BURIED PIPE LEAKAGE DETECTION

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A Graduation Project Report

Electrical Electronics Engineering Department

JUNE 2025

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ABSTRACT

Within the scope of smart urbanism, the detection of leaks in underground clean and wastewater pipelines is an important issue. The waste of water, which is put into use with great effort and costs, due to leaks, constitutes direct material losses. In addition, leaks lead to negative situations such as pressure drops, mixing of pollutants into drinking water, causing a decrease in water quality and posing a risk to human health, as well as negatively affecting the ecosystem [1]. Time Domain Reflectometry (TDR) technology is a very effective but costly method for detecting water leaks. In this project, it is aimed to investigate a method that can increase the efficiency in the application of TDR technology for the detection of leaks in underground clean and waste water pipes. The measuring distance of the TDR units can reach a maximum of several hundred meters according to the characteristics of the environment (soil) and the sensor cable. It is usually around 100 meters. The working principle of TDR is based on analyzing the reflections of a high-speed pulse signal sent to the transmission line [2]. In the system to be developed in this research project, multiple TDR unit will be used, except for one, the others will be embedded. TDR units will be placed at interval based on their measurement range to the ground and a sensor network will be created. The existing TDR units will be adapted to operate underground except for one, and both their energy and communication supplied be provided in a coordinated manner via the same sensor cable. High-cost access, energy continuity, communication and infrastructure requirements will be optimized for other TDR units except the main TDR unit. If the proposed method gives a successful result, more widespread, comprehensive and efficient use of TDR in the detection of leaks or leaks that occur in water management can be achieved.

Keywords: *TDR (Time Domain Reflectometry), Leak Detection of Water, Underground Water Pipelines.*

ÖZET

Akıllı şehircilik kapsamında yer altı temiz ve atık su boru hatlarında oluşan sızıntı ve kaçaklarının tespiti önemli bir konudur. Büyük emek ve maliyetlerle kullanıma sunulan suyun sızıntı ve kaçaklar dolayısıyla ziyan edilmesi doğrudan maddi kayıplar oluşturmaktadır. Ayrıca kaçaklar basınç düşüşleri, kirleticilerin içme suyuna karışması gibi olumsuz durumlara yol açarak suyun kalitesinin düşmesine sebebiyet verir ve hem insan sağlığı için risk oluşturur, hem de ekosistemi olumsuz etkiler [1]. Zaman alanı yansıma (Time Domain Reflectometry, TDR) teknolojisi su kaçaklarının tespitinde oldukça etkili ancak maliyetli bir yöntemdir. Bu projede yer altı temiz ve atık su borularında oluşan kaçakların tespiti için TDR teknolojisinin uygulanmasında verimlilik artışı yapabilecek bir yöntemin araştırılması hedeflenmektedir. TDR ünitelerinin ölçüm mesafesi ortamın (toprak) ve sensör kablosunun karakteristiklerine göre en fazla birkaç yüz metreye ulaşabilmektedir. Genellikle 100 metre civarlarındadır. TDR'nin çalışma prensibi, iletim hattına gönderilen yüksek hızlı bir darbe sinyalinin yansımalarını analiz etmeye dayanır [2]. Bu araştırma projesinde geliştirilecek sistemde biri hariç diğerleri gömülü olmak üzere, birden fazla TDR birimi kullanılacaktır. TDR üniteleri toprağa ölçüm mesafeleri oranında aralıklarla yerleştirilecek ve bir sensör ağı oluşturulacaktır. Elde mevcut olan TDR üniteleri biri hariç toprak altında çalışabilecek hale getirilecek aynı sensör kablosu üzerinden koordineleri bir şekilde hem enerjileri hem de haberleşmeleri sağlanacaktır. Ana TDR ünitesi hariç diğer TDR üniteleri için yüksek maliyetli erişim, enerji sürekliliği, iletişim ve altyapı gereksinimleri optimize edilmiş olacaktır. Önerilen yöntem başarılı sonuç verirse TDR'ın su yönetiminde ortaya çıkan sızıntı veya kaçakların tespitinde daha yaygın, kapsamlı ve verimli kullanımı sağlanabilir.

Anahtar Kelimeler: *TDR (Time Domain Reflectometry), Kaçak Tespiti, Yer Altı Temiz ve Atık Su Boru Hatları, Su Sızıntı ve Kaçakları*

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	**Explanation**
ρ:	Reflection Coefficient
π:	pi number.
Z:	Impedance at The Reflection Point
Z_0:	Characteristic Impedance of The Transmission Line
ε_r	Dielectric Constant
v	Propagation Velocity
c	Speed of Light
$C_{0:}$	Capacitance
w:	$2\pi f$ Angular frequency (rad/s)
V_r:	Reflected Voltage
V_i:	Transmitted Voltage

Abbreviation	**Explanation**
TDR:	Time Domain Reflectometry
UART:	Universal Asynchronous Receiver-Transmitter
PVC:	Polyvinyl Chloride
RS-485:	Recommended Standard 485
RS-422:	Recommended Standard 422
ADC:	Analog to Digital Converter
PC:	Personal Computer
USB:	Universal Serial Bus
BJT:	Bipolar Junction Transistor
LED:	Light Emitting Diode
OTG:	On-The-Go
V:	Volt

1. INTRODUCTION

The rapid increase in urbanization and the need for environmental sustainability necessitate the effective management of water distribution systems. One of the most important problems in these systems is water leaks in pipelines located underground. According to the data of the World Bank, approximately 48.6 billion cubic meters of water are lost annually due to leaks in water distribution systems, which leads to serious damages both economically and environmentally [3]. Leaks not only cause water loss, but also cause pressure drops in the pipes, leading to deterioration of water quality and potentially the mixing of pollutants into drinking water. This situation threatens public health and has negative effects on the ecosystem [1].

Traditional methods for detecting water leaks include acoustic listening devices, leak noise correlation devices, tracer gases, thermography and techniques such as underground radar. Acoustic methods detected leaks by detecting vibration or sound caused by water escaping from the pipe. But the effectiveness of these methods depends on many factors, such as the pressure inside the pipe, environmental noise and pipe material. Especially in plastic pipes, the efficiency of acoustic methods decreases significantly, since the transmission of sound waves is weaker than in metal pipes [1]. In addition, methods such as tracer gas, thermography and radar require costly and complex applications, so their routine use remains limited [1].

In recent years, time domain reflection (TDR) technology has come to the fore as a promising alternative for leak detection in underground pipelines. The TDR method is based on sending high-frequency electromagnetic pulses through the pipe or a sensor element integrated into it. The reflection of the signal makes it possible to detect changes in the dielectric properties of the surrounding environment caused by water leakage. Since water has a very high dielectric constant compared to dry soil (about 80), significant signal changes are observed at leakage points [3], [4]. Among the most important advantages of the TDR are high measurement accuracy, resistance to environmental noise and the ability to work independently of pipe pressure. In addition, thanks to its relatively low cost and portability, it offers the possibility of continuous and automatic inspection [3].

Despite all these advantages, there are still some practical limitations that prevent the spread of existing TDR-based systems. In particular, although TDR can accurately locate leaks along long pipelines, the need for multiple sensor installations to cover larger areas can increase system complexity and operational costs [3], [4]. In addition, meeting the energy supply and communication needs of a large number of sensor units located underground separately can further complicate infrastructure requirements, especially in long-term monitoring applications [4].

This project aims to design and develop an integrated TDR-based sensor network for use in underground clean and wastewater pipelines in order to provide an innovative solution to these problems. In the proposed system, the sensor units will be able to carry out the transmission of TDR signals, energy supply and data communication together over a single common sensor cable. This approach reduces infrastructure and operating costs, expands the scope of monitoring and provides continuous monitoring. By managing the system by a central control unit, measurements are coordinated and it is possible to detect leaks effectively.

From the point of view of electrical and electronics engineering, this system contains complex engineering problems such as high-frequency signal transmission, power management and reliable data communication in a single physical environment, in the harsh conditions of the underground. Advanced circuit design and signal processing methods need to be applied to ensure impedance matching, minimizing signal distortion, and ensuring energy and communication continuity. In these aspects, the project poses an important engineering problem that requires interdisciplinary expertise and innovation.

While the existing TDR-based leak detection systems in the literature usually focus on a single sensor unit or metal pipes, the proposed network structure can be applied to pipes made of different types of materials and offers scalable, cost-effective solutions [4]. The use of the sensor cable as a signal, energy and communication infrastructure greatly reduces the infrastructure requirements of classical systems consisting of independent units. In this way, the long-term ease of use and maintenance requirements of the system are improved.

As a result, this study makes significant contributions to the goals of reducing water losses and sustainable water management by developing a scalable, low-cost and integrated sensor network architecture in the field of leak detection in underground pipelines. The implementation of the system will make it possible to prevent both economic losses and reduce environmental and public health risks with early leak detection.

