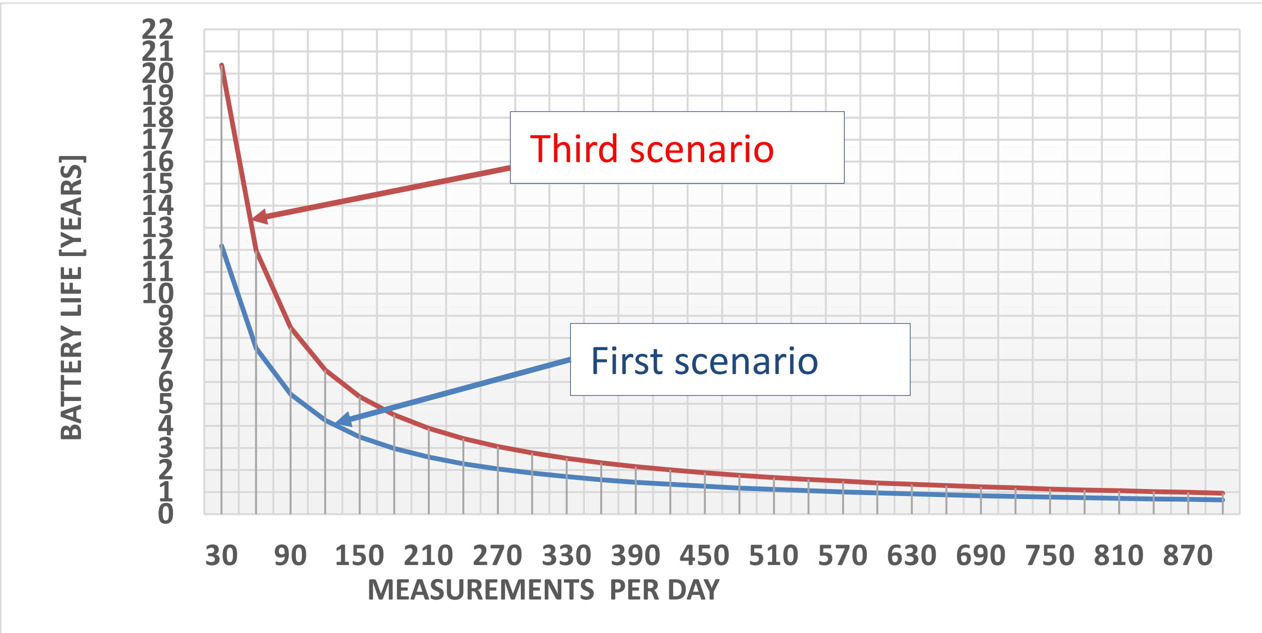

FIG. 2.3.6. Battery life depending on the number of measurements performed per day by the sensor node in the third action scenario

2.4. Conclusions

Energy consumption is one of the most limiting requirements for the design and implementation of wireless communication sensor nodes. An optimized energy model of sensor nodes using LoRa / LoRaWAN technologies is presented. This model allows the analysis of different modes and scenarios of LoRaWAN devices for a specific application of the Internet of Things, based on LoRaWAN class A. It is concluded that receiving a transmission acknowledgment consumes energy that reduces the life of the sensor node.

The developed model allows to study the impact of the hardware and the choice of software on the autonomy of the node. Numerical results show that the energy consumed varies with different LoRa / LoRaWAN parameters, such as propagation factor, coding rate, payload size and bandwidth. Optimizing these parameters is very important to reduce the power consumption of the sensor node.

The operating frequency of the microcontroller is important for optimizing the life of the sensor node. Increasing the frequency of the microcontroller affects the energy consumed, which reduces the autonomy of the sensor node. The use of numerical methods proves that there is a trade-off between the range of LoRaWAN communication, the propagation factor and the transmission power.

Using the proposed and implemented more energy efficient LoRaWAN algorithm, the energy consumption of the sensor nodes is significantly reduced. This increases the lifespan of the sensor node by several years.

In future developments, the energy model can be used in power management algorithms for communication of sensors powered by energy collection sources.

Chapter 3. Design and research of wireless sensor nodes with low power consumption

In this chapter of the dissertation are presented designed and studied wireless sensor nodes with low power consumption with different solutions that optimize the energy consumption of the end nodes.

3.2. Design and research of a wireless sensor node with ATMEGA328 microcontroller, LoRaWAN transceiver and ultra low power consumption

The architecture of the sensor node is shown in Figure 3.2.4. It consists of ATMEGA328 - 8-bit microcontroller with low power, CMOS, based on AVR® improved RISC architecture, RFM95W - transceiver LoraWan. The LoraWan transceiver is connected to the microcontroller via the SPI bus and three input-output pins.

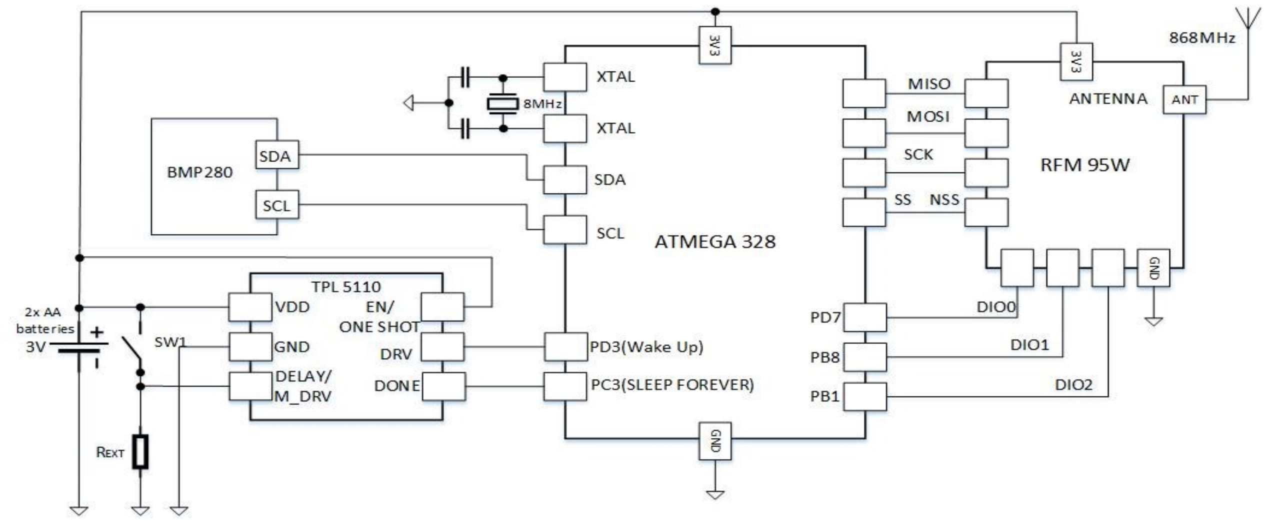

FIG. 3.2.4. Ultra low power sensor node hardware architecture with LoraWan interface

Consuming only 35 nA, the TPL5110 reduces the total current consumed by the system during the low-power mode of the sensor node. The 3V power supply to the sensor node is provided by two AA batteries. The choice of the ATMEGA328 microcontroller was made due to the ability to use the Arduino IDE development environment to develop software for low power sensor nodes.

The TPL5110 nano timer is used to wake the ATMEGA328 microcontroller from low power deep sleep mode via an external interrupt attached to pin PD3 of the microcontroller. The TPL5110 provides selectable time intervals from 100 ms to 7200s, adjustable by an external resistor (REXT) between the DELAY / M_DRV output of the TPL5110 and GND. The SW1 switch provides the possibility for forced waking up and exit from the low-energy mode of the ATMEGA328 microcontroller. Pressing the switch SW1 generates a signal at the DRV-PD3 pins, which is triggered as an external interruption of the microcontroller. BMP280 is a barometric pressure sensor. Data reading is performed via I2C digital communication interface. Its use in the architecture of the sensor node is dictated by its ultra low power consumption.

3.2.3. Experimental results

Measurements of the total current consumption Ic were performed at two sensor nodes in real operating mode. The sensor nodes are located at a distance of 800 m from the LoraWan gateway, which is located on the roof of Plovdiv University "Paisii Hilendarski" in Plovdiv, Bulgaria. There is no direct visibility between the sensor nodes and the LoraWan gateway. It relies only on reflected signals. The gateway is built with RAK831 Lora, based on a Semtech SX1301 hub. It is equipped with a 5dBi, 868MHz external antenna. Its data is forwarded to The Things Network's application servers using the Semtech UDP protocol, where uplink and downlink communication is exchanged in a pseudo-JSON format.

Both sensor inputs are programmed to perform identical tasks. The main difference between them is the presence of an external nano timer TPL5110 at one sensor node, which aims to wake up the ATMEGA328 microcontroller. The sensor node, which is not equipped with an external timer, relies mainly on the integrated WDT timer.

Based on the obtained results from the measurements of the two nodes, the diagrams shown in the following figures are constructed. They express the dependence of battery life in years on the number of measurements per day from the sensor nodes.