2. REQUIREMENTS SPECIFICATION

Leaks in the underground water pipes of the system will be detected with a very high accuracy rate, the signal will be transmitted undisturbed for 100 meters, and the sensor network created with multiple TDR networks will be controlled by a central computer.

- **Physical Requirements**
  1. The distance between the TDR should not exceed 100 meters decoupled from each other.
  2. System must be resistant to conditions under the ground.

- **Performance and Functionality Requirements**
  1. Communication and power supply must be simultaneously provided at the same time.
  2. Power and communication systems should be connected to sensor cables so that distortion is minimal.
  3. The analysis of the data from the sensor network will be carried out via the interface on the central computer.

- **Economic Requirements**

  Consumables (3D printer filament, microcontroller, Integrated circuits, Transistor, passive circuit elements, assembly and sensor cables, silicone, PVC pipe, soil samples, battery) are considered to be 5200TL on average, fixture materials are 1800TL and the manufacturing service of parts that cannot produce with a 3D printer is 2000TL and it is expected to have an average cost of 9000TL.

- **Environmental Requirements**
  1. The test device will be resistant to factors such as temperature, humidity, pressure under the ground.
  2. The system will be compatible with the ecosystem and its design will not harm the environment.

- **Health and Safety Requirements**

  The system will not emit electromagnetic radiation that will negatively affect human health during operation.

- **Manufacturability and Maintainability Requirements**

  The materials of the systems used in the sensor network will be easily available for purchase.

3. STANDARDS

In the project, TDR technology has been used for the detection of leaks in waste water pipes. While making use of this technology, national and international standards have been taken into account. The following standards are specified:

- **ASTM D6780 / D6780M-05(2015):** This standard, which includes definitions for the use of the reflection in the time domain reflectometry (TDR) method to measure the amount of moisture content in the soil, has formed the basis for the measurement approach in the system. The reflection behavior of the TDR signal, dielectric constant calculation methods and calibration procedures were evaluated in accordance with this standard.

- **RS-485 / RS-422 Serial Communication Standard:** The ZK-U485 and MAX490 integrated circuits work according to the RS-485 standard, which is used quite often in data transmission. This standard is designed for operations such as long-distance communication.
- **IEEE Referencing Style (IEEE Citation Format):** All academic resources used are referenced in accordance with the IEEE format

- **ANSI C (American National Standards Institute):** The C programming language was used in the control software of the microcontrollers of the TDR units and was developed in accordance with ANSI standards.

  Python PEP8 Standard (Coding Style Guide for Python): The PyQt5-based interface is created using the Python language. The code structure is written taking into account PEP8 compatibility.

4. PATENTS

- Cataldo, A., & Cannazza, G. (2011). Apparatus and method for detection and localization of leaks and faults in underground pipes. Patent No. BA2011A000034.

5. THEORETICAL BACKGROUND

The signal transmitted along the cable is affected by the parameters of the cable in which it is located, and these parameters are related to frequency. Effects such as skin effect and dielectric dispersion observed at high frequencies are taken into account. In order for TDR systems to be more efficient, the following expressions are also used [5]:

$$R(w) = R_0 + R_1 \cdot \sqrt{w} \tag{1}$$

$$L(w) = L_0 + \frac{L_1}{\sqrt{w}} \tag{2}$$

$$G(w) = G_0 \cdot w \tag{3}$$

$$C(w) = C_0 \tag{4}$$

R(w) = Resistance

L(w) = Inductance

G(w) = Conductivity

C_0 = Capacitance

w = 2πf Angular frequency (rad/s)

$$\rho = \frac{v_r}{v_i} \tag{5}$$

$$z = z_0 \times \frac{1+\rho}{1-\rho} \tag{6}$$

ρ = Reflection Coefficient (ratio of reflected voltage to transmitted voltage)

Vr = Reflected Voltage

Vi = Transmitted Voltage

Z = Impedance at The Reflection Point

Z_0 = Characteristic Impedance of The Transmission Line

The electromagnetic wave traveling on the cable is affected by the parameters of the cable. In order for TDR systems to work more efficiently under the conditions they are in, it is necessary to consider the relationship between the propagation speed of the signal and the dielectric coefficient of the medium. The following formula is used to express this situation.

$$v = \frac{c}{\sqrt{\varepsilon_r}} \tag{7}$$

v = Propagation Velocity

c = Speed of Light

ε_r = Relative Permittivity

6. METHODOLOGY

The design of the sensor network established with TDR, software and tools used are summarized in this section.

6.1 System Hardware

The hardware infrastructure of the system developed in this study is designed to detect leaks occurring in underground clean and wastewater pipelines efficiently and cost-effectively with Time Domain Reflectometry (TDR) technology. The system is configured to increase the communication distance, secure data transmission in embedded environments and create a modular sensor network.

In the context of field application, it is planned that the system will consist of units that are repeated and embedded every 200 meters. Each of these units includes a MAX490 integrated unit, an STM32 microcontroller and a TDR module. The TDR module is positioned in such a way that it sends signals in both directions from the point where it is located, thus covering a line of about 200 meters. The structure in question is shown in the system diagram given in Figure 1.

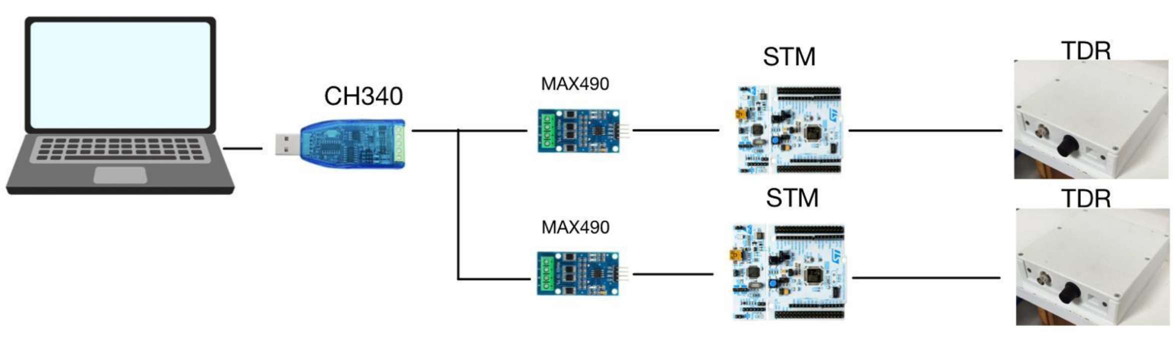

Figure 1. System Hardware

6.1.1 Hardware Architecture

There is a PC at the center of the entire system. This computer is positioned as a user interactive control point and provides communication via USB. Thanks to the integrated ZK-U485 integrated into the PC, the USB interface is converted to the RS-485 protocol. The ZK-U485 has a half-duplex communication structure and serves as a USB-UART (serial port) converter. This integrated device can operate at baudrate values ranging from 9600 bps to 2 Mbps.

The RS-485 signal converted by ZK-U485 is transmitted over a line about 100 meters long, buried underground along with pipes. The MAX490 integrated unit located at the end of the line converts RS-485 signals to the UART protocol with full duplex communication support. The MAX490 is a serial communication integrated device operating in RS-422/RS-485 standards with a baudrate interval between 1200 bps and 5 Mbps.

The STM32 microcontroller, connected to the MAX490, manages communication traffic and conducts the measurement process by controlling the TDR module to which it is connected. Communication between STM32 and TDR is provided via UART protocol, using RX-TX lines. Thus, the measurement commands are transmitted to the TDR and the returned data are processed and transferred to the PC via the RS-485 line.

It is planned to repeat this unit structure every 200 meters. Thus, it has been expanded along long water pipelines and it is aimed to establish a leak detection sensor network in a modular structure.

6.1.2 Power Distribution Strategy

One of the most important goals of the developed system is to enable the embedded units to work without the need for external batteries. In this context, it is aimed to use the sensor (TDR line) and the communication line for energy transportation purposes as well. Thanks to such a structure, it is aimed to reduce maintenance and production costs at the same time, to make the system last longer.

However, the RS-485 protocol is based on the principle of differential communication, and data transmission is performed according to the voltage difference between two lines. This structure makes it technically difficult to transmit both data and energy at the same time and can even cause serious signal disturbances in some cases. For this reason, communication and energy transfer are separated on a time basis.

According to the planned system architecture, energy transmission is carried out at intervals and this energy is stored in capacitive batteries with low internal resistance (for example, supercapacitors). After sufficient energy is accumulated, the system components (STM32, TDR, MAX490) are operated with this energy and the measurement is performed and the results are transmitted to the center. This approach aims to provide an efficient and scalable solution both in terms of energy management and communication.

6.1.3 Power Distribution System Design

In the system developed in this study, sensor data, energy transmission and communication operations were carried out over a single line (A-B line). Time-based switching method was used to ensure this integration. First of all, by applying energy to the line, the supercapacitors in the system are charged, then the energy transmission is interrupted, communication is carried out over the same line and the necessary measurements are taken. As a result of the tests conducted, it has been seen that this method is both reliable and applicable, and the system has been configured in accordance with this principle.

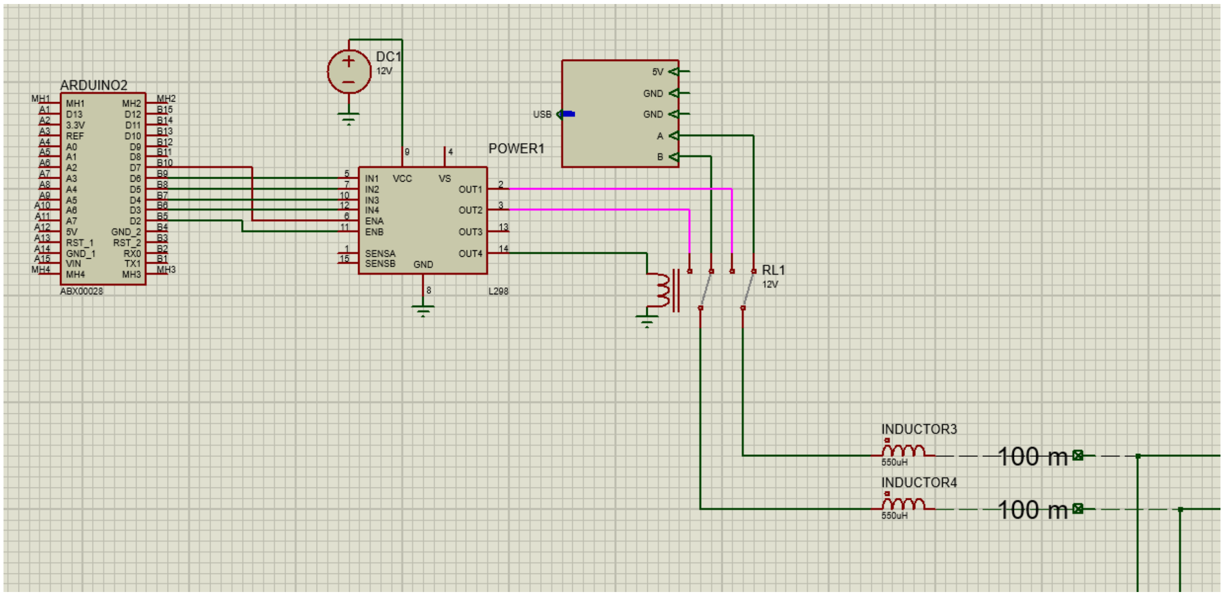

Figure 2. The Communication Decoupling Between The Leak Detection Unit and The User Interface

In Figure 2, the circuit structure that provides communication between the unit that will decode the leak detection and the user interface is shown. Within this structure;

- One Arduino Nano microcontroller
- One L298N motor drive module
- One 12V relay
- ZK-U485 USB to RS485 converter
- Two 500 µH inductors.

The Arduino Nano is powered via the USB port and controls the motor driver connected to the A-B line. Thanks to this control, it is decided whether 12V power should be provided on the line. The motor drive is powered by a 12V power supply and works according to the digital signals it receives from the Arduino. This motor driver controls both the relay and transmits the 12V voltage to the A-B line via pins OUT1 and OUT2.

The relay performs two basic functions in the system:

1- L298N to enable energy transmission by controlling the motor via the drive, To perform the task of switching between communication and power transmission by Decoupling the connection of the ZK-U485 module with the A-B communication lines when necessary.

2- The ZK-U485 converter provides communication over the RS485 protocol and allows the incoming data to be monitored on the computer.

The two 500MH coils used in the system are positioned to ensure the isolation of the measuring line. These coils prevent the passage of high-frequency TDR pulses, making it possible to perform stable and reliable distance measurements in the system.

Thanks to this structure, energy, communication and sensor measurements have been successfully carried out over the same physical line, ease of maintenance and cost advantage have been achieved.

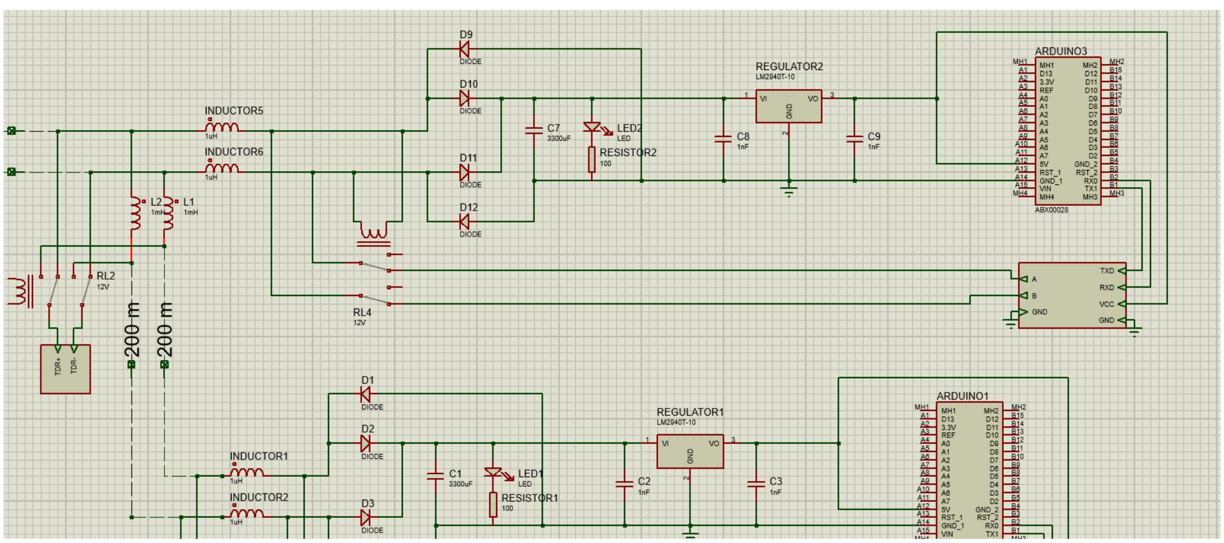

Figure 3. Power Distribution Network Installed with Capacitive Batteris

Figure 3 shows the capacitive battery (energy storage) network of the system. This structure allows the energy transmitted via the A-B line to be safely stored in a capacitor without affecting the TDR measurement line. The main purpose of this energy storage approach is to enable the communication and sensor units of the system to be operated without the need for an external power source.

In addition, due to the fact that differential communication based on the RS-485 protocol does not take place in a healthy way while there is energy on the EU line, and the TDR unit cannot take accurate measurements, the energy is first stored in capacitors, and then even measurement and communication operations are performed by disconnecting the energy transmission, so that the system works uninterruptedly and stably.

A classical diode bridge has been created by using four diodes to rectify the energy and prevent feedback that may occur in the capacitor. Thanks to this bridge, while the energy is transferred to the capacitor in one direction, the reverse current that may occur in the system during measurement is prevented.

An LED has been installed in the system in order to observe the energy accumulated in the capacitor. This LED provides convenience in the testing process by making it possible to visually monitor the energy level.

In order to reduce the stored energy to a suitable and stable level for Arduino Nano and RS-485 TTL converter modules, the LM2940 integrated low dropout voltage regulator has been used. This integrated system converts the 12V level of energy to a 5V constant DC voltage, ensuring the safe operation of microcontrollers and communication units.

The RS-485 TTL converter used in the system is integrated with Arduino to establish UART-based serial communication. This module was used in the tests to provide data transmission from Arduino via serial port.

Just like in the power distribution line, two coils (500 µH) were used in this energy storage network. These coils isolate the measuring line from power and communication lines by preventing the passage of TDR pulses (pulse), thus allowing the TDR system to operate stably and error-free. Figure 4 shows the entire power distribution line. In this design, the TDR is fed from the outside and connected Decoupled between the coils. In these tests, there is a t measurement line, that is, 100 meters of cable between the coils. The tdr also measures at this 100 meter.