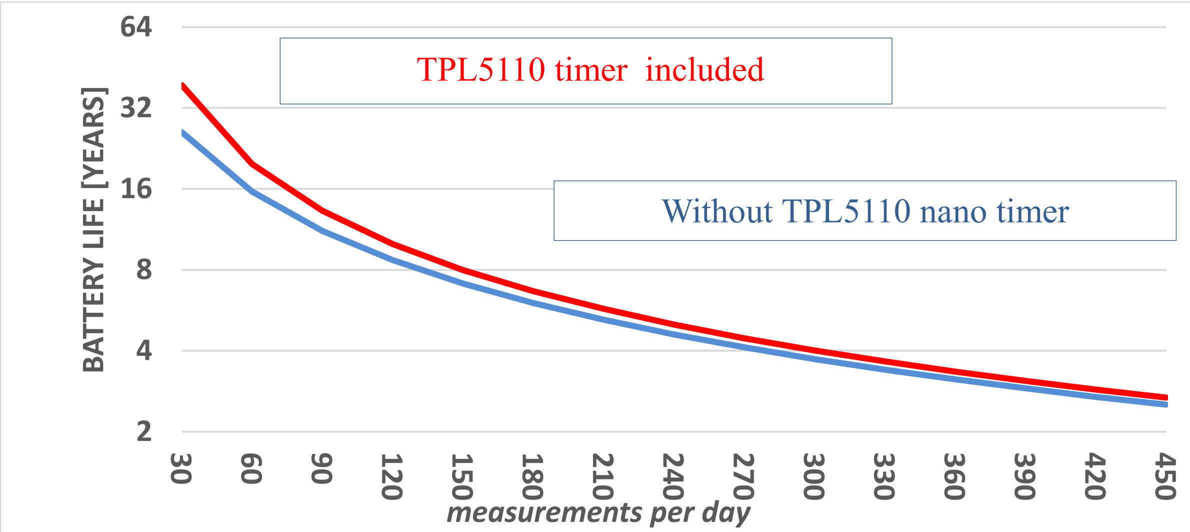

FIG. 3.2.12. Battery life of the two sensor nodes depending on the number of measurements per day

3.3. Design and research of WI-FI sensor node with low power consumption

Figure 3.3.3 shows the schematic diagram of the implemented Wi-Fi sensor node. The designed and implemented wireless WI-FI sensor node for measuring temperature and relative humidity, using MQTT and Node-Red technologies for transmission and visualization of the measured data, is realized by "ESP EASY" firmware, developed especially for ESP 8266 microcontrollers, which firmware optimizes the power consumption of the wireless sensor node.

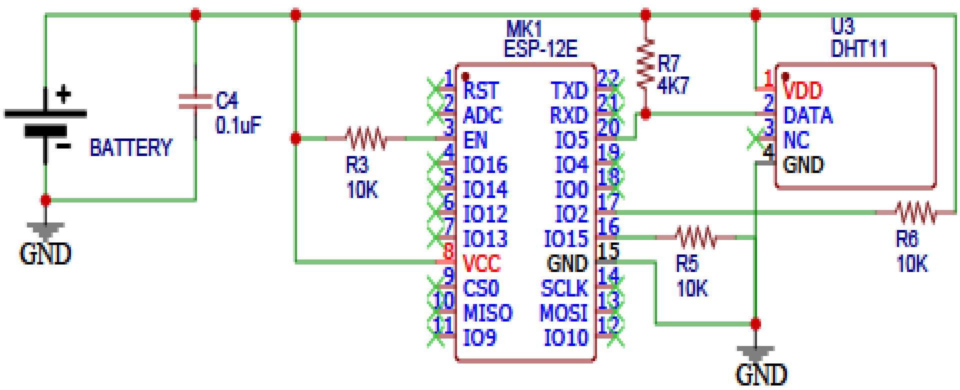

Fig.3.3.3. Schematic diagram of a sensor node with Wi-Fi interface

3.3.4. Experimental results obtained from the study of WI-FI sensor node with low power consumption

To evaluate the designed WI-FI sensor node with low energy consumption, measurements of the total current consumption (Ic) of two sensor nodes in real operating modes were performed. One sensor node has ESP Easy firmware implemented, and the other has NodeMCU stock firmware.

The measurement was performed using an Siglent SDS 1052 DL + oscilloscope and by measuring the voltage drop on a reference shunt resistor with a value of 1Ω and an accuracy class of 0.01%.

Table 3.3.1 presents the comparison of the results of the measurements made for two sensor nodes of the total current consumption in the different energy states of the nodes.

Table 3.3.1. Measurement results made for two sensor nodes

ESP 8266 sensor node with deep sleep and ESP Easy firmware		**ESP 8266 sensor node without deep sleep and ESP Easy firmware**	
Current consumption Ic		Current consumption Ic	
DEEP SLEEP mode	18.6 mA	Active mode without DEEP SLEEP mode	72 mA
Measurements	24.8 mA	Measurements	28.5 mA
Sending data	177.6 mA	Sending data	198.8 mA

Based on the presented results and the performed calculations regarding the energy consumed by the first sensor node, the dependence of the battery life in days on the number of measurements performed for one day is constructed, shown in Figure 3.3.7.

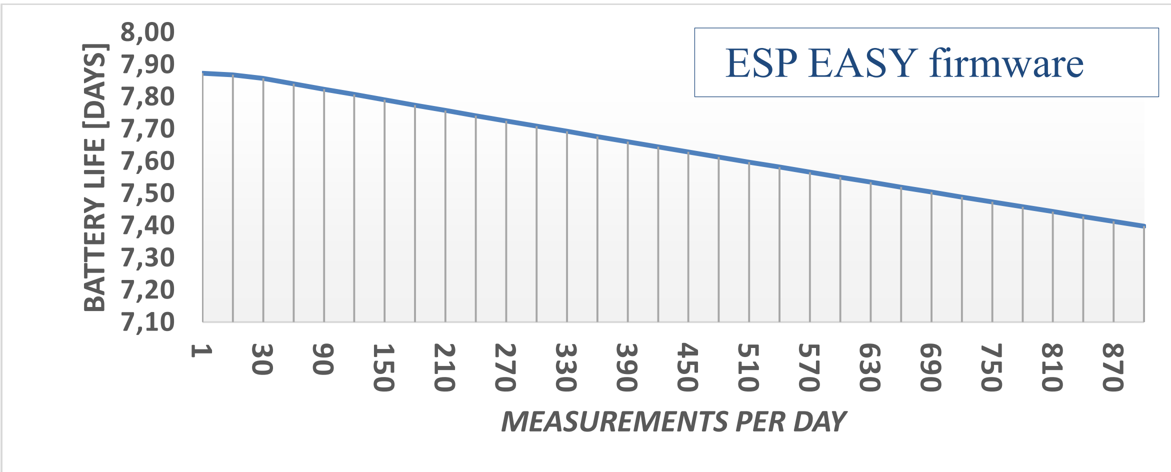

FIG. 3.3.7. Battery life in days depending on the number of measurements per day for the first sensor node

Based on the presented results and the performed calculations regarding the energy consumed by the second sensor node, the dependence of the battery life in days on the number of measurements performed for one day is constructed, shown in Figure 3.3.8.

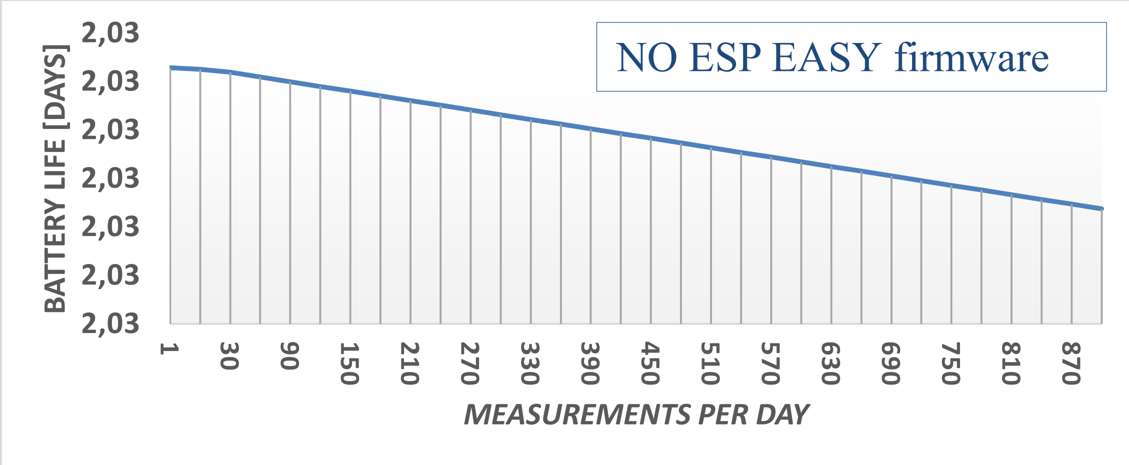

FIG. 3.3.8. Battery life in days depending on the number of measurements per day for the second sensor node

3.4. Design and research of a sensor node with ultra low energy consumption, with FRAM and nano timer

3.4.2. LoRaWAN hardware architecture sensor node with ultra low power consumption, with FRAM memory and nano timer

A hardware implementation of a final sensor node with LoraWan interface with ultra low power consumption is presented.

The final sensor node is powered by batteries (2xAA 1.5V batteries) using a nano timer to reduce the total power consumption of the sensor node. The presented wireless sensor node uses FRAM memory, which is designed to store NwkSKey and AppSKey needed by the node to transmit data from the sensor to the LoRaWAN network.

The architecture of the sensor node is shown in Figure 3.4.1.

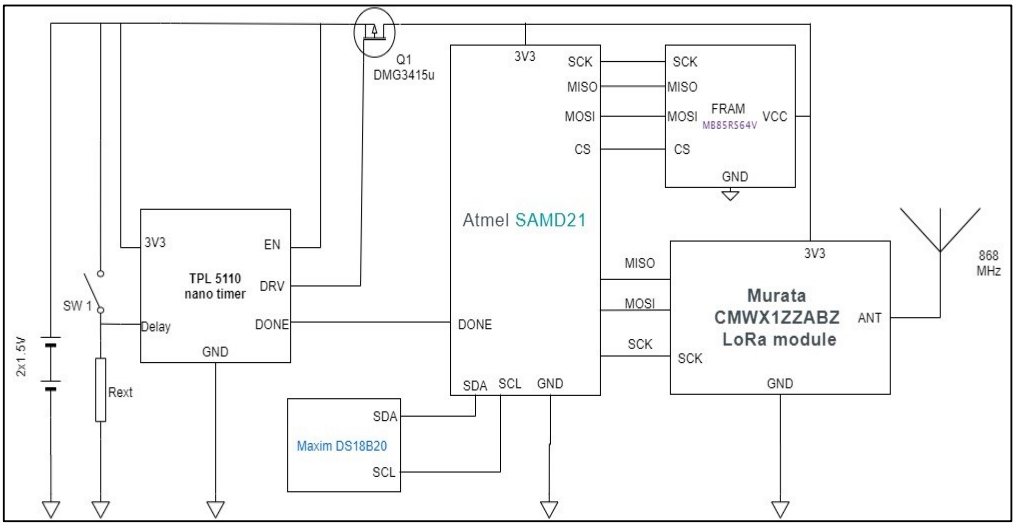

FIG. 3.4.1. Hardware architecture of sensor node with ATMEL SAM D21 and LoraWan interface

It consists of a low-power ATMEL SAM D21 microcontroller using a 32-bit processor. The choice of the ATMEL SAM D21 microcontroller was made due to the fact that the microcontroller has two SPI communication interfaces, which are necessary for communication with the LoRaWAN Murata modem and the FRAM memory. In addition to the choice, it is possible to use the Arduino IDE development environment to develop software for sensor nodes, as well as for supported low-power modes.

Wireless communication is performed by the Murata CMWX1ZZABZ LoraWAN transceiver, which is connected to the microcontroller via the SPI interface.

An important component of the architecture is the FRAM memory - MB85RS64V. Because the device is completely turned off during sleep, FRAM is used to store LoRaWAN session keys and frame counters.

FRAM memory is a non-volatile memory and is able to store data without using a spare battery, unlike what is needed for DRAM. The DS18B20 digital thermometer is connected directly to the ATMEL SAM D21 microcontroller. The TPL5110 nano timer is a low power timer with a built-in MOSFET driver. Consuming only 35 nA, the TPL5110 can activate the power line and drastically reduce the total standby current of the system during sleep. Such energy savings allow the use of significantly smaller batteries for wireless sensor applications.

The power supply of 3V voltage of the sensor node is provided by two AA 1,5V batteries.

3.4.4. Experimental results obtained from the study of the sensory node

The sensor node is located at a distance of 100 m from the LoraWan gateway, which is positioned on the roof of PLOVDIV UNIVERSITY "PAISIY HILENDARSKI" in Plovdiv. Direct visibility is provided between the sensor node and the gateway, which is implemented with RAK831 Lora, based on the Semtech SX1301 hub. The gateway is equipped with a 5dBi, 868MHz external antenna.

The ultra-low-power sensor node with LoraWan interface uses over-the-air authentication (OTAA) with The Things Network servers only for the first time when the sensor node is turned on or if no data is stored in the random access ferroelectric memory. After the join procedure, NwkSKey and AppSKey are written to the FRAM memory for future and subsequent connection to the TTN servers using ABP activation. The following figure shows the realized wireless sensor node.

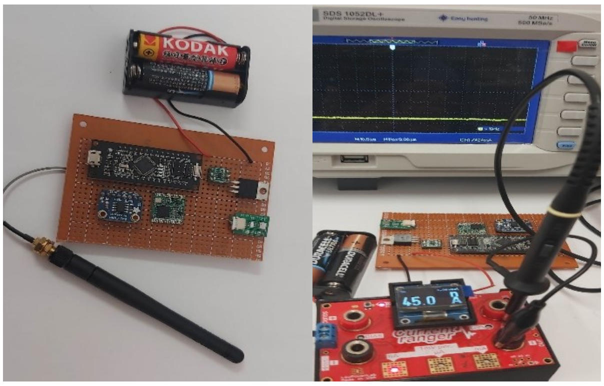

Fig.3.4.6. Implemented wireless sensor node

The results of the measurements of the total current consumed by the sensor node are summarized in Table 3.4.1.

Table 3.4.1. Results of measurements of the designed node

LoRaWAN sensor node with MCU ATMEL SAM D21 and FRAM		
LORA, "SF9BW125", CR: "4/5","rssi": -107dB, "snr": 11dB		
Power mode	**Time**	**Ic**
Timed with TPL5110, MCU off	5 min	45 nA
Data measurement and calculating	4.3 sec	20.4 mA
Sending data	2 sec	25.6mA
Waiting for Rx windows and sleep preparation	1.2 sec	20 mA

Figure 3.4.7 presents an oscillogram of the performed experimental measurements of current consumption Ic, from the sensor node in real operating mode and with parameters Lora modulation "SF7BW125".

The transmission duration is 2s with a total current consumption of 25mA, with a spreading factor of 7, a bandwidth of 125KHz and a coding speed of 4/5.

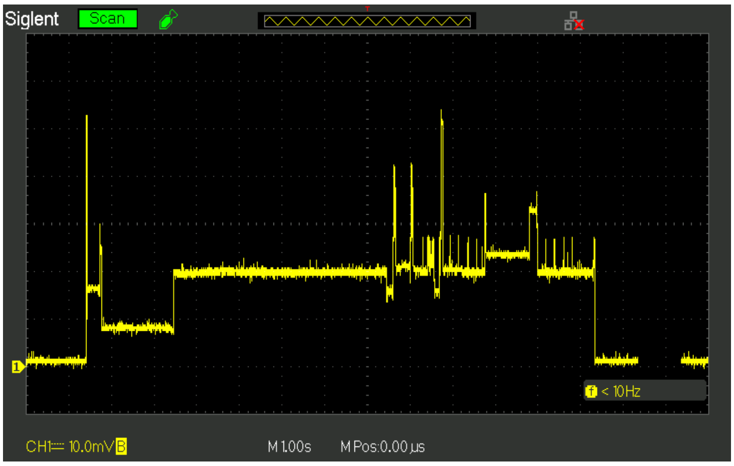

FIG. 3.4.7. Oscillogram of current consumption Ic from LoRaWan node in operating mode, with modulation Lora and "SF7BW125"

In order to illustrate and demonstrate the low power consumption of the designed sensor node, a second sensor node that does not use a nano timer TPL5110 and FRAM memory to store the activation keys is also tested.

To illustrate and analyze the results obtained for the two sensor nodes, the graphical dependence is constructed, presented in Figure 3.4.11. It gives reason to draw the following conclusion: with the sensor node using TPL5110 nano timer and FRAM memory, in order to store data, the battery life increases dramatically with the frequency of translated measurements from the sensor node per day from 1 to 120 measurements.

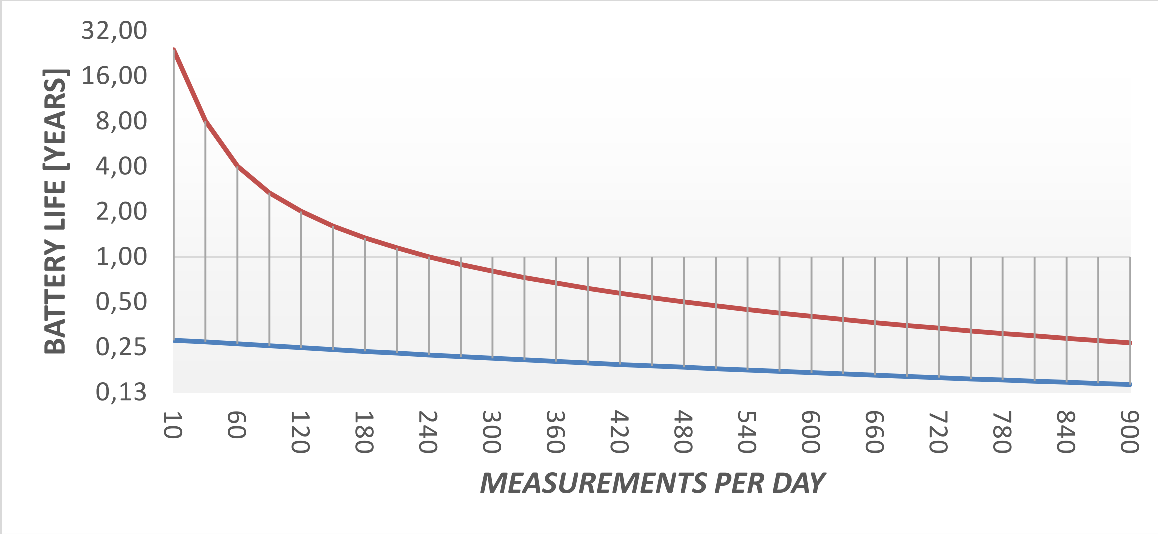

FIG. 3.4.11. Comparison of battery life in days depending on the number of measurements per day for the two sensor nodes

3.5. Design and optimization of power consumption of a wireless sensor node with LoraWan transceiver and ESP32

This part of the dissertation presents a method for optimizing the power consumption of a sensor node with LoraWAN interface and ESP32 microcontroller. Using the Ultra-Low-Power (ULP) coprocessor included in the structure of the ESP32 microcontroller to perform measurements, instead of the 32-bit LX6 Xtensa® microprocessor, reduces the power consumption of the microcontroller.

3.5.2. Hardware architecture of the wireless sensor node

The designed LoRaWAN sensor node is of class A. In fig. 3.5.1. the hardware architecture of the designed sensor node with ESP32 microcontroller is presented. The structure of the final sensor node is realized by using an Espressif ESP32 microcontroller. The next component is the BMP280. Another component of the hardware architecture is the SEMTECH SX1276 transceiver, which connects to the ESP32 microcontroller via the SPI (Serial Peripheral Interface) communication interface. SEMTECH SX1276 is a transceiver with low power and long range.

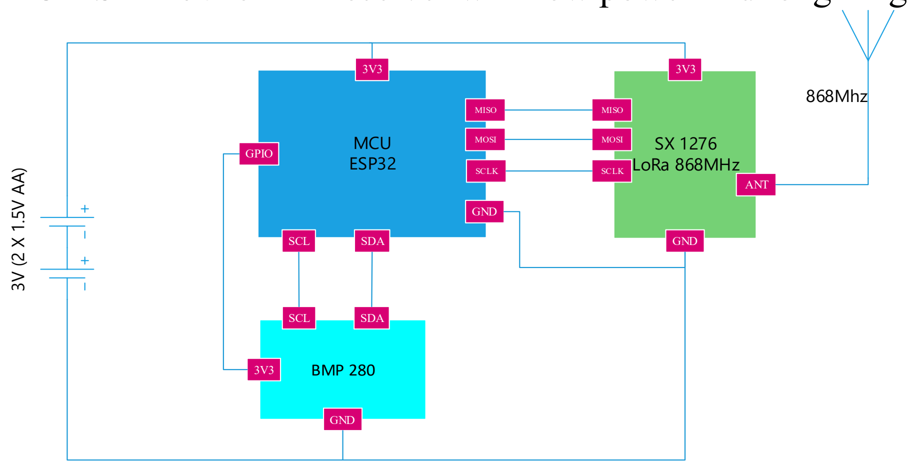

FIG. 3.5.1. Hardware architecture of wireless sensor node with ESP32

3.5.4. Experimental results

Two identical prototypes of wireless sensor assemblies using the Espressif ESP32 microcontroller, designed to collect and send data from a BMP280 temperature and barometric pressure sensor, have been implemented. The collected data is sent via a LoraWAN SX1276 transceiver to the LoraWAN gateway. The gateway is built by RAK831 Lora, based on the Semtech SX1301 hub.