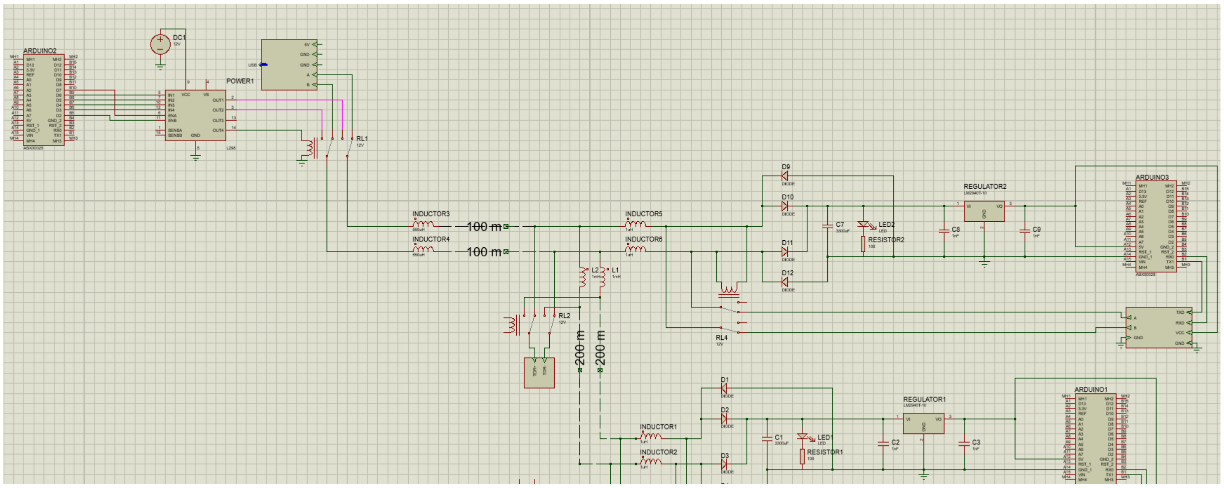

Figure 4. Power Distribution Line

6.1.3 Test Equipment and Baudrate Analysis-

In order to evaluate the reliability of the communication over the RS-485 line, tests were carried out at various baudrate levels. The purpose of these tests is to determine at which baudrate levels data transmission can be performed without errors, especially on the RS-485 line with a length of 100 meters with the STM32 microcontroller.

In this context, the test circuit shown in Figure 5 has been installed. This circuit is configured as PC → ZK-U485 → RS-485 line → MAX490 → STM32. Consecutive numerical data (counter) were created by the computer and sent to the system; STM32 transmitted these -

data back exactly the same way after receiving it. Communication security has been evaluated by comparing the sent and received data.

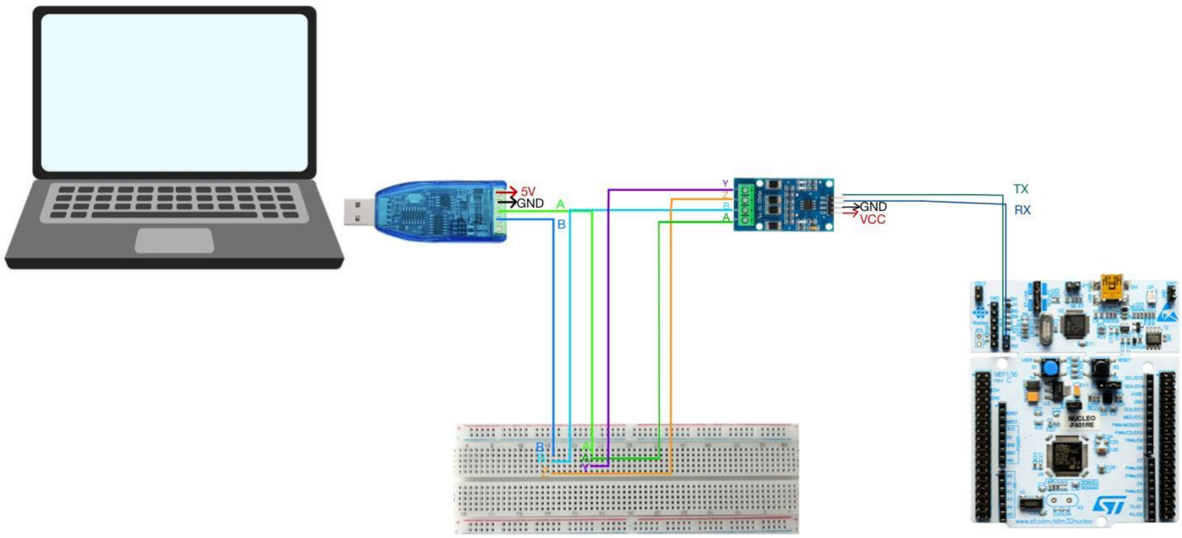

Figure 5. Circuit for Baudrate Tests

In these tests, a special embedded software was installed on the STM32 microcontroller. By reading the data received via the UART on a byte basis, the software detected the \n character at the end of the array as a sign and determined that the package was completed. The received data was then transmitted directly back, so that the communication performance was analyzed. Detailed technical explanations of this embedded software will be presented in the section titled Software in the thesis.

Initially, the tests were performed manually with PuTTY, a terminal application. However, since it has become difficult to conduct systematic testing with this method, a Python interface has been developed that allows the automation of tests. This interface allows the user to flexibly set parameters such as COM port selection, setting the baudrate, the amount of data to be sent, and the initial counter value. In addition, the success rate was calculated instantaneously by comparing the sent and received data. The details of the Python interface and algorithm will also be explained in the Software section.

These tests allowed the baudrate limits of the system's ability to operate safely on long-distance RS-485 lines have been determined; concrete findings have been obtained about the extent to which the system can perform stable data transmission in field applications. All test protocols, the baudrate values used and the observed error rates will be presented in detail in the Experiments section of the thesis.

6.1.5 Alternative Communication Experiment: USB-Based STM32-STM32 Communication

An alternative architecture has been tried in order to make the hardware structure simpler and to maintain communication without receiving an RX/TX connection from the TDR module. For this purpose, instead of physically communicating the TDR unit via UART, a structure was tested in which two STM32 microcontrollers are connected to each other directly via USB.

In this structure the PC– ZK-U485–MAX490–STM32 communication line, a second STM32 microcontroller is connected; second microcontroller is configured as a unit simulating the TDR module. This structure is shown in Figure 6.

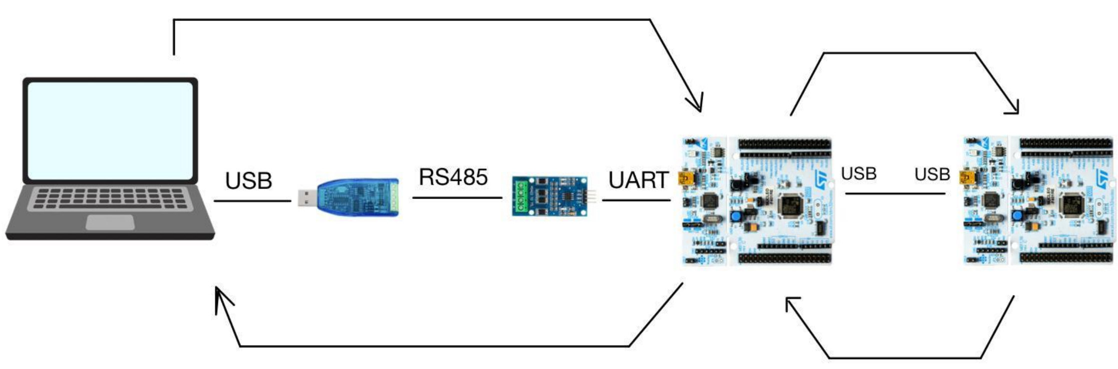

Figure 6. Circuit for Communicate 2 Stm32

The purpose of this installed alternative circuit is to provide data exchange between two microcontrollers via USB and no UART connection is needed. However, this attempt was unsuccessful due to the architecture of the USB protocol.

The USB communication protocol is one device is the host (i.e. the managing part) and the other device is the peripheral. On standard USB connections, embedded systems typically taking on the role of a PC host. The STM32 Nucleo-F401RE development board used in this system supports USB Device mode; however, it does not support USB Host mode hardware-wise. For this reason, communication could not be achieved by establishing a direct USB connection between the two STM32 devices.

In addition, since the enumeration (identification process) in the USB protocol is initiated by the host, it is not possible to exchange any data if both parties work as a device. Some models in the STM32 family (for example, certain members of the STM32F4xx series) can work as both host and device by offering USB OTG (On-The-Go) support. However, the Nucleo-F401RE card used does not support this feature and this caused the test to fail.

This experiment was carried out as part of the search for a solution to simplify the communication architecture, but it was canceled due to the inability to meet the structural requirements of the USB protocol. The findings obtained have been of a guiding in the evaluation of alternative communication scenarios in similar systems.

6.2 Software

6.2.1 Baudrate Test Interface

Ensuring reliable communication of the hardware units designed within the scope of the project is of great importance for the performance of the system. In measurement tools such as the TDR device, it is very important not only to transmit the data correctly, but also to receive the reflected data with the same degree of accuracy. The overall accuracy and reliability of the system depends on the healthy provision of this communication.

Communication is mostly established between the TDR device and the control unit via the UART(Universal Asynchronous Receiver-Transmitter) protocol. Decryption of the TDR device is carried out by means of the UART (Universal Asynchronous Receiver-Transmitter) protocol. In UART-based communications, the data transmission rate “baudrate” must match both the receiving and transmitting units. In cases where this match is not provided, situations such as synchronization failures, data loss or incorrect reading of the data are encountered in the transmission of data. This situation causes the accuracy of the measurement data of the system to reduce. In particular, such errors affect the performance of TDR systems that perform precise measurements at high frequencies.

For this reason, it is necessary to determine the most stable and reliable baudrate values for TDR systems. In line with this need, an interface has been needed where the user can perform serial communication tests with different baudrate values, transmit data, receive data and analyze erroneous data in detail.

For this purpose, an interface based on PyQt5 has been developed for testing and analysis operations. In the developed interface, parameters such as serial port, baudrate, number of messages are adjusted according to user preferences; at the same time, it is ensured that the user has information about the performance of communication by analyzing the data transmitted and received in real time.

For the serial communication structure used for the interface, the PySerial library was used, which makes UART communication possible in the Python. With PySerial, operations such as port scanning, connection opening, and baudrate selection can be performed securely. In this way, tests can be carried out in a repeatable way using the values selected by the user with secure communication between software and hardware.

This software developed becomes a suitable platform not only as a test environment, but also for calibration and verification of the system. With this structure, the communication of TDR devices can be evaluated with secure and repeatable tests and the most ideal working conditions can be determined.

6.2.1.1 User Interface (GUI) Design

This interface, designed with the PyQt5 library, offers the user the opportunity to visually control the tests with its simple structure and parameters that can be defined by the user (port, baudrate, number of messages, etc.) it has a structure that initiates communication operations with, can visually transmit data transmission and data reception to the user instantly, and shows measurement results to the user. The appearance of the interface is shown in Figure 7.

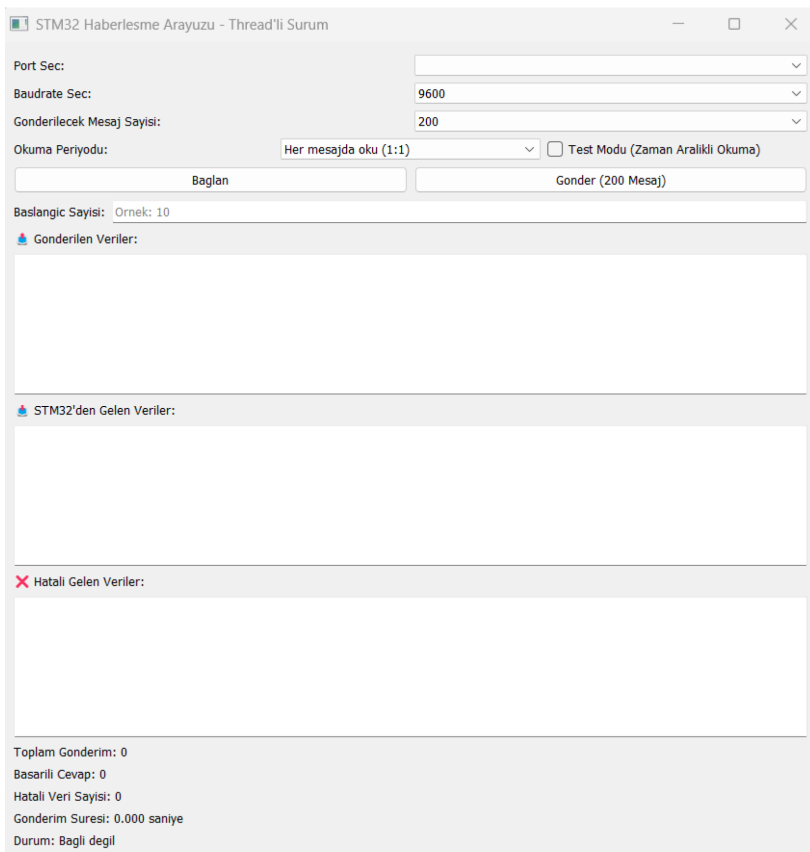

Figure 7. Interface for Baudrate Tests

6.2.1.2 Parameter Definitions

The control units located at the top of the interface enable the configuration of the communication process by the user. The user can configure the ports of the system to which is connected, determine the baudrate values that wants to perform the test. It can also set the total number of messages to be sent according to its preference from here. It can also determine how often the message reading process will be performed with the reading period setting

6.2.1.3 Test Modes and Advanced Settings

The “Test Mode”, which can be activated according to the user's preference, provides the reading process depending on the time interval. This feature is used to evaluate the timing sensitivity and response time of communication. In addition, entering the initial value of the user makes the test scenarios more controlled.

6.2.1.4 Data Tracking Panels

The interface provides detailed information about the communication process to the user about the transmitted, received and incorrectly received data. By adding a time stamp to each data, it is ensured that the analysis process establishes temporal integrity. In this way, the user knows to observe which data are correct and which are incorrect and has information about the performance of the system.

6.2.1.5 Feedback and Status Information

During the test process, the number of data transmitted, the number of data successfully received, the number of errors data and the total elapsed time are constantly updated the information fields located in the lower section of the interface, and the user can track the process in real time. In addition, information such as whether the system is connected or not is also transmitted to the user in this section.

6.2.1.6 Communication Infrastructure

In the designed system, the communication between the computer and the TDR device (or STM32) uses the UART protocol. The PySerial library has been used as the equivalent of this infrastructure on the Python side. With PySerial, operates such as port operations, baud rate adjustment, data transmission are presented to the user. In this way, serial communication with the hardware is provided.

Via the PyQt5-based interface, it converts the user's preferred parameters into a serial connection via PySerial. The system automatically detects the existing serial ports that are in connection with the computer and presents these ports in such a way that the user can choose from the interface. In this way, the port selection error is reduced.

Serial port connection is provided according to the parameters determined by the user and communication takes place with this connection. The data is transmitted bidirectionally and this process can be controlled with high accuracy thanks to the PySerial library.

The data reading process is provided by a thread that works independently of the designed interface. This structure ensures the reactive operation of the system by checking the data at intervals. In this way, the blockages that may occur on the interface are prevented and it is possible to synchronize the data.

The “buffer” data from previous test that may occur during communication is automatically cleared and thus the tests are performed safely.

6.2.1.7 Functional Architecture

The developed system has a visual interface, uses also uses a multi-threaded architecture in the background to enable reliable and sustainable data transmission. The designed structure separated the data reading and data sending processes by using the QThread class offered by PyQt5. Thus, a stable state has been achieved in terms of performance and reaction processes. The UML diagram showing the structure of the system is shown in figure 8.

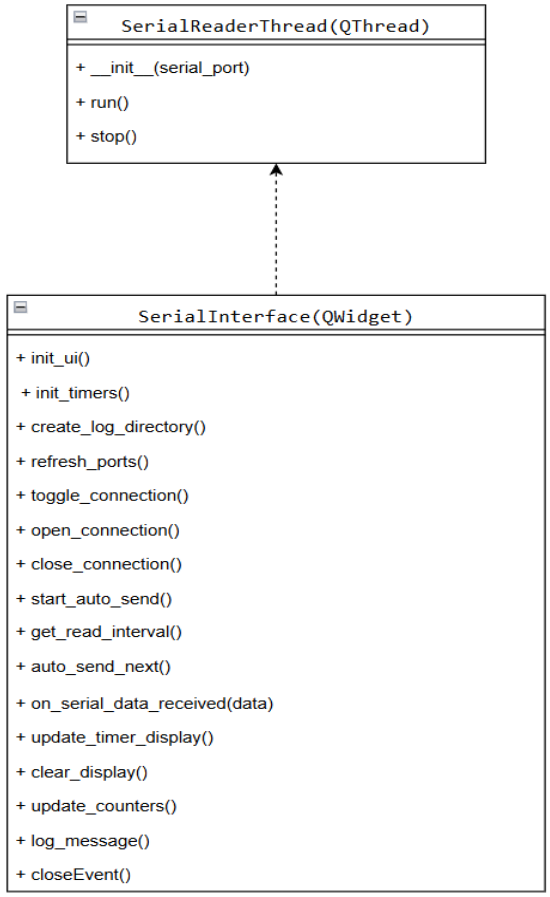

Figure 8. UML Diagram of Baudrate Interface

6.2.1.7.1 Classes and Tasks

The designed software architecture is divided into two classes:

- **SerialInterface:** It is the main class where interface and control systems take place. The creation of UI components is performed with the functions init_ui(), initialization of schedulers init_timers(), updating of port lists refresh_ports(), opening and closing of port connections open_connection() and close_connection(), sending data start_auto_send() and auto_send_next().
- **SerialReaderThread:** The structure derived from the QThread class is an independent thread that continuously performs data reading in the background. with the run()

function, the thread listens for data and the signal is transmitted to the interface via pyqtSignal when the data is received.

6.2.1.7.1 Reading Data

Data reading operations are performed with the run() function in SerialReaderThread. It is in a continuous loop and checks whether there is any pending data. If a pending data is detected, it decodes this data in UTF-8 format and passes it to the on_serial_data_received(data) function of the SerialInterface class. Thanks to this, the interface does not bother with the port and receives the data directly.

The stop operation is controlled by the stop() function. If the application is closed or disconnected, it ensures that the thread is terminated safely.