To illustrate and analyze the obtained results for the two sensor nodes, the graphical dependence is constructed, presented in Figure 3.5.14. It gives reason to draw the following conclusion: in the case of the sensor node using the ULP coprocessor for reading data, the power consumption is 22.9% lower than in the case of the sensor node using the 32-bit LX6 Xtensa microprocessor. There is a significant difference in the frequency of measurements per day from 60 to 360 measurements.

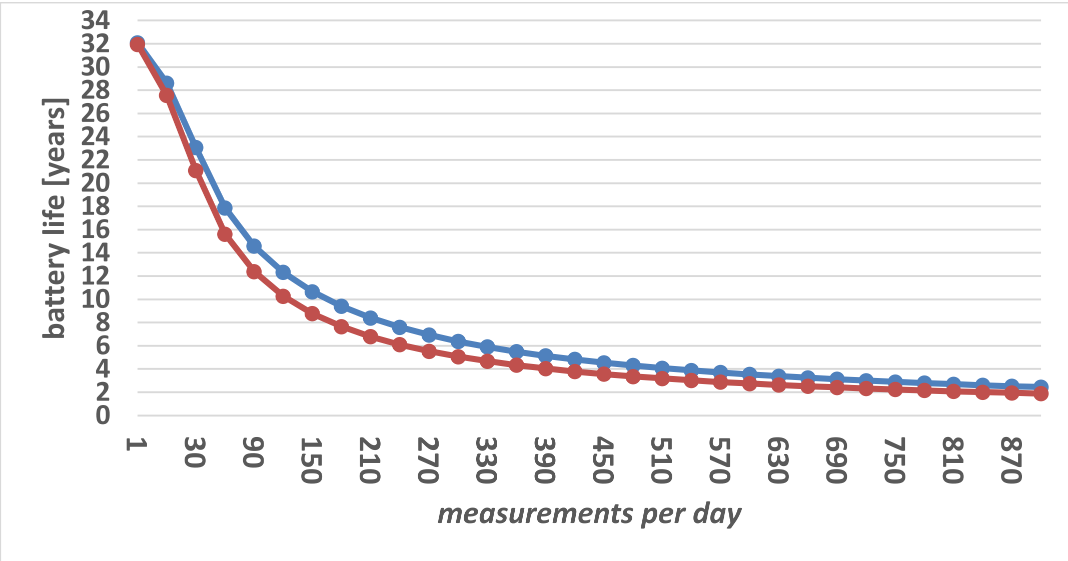

FIG. 3.5.14. Comparison of battery life in days depending on the number of measurements per day for the two sensor nodes

3.6. Conclusions

For each of the presented wireless sensor nodes, experimental studies of their conventional implementations and their optimized hardware and software solutions were performed in order to achieve low power consumption and extend the life of their batteries.

For an objective assessment of the presented wireless sensor nodes, their energy consumption and the lifespan of their battery power supply are taken into account.

For the designed LoRaWAN wireless sensor node with ATMEGA328 microcontroller, the test results show a significant difference in the small number of measurements per day from the sensor nodes. The proposed sensor node that uses the TPL 5110 nano timer can reach a theoretical battery life of up to 512 years, while the conventional sensor node without a nano timer achieves a battery life of up to 64 years.

For the Wi-Fi wireless sensor node with the ESP8266 microcontroller with the implemented "ESP Easy" firmware, the research results show that the battery life is increased by 300% compared to the conventional sensor node. The realized sensor node with ESP Easy firmware, with its energy advantages, displaces the application of conventional sensor nodes.

For the LoRaWAN wireless sensor node with ATMEL SAMD21 microcontroller, with FRAM memory and TPL5110 nano timer, the research results show that the battery life increases dramatically with the frequency of translated measurements from the sensor node per day from 1 to 120 measurements.

For the LoraWAN wireless sensor node with ESP32 microcontroller, the research results show that the sensor node using the ULP coprocessor for reading data has 22.9% less power consumption than the sensor node using the 32-bit LX6 XP microprocessor.

There is a significant difference in the frequency of measurements per day from 60 to 360 measurements.

CHAPTER 4. OPTIMIZATION OF WIRELESS LOW ENERGY SENSOR NODES THROUGH HARVESTER SYSTEMS

This chapter presents approaches and methods for realizing battery-free wireless LoRaWAN sensor nodes with low power consumption. The implementation of battery-free wireless sensor nodes is based on the use of harvester systems to collect energy from the environment and store this energy in supercapacitors to replace the traditional battery power supplies of the end wireless sensor nodes.

Measuring and optimizing the current consumption and execution time of various tasks of IoT applications is crucial for the proper operation of devices without batteries.

The main advantage of the wireless sensor nodes implemented in this chapter of the dissertation is the extremely low value of energy consumption, which allows the use of a supercapacitor and solar energy collection to power the microcontroller and sensors. An integrated circuit for generating and collecting nano energy LTC3588, a solar panel and a supercapacitor was used to power the wireless sensor node.

A model of a sensor node without batteries in the middle of MATLAB / SIMULINK has been created. Simulation studies have been conducted offering optimal approaches for selecting a supercapacitor to ensure autonomous operation of the device.

4.1 Simulation and optimization of energy model of LORAWAN sensor nodes without batteries

4.1.2. Wireless sensor node architecture without battery

For the realization of the energy profile of a sensor node without batteries, a final wireless sensor node with LoRaWAN interface, designed by a solar energy collection system, has been designed. The architecture of the sensor node is shown in Figure 4.1.2. It consists of ATMEGA328P - low microcontroller power and HOPE RFM95W - LoRaWan transceiver. The collected energy is stored in a supercapacitor 3.6V, 1.5F; connected to the harvester output. A 10V solar panel is used for a power source connected directly to the LTC3588 harvester. The choice of the ATMEGA328 microcontroller was made due to the ability to use the Arduino IDE development environment through which the sensor node software was developed.

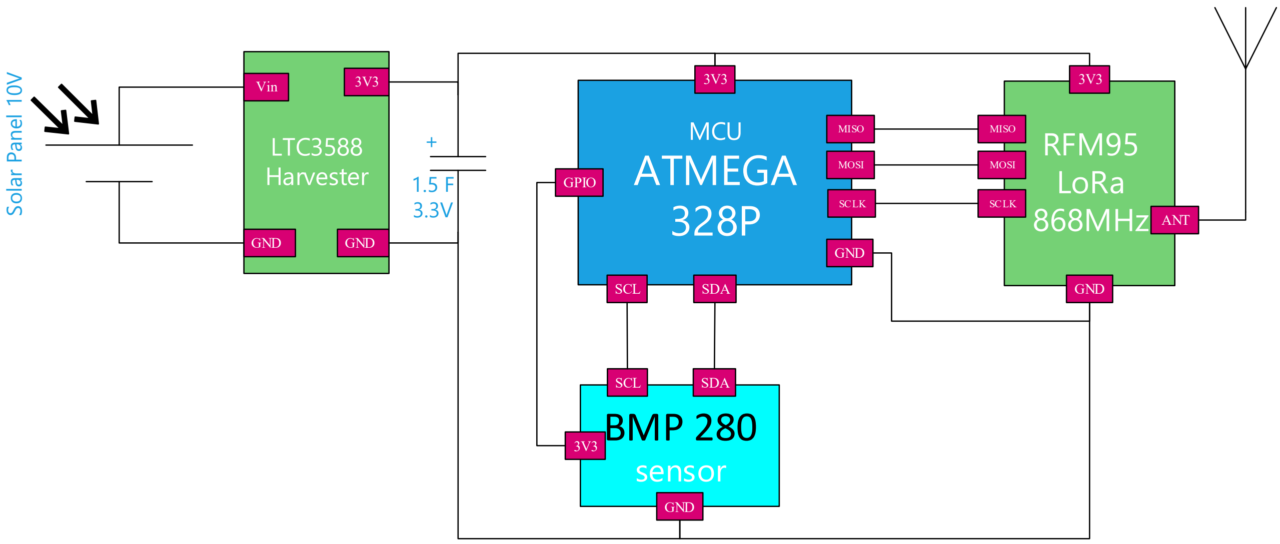

FIG. 4.1.2. LoRaWAN sensor node architecture without batteries

4.1.3. Theoretical model for a device without LoRaWAN batteries

Figure 4.1.3 shows an equivalent electrical model of a battery-free terminal node that looks at the three main parts of the sensor node: the harvester (power source), the capacitor (energy storage), and the power consumer (ie, MCU, radio, and sensors). It is noted that the use of a power source is more realistic for popular energy-gathering harvesters, such as photovoltaic cells.

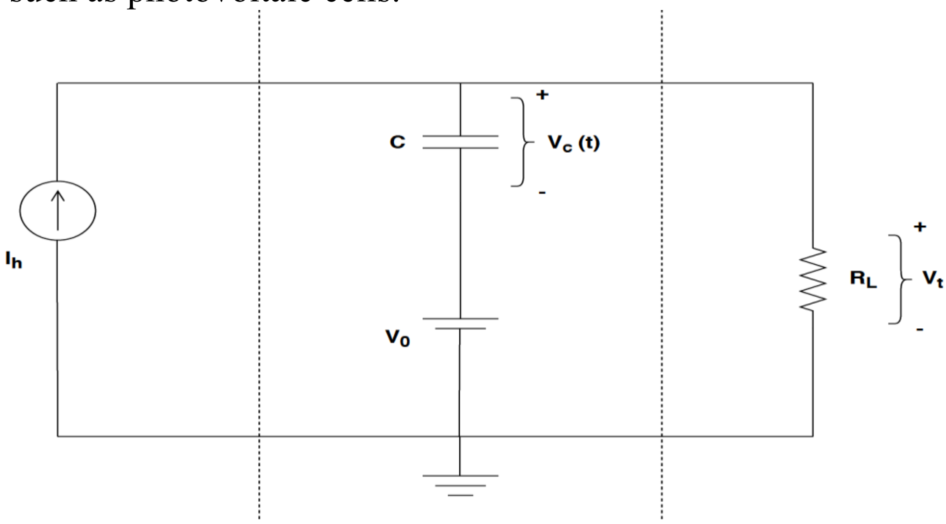

Fig.4.1.3. Equivalent electrical model of a battery-free endpoint for IoT

All active components such as sensors, radio or MCU consume power from the capacitor. Each state of the device, which combines specific states of the individual components of the device, has a specific current consumption and is modeled as a load resistance R_L (in Ω). The load resistance is modeled as a function of p (Is) [Ω] and is calculated by:

$$p(\mathrm{Is}) = \frac{Vref}{Is} \tag{4.1}$$

where:

I_s - is the current consumption for a specific combination of states of the device components (eg sensor off, active MCU and radio transmitter);
V_{ref} - is the reference voltage at which ***Is*** is obtained.

The function vt (V0, t, Is) returns as a result the minimum value between the capacitor voltage (Vt) after ***t*** seconds, starting from voltage V0, while the device consumes current Is and the maximum allowable operating voltage E.

$$vt(V0, t, Is) = \min(Ih.p(Is)\left(1 - e^{\left(\frac{-t}{p(Is)C}\right)}\right) + (Vo)\left(e^{\left(\frac{-t}{p(Is)C}\right)}\right), E) \quad (4.2)$$

where ***I_h*** is the current produced by the harvester in amperes and ***C*** is the capacitance in farads. This formula is used to determine if the device is able to successfully perform a specific task by checking that ***V_i*** remains above the minimum operating voltage ***V_{min}***. If the voltage of the capacitor falls below ***V_{min}***, the device cannot remain switched on and will switch off until it has collected enough energy to switch on again.

The function υ0 (Vt, t, Is) calculates the starting voltage of the capacitor (V0), taking into account the final voltage Vt, the transpiration time ***t***, and the total current consumption of the device is ***Is***:

$$v0(\mathrm{Vt}, \mathrm{t}, \mathrm{Is}) = \frac{Vt - Ihp(Is)(1 - e^{\left(\frac{-t}{p(Is)C}\right)})}{e^{\left(\frac{-t}{p(Is)C}\right)}} \quad (4.3)$$

The time required to obtain a voltage level Vt starting from the initial voltage V0 and the total current consumption ***Is*** is modeled as a function of τ (V0, Vt, Is) and can be obtained from equation (4.3) by deciding on time instead of voltage as follows:

$$\tau(\mathrm{V0}, \mathrm{Vt}, \mathrm{Is}) = -\mathrm{p(Is)C}\ln\left(\frac{Vt - Ih.p(Is)}{V0 - Ih.p(Is)}\right) \quad (4.4)$$

4.1.4. Approach to scheduling tasks

For efficient use of battery-free IoT devices, applications running on them must be able to handle interruptions properly. To this end, a smart task planning approach is presented for battery-free IoT sensor applications using LoRaWAN, based on the available and collected power of the device. The main problem with battery-free devices is their periodic behavior and based on how to schedule tasks to avoid power outages.

The following scenario of operation from the battery-free sensor node was used.

The microcontroller exits deep sleep mode when it reaches the capacitor voltage ***Vm*** required to start the measurement from the sensor Figure 4.1.4. It processes the data and prepares it for transmission via the LoRaWan transceiver. The voltage of the capacitor decreases to ***Vsend***. The LoRaWan transmitter turns on and sends the data to the LoRaWAN gateway and waits for the two Rx message windows facing down. At

Vsleep voltage, the sensor is set to a low-energy deep sleep mode (the period during which the capacitor is charged).

The following limits are set in the described action scenario: maximum operating voltage is 3.6V; minimum operating voltage ***Vmin*** is 2.8V. These are the optimum capacitor limit voltages between which the sensor node operates normally.

For the experiments, two different approaches were defined and analyzed to determine the voltages and calculate the value of the capacitor required to ensure normal and continuous operation of the sensor node.

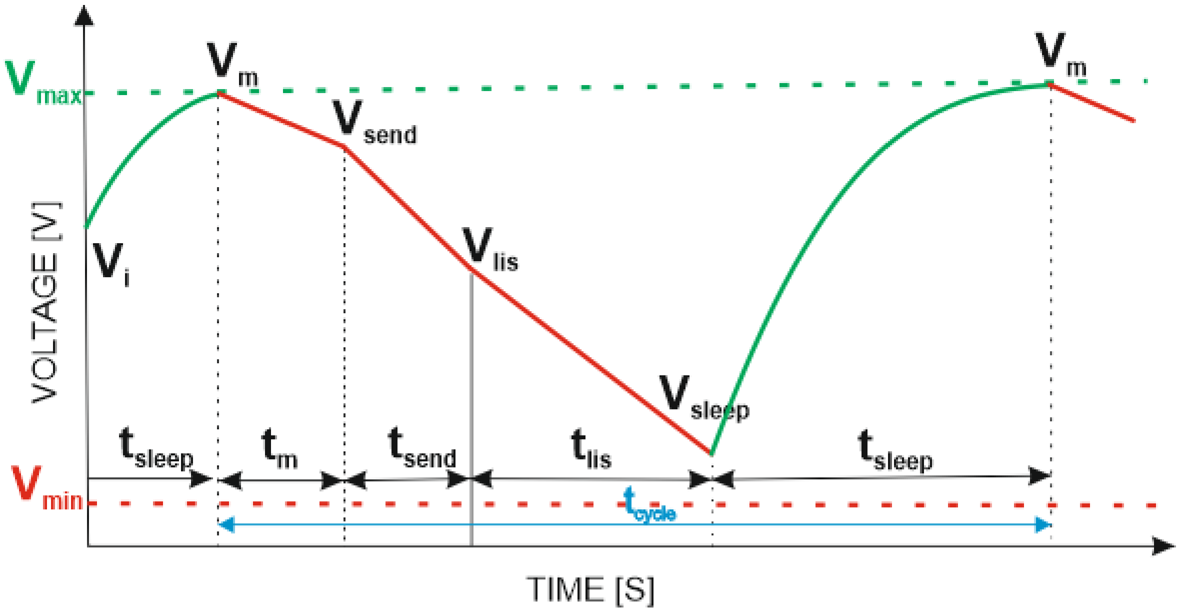

FIG. 4.1.4. Voltage diagram of the sensor node capacitor without batteries

4.1.4.1. Approach 1

In this approach, first determine the time required to fully charge the capacitor, tsleep, using equation (4.4), at an initial voltage V_{min}:

$$t_{sleep} = \tau\ (V_{min}, V_{max}, I_{sleep}), \tag{4.5}$$

where: V_{min} is the minimum allowable voltage (2.8V), V_{max} is the maximum operating voltage (3.6V), and I_{sleep} is the current consumed during the low-energy deep sleep mode.

Once the capacitor is charged to 3.6 V, the voltage V_m = 3.6V. When V_m is found, then V_{send} can be calculated using formula (4.2):

$$V_{send} = \upsilon t\ (V_{\boldsymbol{m}}, t_{\boldsymbol{m}}, I_{\boldsymbol{m}}), \tag{4.6}$$

where: t_m is the duration of the measurement time, I_m is the current consumed during the measurement. The voltage V_{lis} can be calculated by the formula (4.2):

$$V_{lis} = \upsilon t\ (V_{send}, t_{send}, I_{send}), \tag{4.7}$$

where: tsend is the time to send the packet, and Isend is the current consumed during sending. Vsleep can be calculated using (4.2):

$$V_{sleep} = \upsilon t\,(V_{lis},\ t_{lis},\ I_{lis}), \tag{4.8}$$

where: tlis is the time to wait for the windows Rx and prepare for sleep, and Ilis is the current consumed in this interval.

The problem with optimization in this approach is to find and calculate the capacitor that can be fully charged and can power the sensor node during sensor tasks, and the Vsleep voltage can be greater than 2.8V (***Vmin***).

4.1.4.2. Approach 2

If it is assumed that the minimum operating voltage at which the sensor node is in operating mode, namely 2.8 V, then the voltage Vsleep can be calculated by equating it to the minimum Vmin and adding an advance of 0.1V, for to ensure the normal transition of the sensor node from active mode to low-energy deep sleep mode, through which the capacitor is charged. Knowing Vsleep, you can calculate Vlis using:

$$V_{lis} = v0\,(V_{sleep},\ t_{lis},\ I_{lis}), \tag{4.9}$$

where: t_{lis} is the time to wait for windows Rx and prepare for sleep, and Ilis is the current consumed in this interval. Vsend is calculated by the formula (4.3):

$$V_{send} = v0\,(V_{lis},\ t_{send},\ I_{send}), \tag{4.10}$$

where: t_{send} is the time to send the packet, and Isend is the current consumed during sending. ***Vm*** is calculated:

$$V_{m} = v0\,(V_{send},\ t_{m},\ I_{m}), \tag{4.11}$$

where: t_m is the duration of the measurement time and Im is the current consumed during the measurement.

The problem with optimization in this approach is to find and calculate the capacitor that can be fully charged and can power the sensor node during sensor tasks, and the voltage Vm is below or equal to 3.6V (Vmax).

To determine the required time to charge the capacitor, results were simulated for 11 values of capacitors and different values of harvester current Ih.

Based on the obtained results, the diagram of Figure 4.1.5 is constructed, showing the minimum times required for charging capacitors with different values, depending on the harvester current Ih. These minimum times are a prerequisite for determining the minimum time in which the sensor node must be in low energy mode.