6.2.1.7.1 Port Connection

The toggle_connection() function is executed via the “Connect” button on the interface. This function checks whether there is a connection and activates the open_connection() or close_connection functions.

- open_connnection(): Creates a PySerial connection with the user's preferred parameters(port, baudrate). Performs buffer cleaning before the operation and starts the data read thread.
- close_connection(): Performs the connection termination process, the active thread is stopped.

6.2.1.7.1 Data Transmission and Timing Structure

The data forwarding process is triggered when the start_auto_send() function is started. This function:

- Receives the parameters of the initial value and the maximum number of messages requested to be transmitted.
- QElapsedTimer is started to measure the message sending time.
- QTimer is started by calling the auto_send_next() function at intervals.

The auto_send_next() function updates the counters in the GUI by sending a message to the serial port. When the sending process is completed, the sending time is transmitted to the user via update_timer_display().

6.2.1.7.1 Verification of Data

on_serial_data_received(data) function with the data import process is performed. The incoming data is compared with the expected message had been a match, this situation is considered as an error and the log_message() function incorrectly logged when data is written to it. At the same time, it also records successful transactions.

In addition:

- All text boxes are reset with the clear_display() function.
- With the log_message() function, data exchange is logged with a timestamp.
- the update_counters() function updates the total number of data sent and how many of them succeeded and how many failed.

6.2.2 TDR Test Interface

Using TDR methods, an interface was developed to enable the detection of leaks along the transmission line, especially in underground water pipes.the reflections of the signals sent by TDR are analyzed through this interface, and distance-dependent detection of distortions along the line is provided. The interface developed in this context performs functions such as visualization of the results obtained by communicating with the TDR device, adjustment of measurement parameters, distance measurement and data recording measurement. This interface is seen in figure 9.

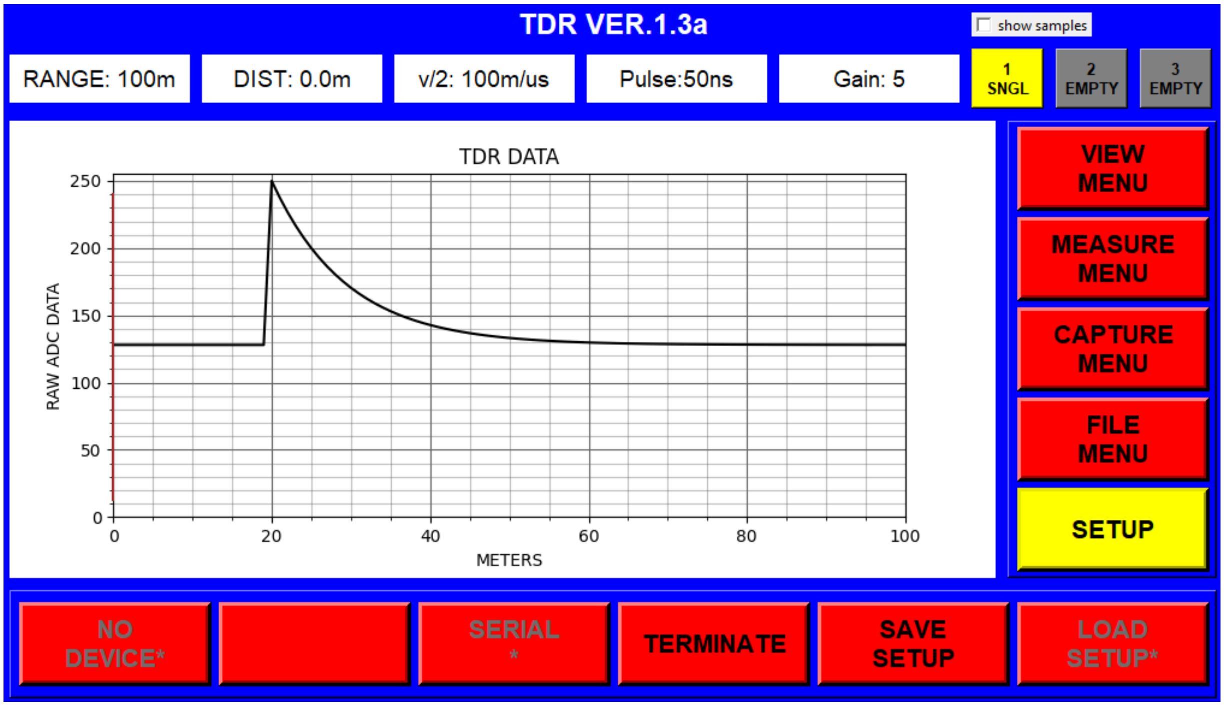

Figure 9. TDR Test Interface

6.2.2.1 Components of the Interface

6.2.2.1.1 Upper Area

- **Range:** indicates the maximum distance at which the measurement will be performed
- **DIST**: Specifies the distance decoupled from the markers
- **v/2**: Specifies the signal propagation speed
- **Pulse:** Specifies the duration of the transmitted signal
- **Gain:** Shows the gain of the received signal

6.2.2.1.2 Graphic Area

- The horizontal axis shows the distance in meters. The vertical axis shows the ADC value of the signal.
- The point where the reflection starts indicates the location where there is a fault or connection change.

6.2.2.1.3 Right Menu

- **VIEW MENU, MEASURE MENU, CAPTURE MENU, FILE MENU, SETUP:** Thanks to these menus, the user can perform measurement, visualization, data retrieval operations.

6.2.2.1.4 Bottom Menu

- **NO DEVICE, SERIAL, TERMINATE:** The connection and port settings of the device are controlled from this menu.

6.2.2.2 Software Features

The developed interface is equipped to provide a wide-ranging analysis opportunity for the user. The interface allows to visualize the signal data by using the matplotlib library. Thus, the user can perform instant analysis according to time and distance. The pyserial library is used to provide serial communication operations. In this way, data reception, command sending can be performed. This structure created allows data flow between the TDR device and the user interface Decoupled from the TDR device. By offering multi-channel support, the interface can enable three different data sets to be received simultaneously and displayed graphically. In this way, it is ensured that different measurements are compared and analyzed.

6.3 Tools

- Visual Studio Code
- Spyder
- STM32CubeIDE
- Proteus 8

7. EXPERIMENTS

7.1 Experiment Setup

In order to analyze the performance of the TDR-based leak detection system developed in this study comparatively in different environments (air, water and soil), a laboratory device has been designed and constructed in which controlled and repeatable measurements can be made. In Figure 10, the general layout of this experimental setup is seen.

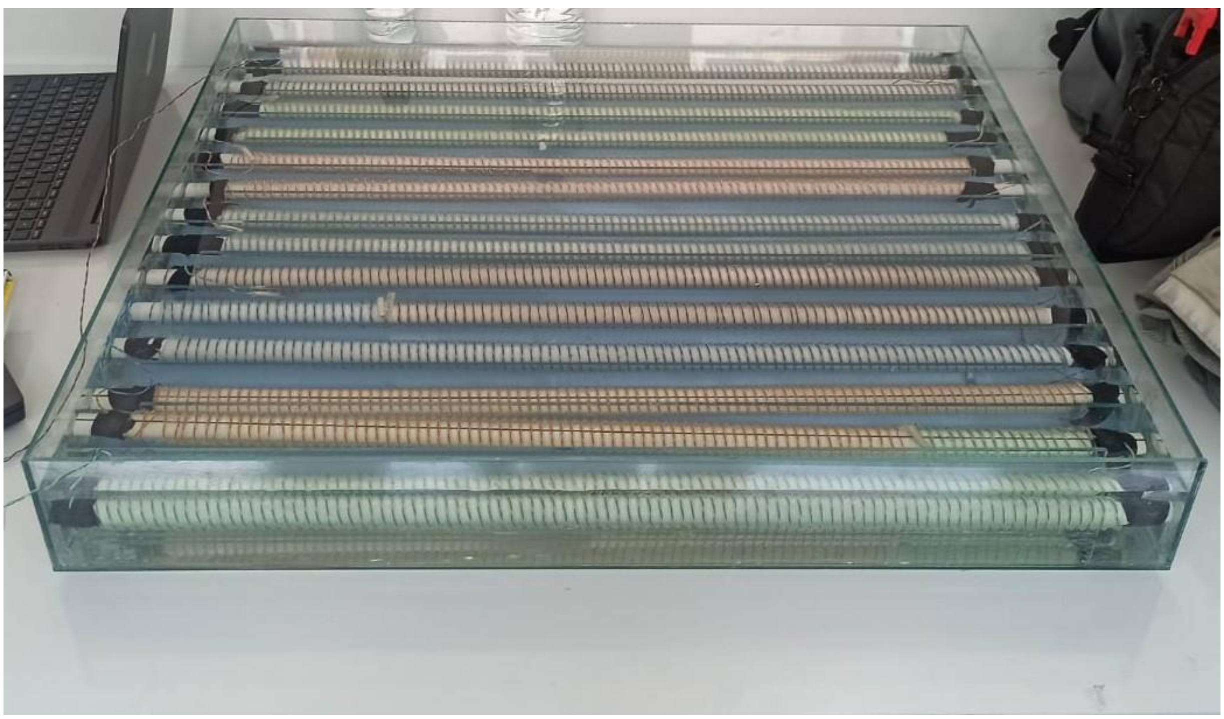

Figure 10. Experimental Setup

The experimental setup consists of 14 separate compartments, which are positioned consecutively so that each one has a length of 75 cm. These compartments are made of glass and the total length is determined as 10.5 meters. Each section is designed in such a way that real environmental conditions (air, water, soil) can be physically modeled.

PPRC (Polypropylene Random Copolymer) pipes with an inner diameter of 18 mm have been preferred for conductor cable winding. These pipes have been preferred both because of their internal volume, which will make electromagnetic wave transmission possible, and because of their suitability for conductor winding. Approximately 7.5 meters long conductor is wrapped in each pipe and a total of 117 meters long sensor cable is integrated throughout the entire system.

In order to prevent interference that may occur in the cable transition zones and minimize the external signal effects, the transition points have been kept as short as possible; the ends that have contact with the external environment have been insulated with silicone material. This measure has been taken in order to protect the integrity of the measurement while ensuring electrical safety.

After the installation of the device, measurements were made by using the TDR (Time Domain Reflectometry) device for signal generation and data processing processes together with the Python-based TDR interface software specially developed in this study.

7.2 Tests in Air Medium

The first stage of the tests covers the scenario in which electromagnetic waves propagate only in the air and there is no dielectric change. The purpose of this test is to analyze the basic signal transmission and reflection characteristics of the system and to create a reference starting point.

In this context, the outputs of pipes numbered 3, 6, 8, 10, 12 and 14 selected from 14 sections were left open circuit and the reflection behavior of the signals transmitted up to these points was studied. In each measurement, the amplitude of the sent signal and the amplitude of the returned signal were compared and the obtained data were digitized and analyzed via the Python interface.

As a result of these analyses, changes in the amplitude of the reflected signal were observed as the distance increased, and the nonlinear transmission behavior of the system was determined. It is estimated that such behaviors are caused by the effects of cable internal structure, impedance mismatch and open circuit conditions on the signal form.

Table 1. Calculation of Losses According to Changing Cable Lengths

Ports (metre)	The Amplitude of The Transmitted Wave	The Amplitude of The Reflected Wave	Error
24	255	184	71
48	255	182	73
64	255	180	75
80	255	178	77
96	255	176	79
113	255	174	81

Table 1 shows how the difference(error) between the wave amplitude measurements sent from different connection points and the amplitude of the reflected wave is affected depending on the distance. Based on these data, it is observed that as the measurement distance increases, the difference between the amplitude of the sent signal and the amplitude of the reflected signal. This is due to propagation losses or environmental factors that the signal encounters while moving. Increasing the distance causes more distortion of the signal, which leads to a decrease in the amplitude of the signal. The data obtained from the table shows that the distance-dependent attenuation effect of the TDR system should be paid attention to and may negatively affect the accuracy of measurements made at long distances.

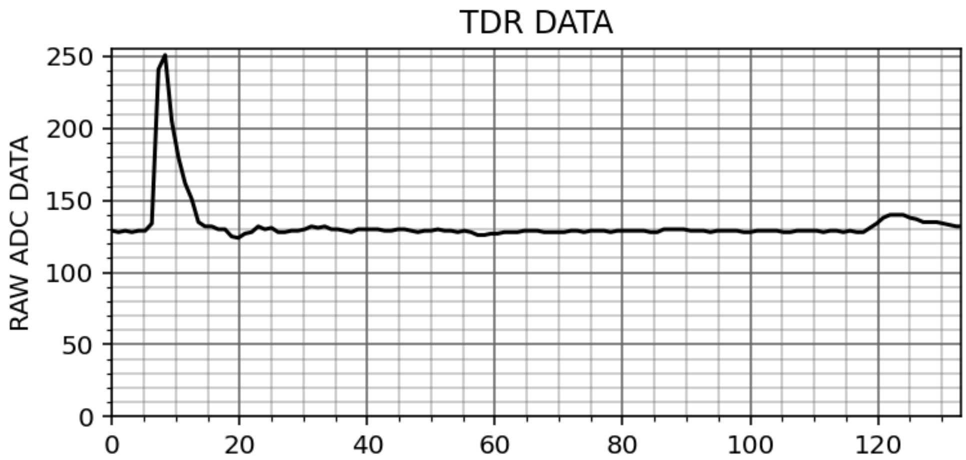

Figure 11. TDR Data

In Figure 11, it is seen that when the signal reaches the end of the transmission line, the amplitude of the reflected wave decreases. The reason for this is that it shows that the signal undergoes damping during transmission and the energy of the reflected wave decreases. In addition, the reason why this amplitude is low also supports that the impedance change at the end of the line is not very large and that the system has a homogeneous structure.

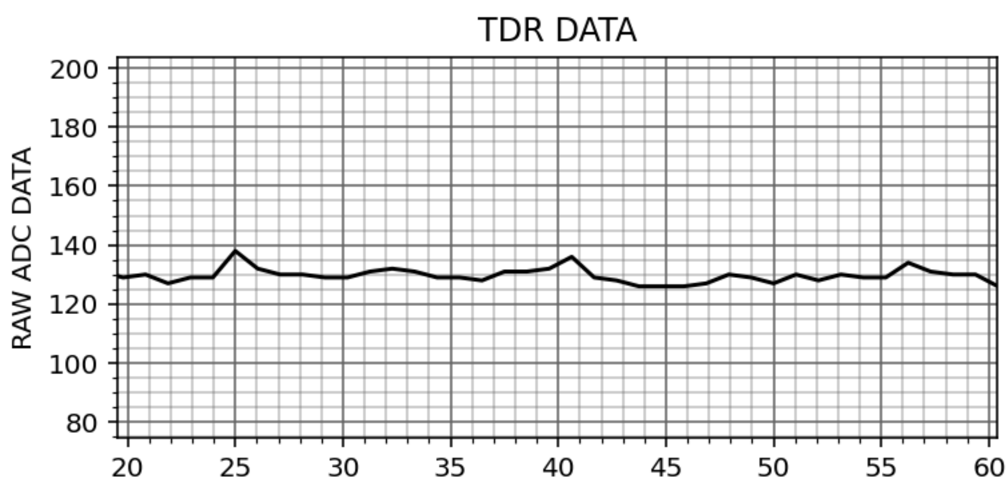

Figure 12. Distortion of The Connection Points

In Figure 12, positive directional reflections are formed due to the electromagnetic wave at the connection points contacting the air. These show the impedance increases along the line. Due to the low dielectric coefficient of the air, the impedance beats in these regions and positive directional reflections are seen on the graphs. These reflections are important for detecting situations that may affect the integrity of the signal positively.

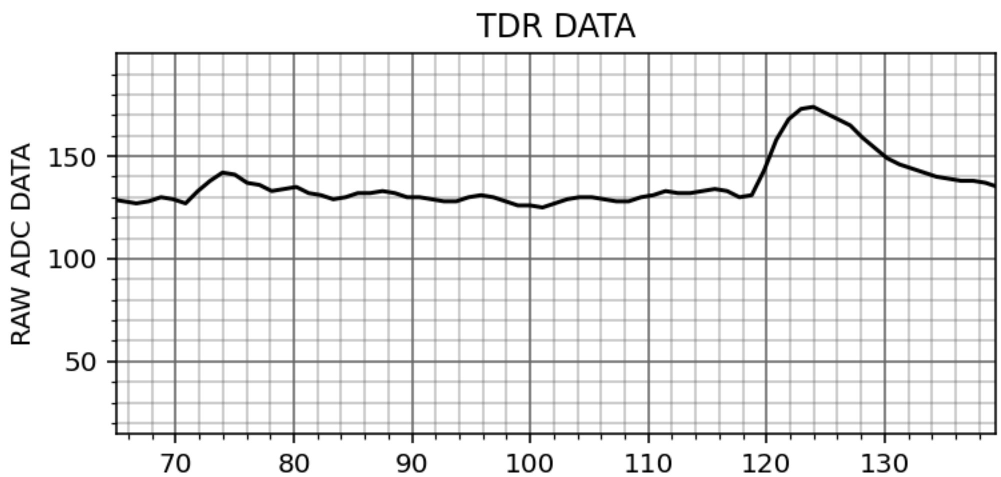

Figure 13. Reflection at The Moment of Transition From The Old Cable To The New Cable

In Figure 13, at 72nd meter, positive directional reflection observed on the meter indicates that there is an impedance increase on the transmission line. The reason why the amplitude of this reflection differs from other reflection amplitudes is because the cable used has changed and the impedance of the new cable is higher than the previous cable. This impedance increase creates a positive directional reflection in the signal. In addition, the magnitude of the amplitude also provides information about the impedance difference. It is very important that such discontinuities, which may disrupt the integrity of the signal, are detected by TDR.