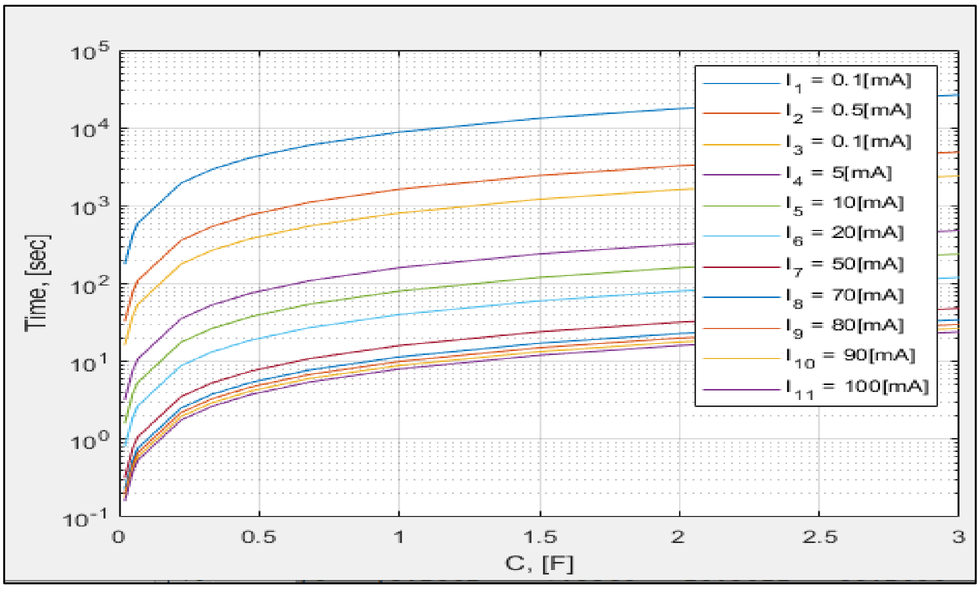

FIG. 4.1.5. Capacitor charging times depending on harvester current

4.1.5. MATLAB SIMULINK model of battery-free sensor node

Figure 4.1.6 shows a model of a battery-free sensor node developed in the middle of MATLAB / SIMULINK.

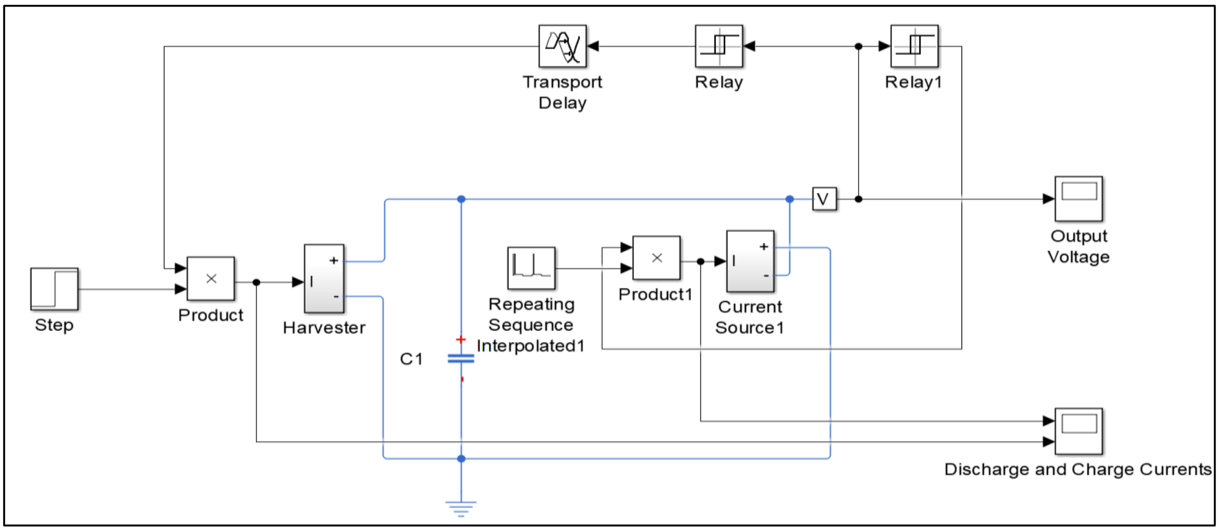

FIG. 4.1.6. Battery-free sensor node model in MATLAB

The model presents the three main components of the theoretical equivalent electrical circuit of a sensor node without batteries. The harvester is modeled with a current source (Harvester in Figure 4.1.3.) And the amount of current generated by the harvester can be set and simulated. The second functional component is the capacitor (C1 in Figure 4.1.3), which is used for energy storage.

The model allows to change its parameters, such as capacity and initial charge. The third part is the consumer (microcontroller, radio transmitter, sensors, etc.), which is presented as a current source (Load in Figure 4.1.3), which can also be simulated by setting the calculated values for the current consumed by the sensor node.

A key point in this model is that this source is connected in the opposite direction to the current source of the harvester and acts as a load with alternating current values, just as in the real case.

Using the model, we can simulate the operation of the sensor node without batteries, changing the current generated by the harvester, thus determining the input parameters from the environment, capacitor capacity and current consumption from the load at different propagation coefficients and coding speeds , bedtime, etc.

4.1.6. Experimental results

For the experimental researches, the current consumption and the time for execution of the different energy states of the sensor node - measurement, transmission, listening and falling asleep of the device were measured. The experiments and tests were performed using Siglent SDS 1052 DL +. The experimental studies were performed with the realized battery-free sensor node shown in the following figure.

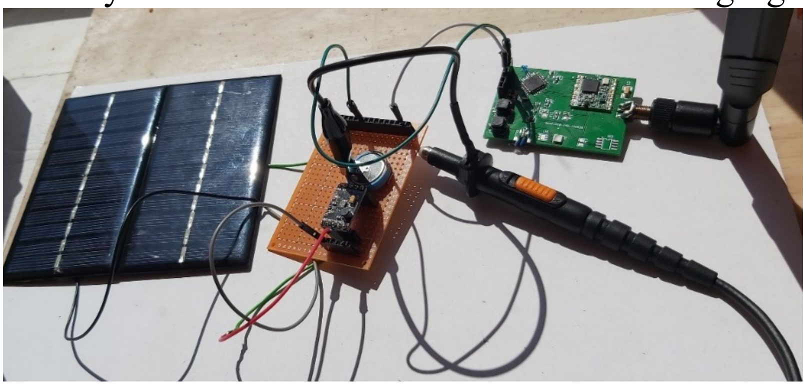

FIG. 4.1.7. Implemented battery-free sensor node

Using the MATLAB environment, the operation of the sensor node is modeled. Figure 4.1.9 shows the simulation results at a given capacity of 1.5F and an initial voltage of 3V.

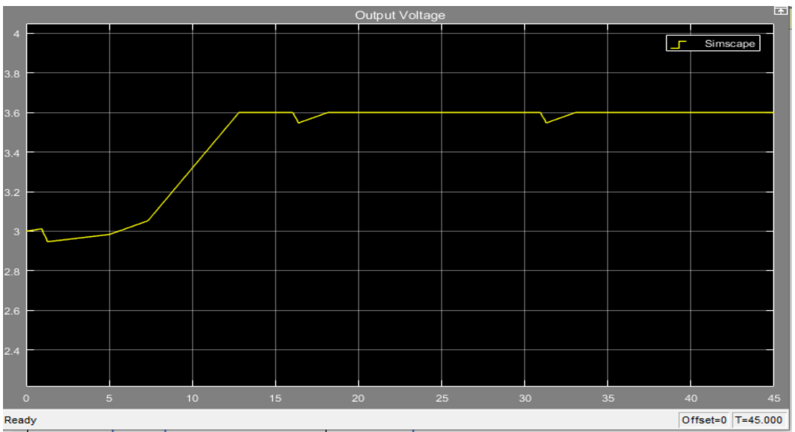

FIG. 4.1.9. Capacitor voltage during operation started at 3V

Figure 4.1.10 shows the graph of the current consumed by the sensor node, the values being measured by the actually operating sensor node described in the previous sections, as well as the value of the harvester current, which varies from 0.02 to 0.03A.

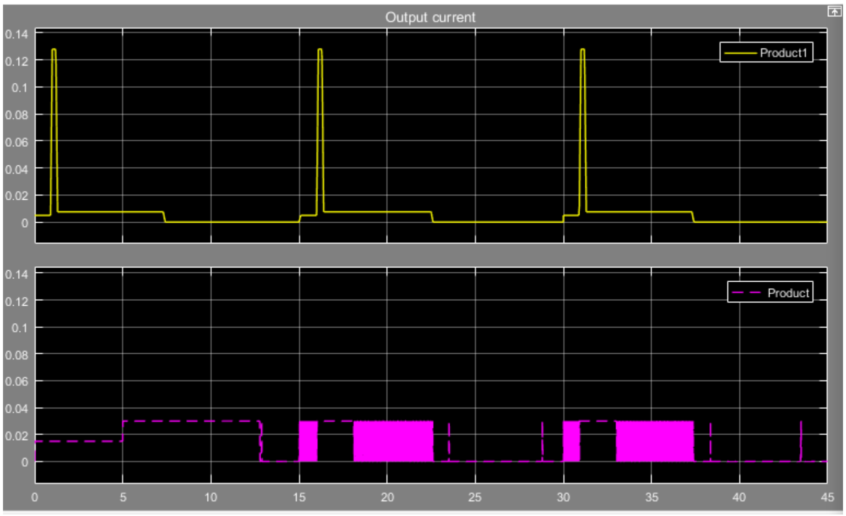

FIG. 4.1.10. Graphs of the current consumed by the sensor node and the current generated by the harvester

At a current generated by the harvester with a value of 0.03A, a capacitor with a capacity 1.5F supplies power to the sensor node, and within one cycle of the low-power mode of the sensor node, the harvester recharges the capacitor to 3.6V. This circumstance is extremely favorable for the realization of a fully autonomous sensor node without batteries.

4.2. Battery-free wireless LoRaWAN end sensor node for IoT applications

4.2.2. Architecture of lorawan sensor node without batteries

This section describes the design and hardware implementation of the battery-free LoRaWAN wireless sensor assembly with low power consumption and the use of a supercapacitor. A Class A sensor node has been designed to operate in the 868MHz band. It is powered by a 10V solar panel. The ultra-low-power sensor node with LoraWan interface uses Air Authentication (OTAA) with The Things Network servers, where after the connection procedure NwkSKey and AppSKey are generated dynamically and exchanged with the end node "over the air". This ensures that the keys cannot be compromised before activation.

The architecture of the sensor node is shown in Figure 4.2.1.

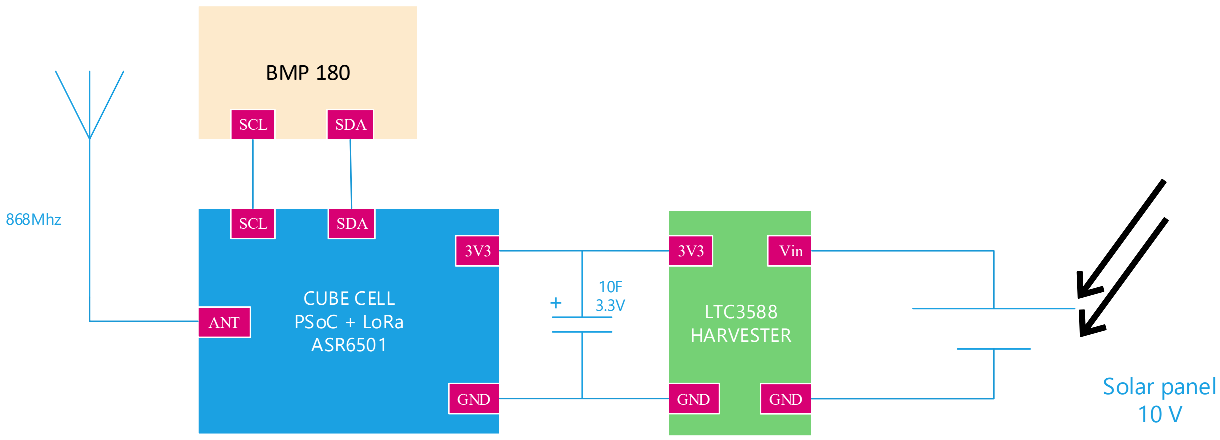

FIG. 4.2.1. Battery-free LoRaWAN sensor node architecture

The LoRa wireless communication module, designed by the ASR6501, provides ultra-wide range and ultra-low power. The choice of the ASR6051 microcontroller is based on the fact that the Arduino IDE can be used to develop software for the implementation of LoRaWAN end sensor nodes.

4.2.3. Input parameters of the study

The sensor node is located at a distance of 100 meters from the LoraWAN gateway. The gateway is built with the RAK831 board. The antenna of the external gateway has parameters: 5dBi, 868MHz. The gateway data is forwarded to the TTN application servers and then the data sent by the sensor is integrated into the Cayenne LPP myDevices cloud service. The wireless sensor node uses over-the-air authentication (OTAA) with TTN servers only the first time the sensor node is turned on. After the connection procedure, NwkSKey and AppSKey are saved and use ABP activation for future connection to the TTN servers.

4.2.4. Experimental results

The experimental studies of the wireless sensor node were performed with the implemented device shown in the following figure.

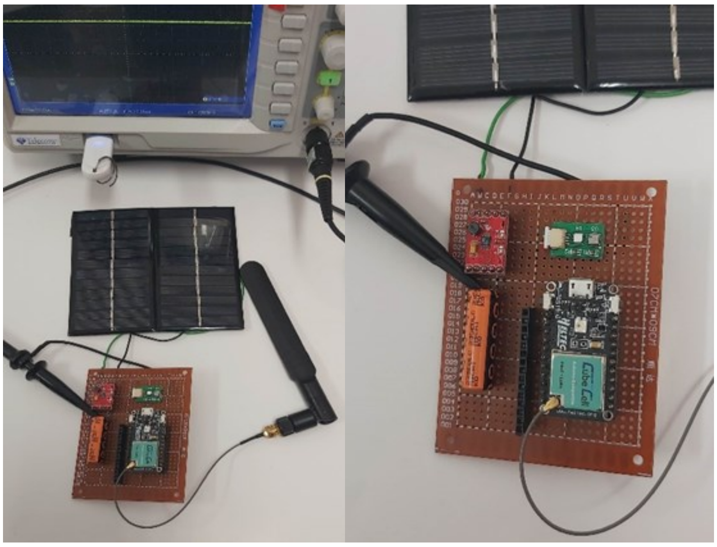

FIG. 4.2.4. Implemented wireless sensor node

The number of packets that the sensor node could send with a fully charged supercapacitor without the presence of the solar panel, as well as at a capacitor voltage of 3.3V to 2.8V, was measured.

The duration of the time interval in which the sensor node is in ultra low energy mode is 15s. The parameters of the radio connection are modulation: LORA, SF: 7, BW: 125, CR: 4/5, RSSI: -32.00dBm, SNR: 8.00dB.

The results of the study are presented in Figure 4.2.6.

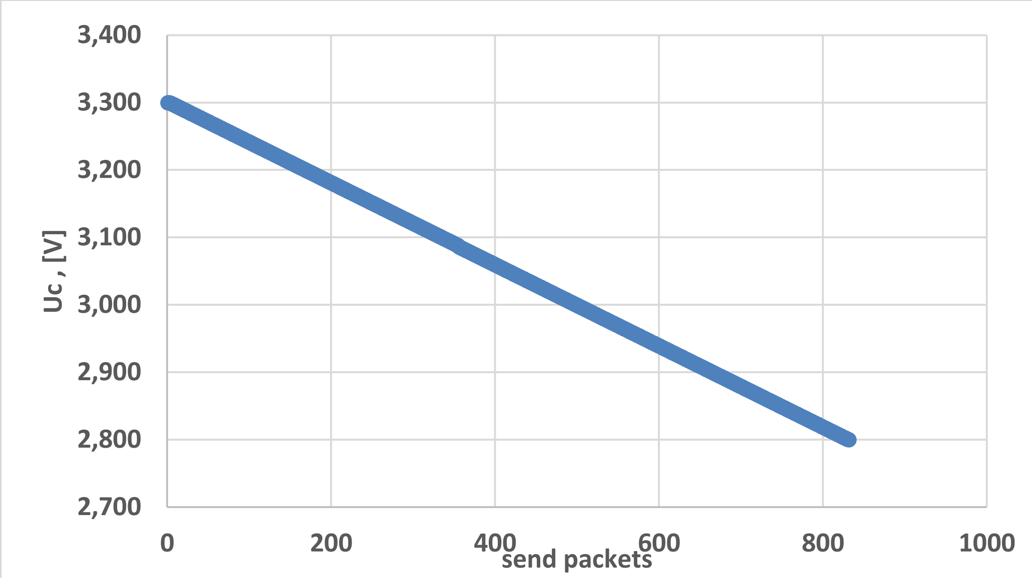

FIG. 4.2.6. Diagram of the number of packets sent, depending on the voltage of the capacitor

As shown in the diagram, the sensor node implements and successfully sends 830 data packets to the gateway, using only the energy stored in the supercapacitor.

To ensure long-term and autonomous operation of the battery-free sensor node, the charging time of the supercapacitor from the solar panel was measured at three different brightness values - in direct sunlight (44400 lux), in indirect sunlight (4380 lux) and in cloudy time (1000 lux).

Figure 4.2.7 shows the time intervals for charging the super-capacitor in the presence of direct sunlight on the solar panel, in the operating mode of the sensor node and at a 15-second interval in the low-energy mode of the sensor node. The result of the study shows that the harvester system manages to charge the capacitor from 2.8V to 3.3V in 3.25 minutes.

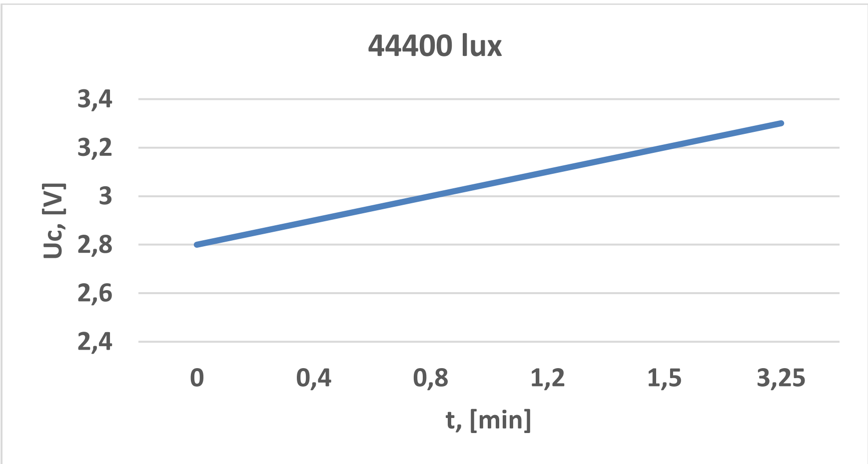

FIG. 4.2.7 Charging diagram of the supercapacitor in direct sunlight

In indirect sunlight, the harvester system manages to charge the supercapacitor from 2.8 to 3.3V for a time of 10.38 minutes (Figure 4.2.8).

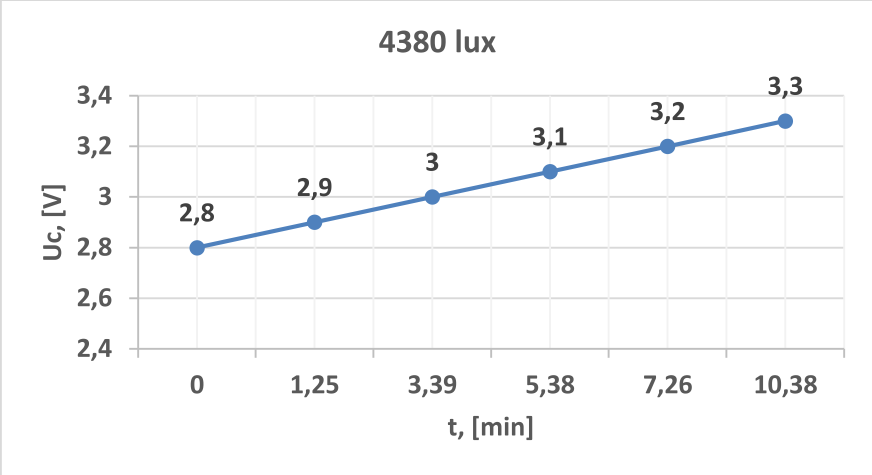

FIG. 4.2.8. Charging diagram of the supercapacitor in indirect sunlight

In cloudy weather with significantly reduced illumination of the solar panel, the harvester system manages to charge the supercapacitor from 2.8 to 3.3V for a time of 25.13 minutes (Figure 4.2.9).

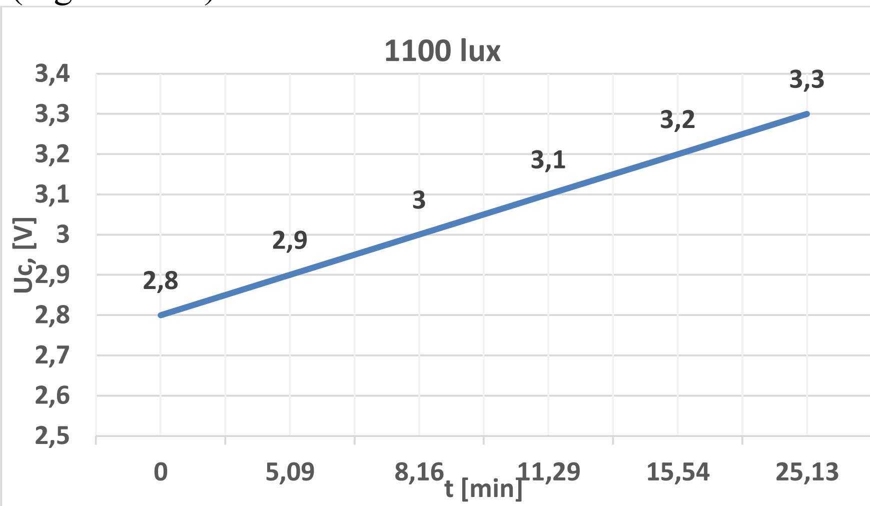

FIG. 4.2.9. Charging diagram of the supercapacitor in cloudy weather

4.3. Conclusions

In this chapter, a mathematical model has been developed that has applicability for determining the capacitance values of capacitors depending on the magnitude of the harvester current. Approaches for mathematical calculation of the values of the capacitors are proposed, which are useful in optimizing the time interval of the low-energy state of the sensor node.

A simulation model of a battery-free sensor node, developed in the middle of MATLAB, is presented in order to simulate the dependence of the capacitor capacity on the magnitude of the current generated by the harvester. The results of the simulation tests are presented in tables and are graphically visualized.

Two battery-free wireless LoRaWAN end sensor nodes for IoT applications have been developed and tested. The results of the conducted experimental researches are presented in a table, which are graphically visualized and analyzed.

CONCLUSION

The following problems have been defined from the conducted literature research:

- Need to develop new methods and technological solutions leading to a reduction in energy consumption by endpoints.
- The main problem is the limited power supply to the nodes, which creates a precondition for interruption or failure of the wireless network due to lack of power supply to the nodes.
- The main requirement for wireless sensor nodes is their autonomy, which can be met by reducing the power consumption of the end nodes.
- Battery power is used as a power source for the end sensor nodes, which contradicts the requirement for their autonomy.

The second chapter of the dissertation presents an optimized energy model of sensor nodes using LoRa / LoRaWAN technologies. This model allows analysis of different modes and scenarios for specific applications in the Internet of Things, based on LoRaWAN class A end devices. The energy consumption of a wireless LoRaWAN sensor node was evaluated through different action scenarios.

The developed model allows to study the impact of the hardware and the choice of software on the autonomy of the node. Digital results show that the energy consumed varies with different LoRa / LoRaWAN parameters, such as propagation coefficient, coding rate, payload size, bandwidth and operating frequency of the microcontroller. Optimizing these parameters is important to reduce the power consumption of the sensor node.

Using the proposed energy efficient LoRaWAN protocol, the energy consumption of the sensor nodes is significantly reduced. This increases the lifespan of the sensor node by several years.

In future developments, the energy model can be used in power management algorithms for communication of sensors powered by harvester systems for collecting energy from the environment.

The third chapter of the dissertation presents the designed, implemented and researched - LoRaWAN wireless sensor node with microcontroller ATMEGA328, Wi-Fi wireless sensor node with microcontroller ESP8266, LoRaWAN wireless sensor node with microcontroller SAM D21 and wireless sensor node with ESP32 microcontroller. For each of the presented wireless sensor nodes, experimental studies of their conventional implementations and their optimized hardware and software solutions were performed in order to achieve low power consumption and extend the life of their batteries. For an objective assessment of the presented wireless sensor nodes, their energy consumption and the lifespan of their battery power supply are taken into account.

A fourth mathematical model has been developed in Chapter Four, which has applicability for determining the capacitance values of capacitors depending on the magnitude of the harvester current. Approaches for mathematical calculation of the values of the capacitors are proposed, which are useful in optimizing the time interval of the low-energy state of the sensor node.

A simulation model of a battery-free sensor node, developed in the middle of MATLAB, is presented in order to simulate the dependence of the capacitor capacity on the magnitude of the current generated by the harvester. The results of the simulation tests are presented in tables and are graphically visualized.

Two battery-free wireless LoRaWAN end sensor nodes for IoT applications have been developed and tested. The results of the conducted experimental researches are presented in a table, which are graphically visualized and analyzed.

CONTRIBUTIONS TO THE DISSERTATION

Scientific contributions:

1. A developed and implemented energy efficient LoRaWAN protocol is proposed, through which the consumed energy is reduced by up to 35% compared to the conventional protocol.
2. A mathematical model of the energy life cycle of a battery-free wireless sensor node has been developed. Approaches for mathematical calculation of the values of the capacitors are proposed, which are useful in optimizing the time interval of the low-energy state of the sensor node.
3. A simulation model of a battery-free sensor node in the middle of MATLAB has been created.
4. Innovative circuit solutions are proposed to reduce the power consumption of LoraWan wireless sensor nodes in low-energy mode - "deep sleep" by using a nano timer and FRAM memory to record the parameters of the LoraWan connection during power off of the microcontroller and the radio transceiver.

Applied contributions:

1. The parameters influencing the energy consumed by the wireless LoRaWAN sensor nodes have been determined and proven.
2. A sensor node with LoRaWAN interface and ATMEGA328 microcontroller with low power consumption has been designed, developed and tested.
3. Class A LoRaWAN sensor node with ATMEL SAM D21 microcontroller, TPL5110 nano timer and FRAM memory, characterized by ultra low power consumption, was designed, developed and tested.
4. A Wi-Fi sensor node with ESP 8266MOD microcontroller with low power consumption has been designed, developed and tested.
5. LoraWAN wireless sensor node with ESP32 microcontroller with ultra low power consumption is designed, developed and tested.
6. Two battery-free wireless LoRaWAN end sensor nodes for IoT applications have been developed and tested.

LIST OF PUBLICATIONS RELATED TO THE DISSERTATION

1. D. Tokmakov, S. Asenov and S. Dimitrov, "Research and development of ultra-low power LoraWan sensor node," 2019 IEEE XXVIII International Scientific Conference Electronics (ET), 2019, pp. 1-4, doi: 10.1109/ET.2019.8878674

2. S. M. Asenov and D. M. Tokmakov, "Development of Ultra-Low Power Sensor Node Using FRAM and Nano Timer," 2020 XI National Conference with International Participation (ELECTRONICA), Sofia, Bulgaria, 2020, pp. 1-4, doi: 10.1109/ELECTRONICA50406.2020.9305121.

3. S. M. Asenov and D. M. Tokmakov, "Power Optimization of LoRaWAN Wireless End Sensor Node," 2020 XXIX International Scientific Conference Electronics (ET), Sozopol, Bulgaria, 2020, pp. 1-4, doi: 10.1109/ET50336.2020.9238204.

4. S. Asenov and D. Tokmakov, "Battery Free Wireless LoRaWAN End Sensor Node for IoT Applications," 2020 28th National Conference with International Participation (TELECOM), Sofia, 2020, pp. 121-124, doi: 10.1109/TELECOM50385.2020.9299539.

5. S. Asenov and D. Tokmakov, " Power Profile Simulation And Optimization of Battery-Less LoRaWAN Sensor Node," 2021 XII National Conference with International Participation (ELECTRONICA), Sofia, Bulgaria, 2021, (под печат)

6. S. M. Asenov and D. M. Tokmakov, "Enhancing Energy Efficiency of LoRaWAN Protocol," 2021 XII National Conference with International Participation (ELECTRONICA), Sofia, Bulgaria, 2021.

7. Asenov S., Tokmakov D., (2020). RESEARCH AND OPTIMIZATION OF LOW POWER WIFI SENSOR NODE. SCIENTIFIC PAPERS OF THE UNION OF SCIENTISTS IN BULGARIA - PLOVDIV SERIES B. TECHNIQUE AND TECHNOLOGIES, Vol. XVIII, pp. 67-70, ISSN 1311-9419 (Print), ISSN 2534-9384 (Online).

8. Asenov S., (2021)., REVIEW OF LOW POWER WIRELESS SENSOR NODES. SCIENTIFIC PAPERS OF THE UNION OF SCIENTISTS IN BULGARIA - PLOVDIV SERIES C. TECHNIQUE AND TECHNOLOGIES, Vol. XIX, pp. 20-23, ISSN 1311-9419 (Print), ISSN 2534-9384 (Online)