7.2 Tests in Air Medium

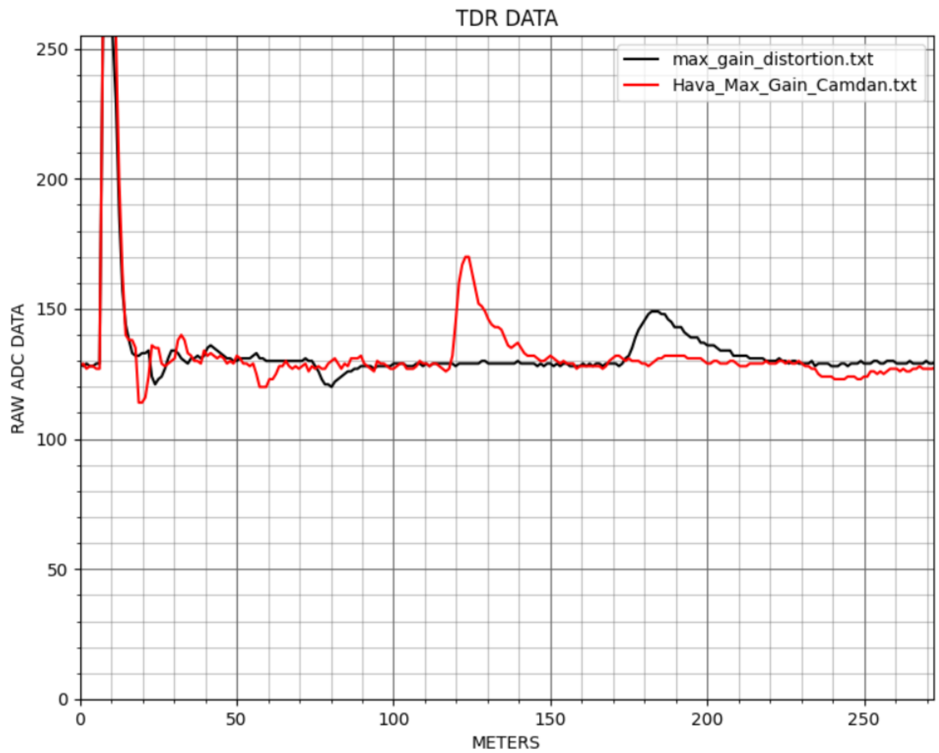

Figure 14. Tests Performed on The Air and Water Environment

At Figure 14, the graphs observed in the figure are the TDR test results performed in air and water environments. These tests were conducted in order to observe how the TDR device is affected in measurements based on electromagnetic wave reflections depending on environmental conditions. Due to the impedance values in different environments, cables with the same physical properties may react differently and cause these deviations. Negative reflections are observed at the 55th meter of the test result graph in the air environment and at the 75th meter in the test in the water environment. The reason for these negative reflections obtained is due to the fact that the impedance values of the cables in the spiral structure used for the test are lower than those of straight cables. The reason why the spiral cable has a lower impedance value is that it brings the conductors closer to each other and therefore leads to an increase in capacitance. Although these reflections observed in both environments pass through the same spiral cable, they are observed at different distances on the graph. This is because the dielectric coefficients of the media affect the signal propagation rate. The propagation speed of a transmitted signal is inversely proportional to the dielectric constant (ε_r) of the medium, and the formula expressing this state is as follows.

$$v = \frac{c}{\sqrt{\varepsilon_r}} \tag{8}$$

$$\varepsilon_r = The\ dielectric\ constant\ of\ the\ medium\ is$$
$$v = propagation\ speed$$
$$c = the\ speed\ of\ light$$

The dielectric constant of water is about 80 times that of air, which has a dielectric constant is 1. This indicates that an electromagnetic wave will travel more slowly in an aquatic environment.

In the software of our TDR device, it is stated that the signal is moving at a constant (at the speed of light). The time is getting longer because the signal is moving slower in the water environment, but our TDR device thinks it is traveling a longer distance because it considers the speed constant and the time is getting longer. For this reason, the impedance drop observed during the transition to the spiral cable was observed at a further distance in the water environment are observed.

As a result, the spiral cable produced negative directional reflection due to its low impedance, but due to the dielectric autonomy of the media, these reflections were observed in different locations due to the difference in propagation speed.

7.3 Tests in Soil Medium

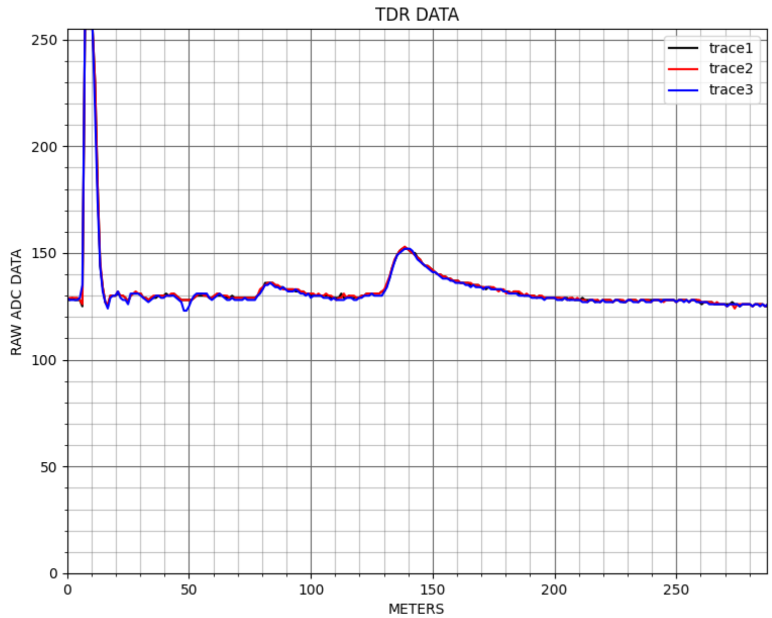

Figure 15. Test Results of Soil Enviroment

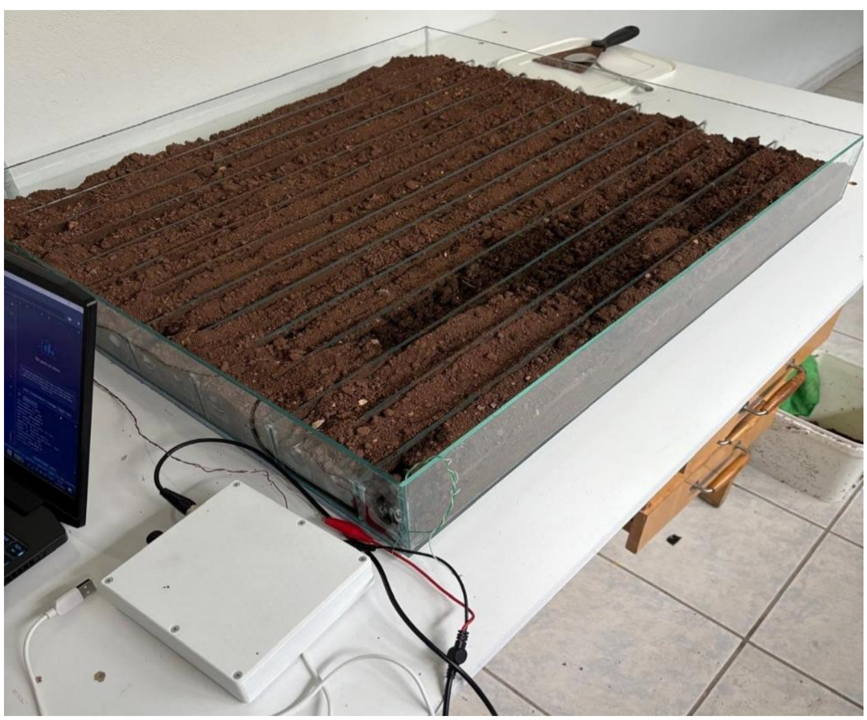

Figure 16. Soil Test Setup

In Figure 15, 3 different TDR measurements(trace1, trace2, trace3) are plotted. Point at 47th meter the Trace 3, a distinctly negative directional reflection was observed, unlike other trace graphs. This reflection was caused by water spilled into the soil during the test in Figure 16. Negative directional reflection was observed because the signal traveling along the line encountered a medium with a lower impedance value due to the dielectric constant of water.

As a result of tests performed at different baudrate levels, it has been observed that the system can transmit data with high accuracy at certain sending intervals and that the error rate increases when it goes below these intervals. Figure 17 and Table 2 show the results obtained for the baudrate value of 9600 bps. Accordingly interval value 80, the system worked stably with minimum error in the sending interval; when it was lowered below this interval, a noticeable increase in the error rate occurred.

7.5 Baudrate Tests

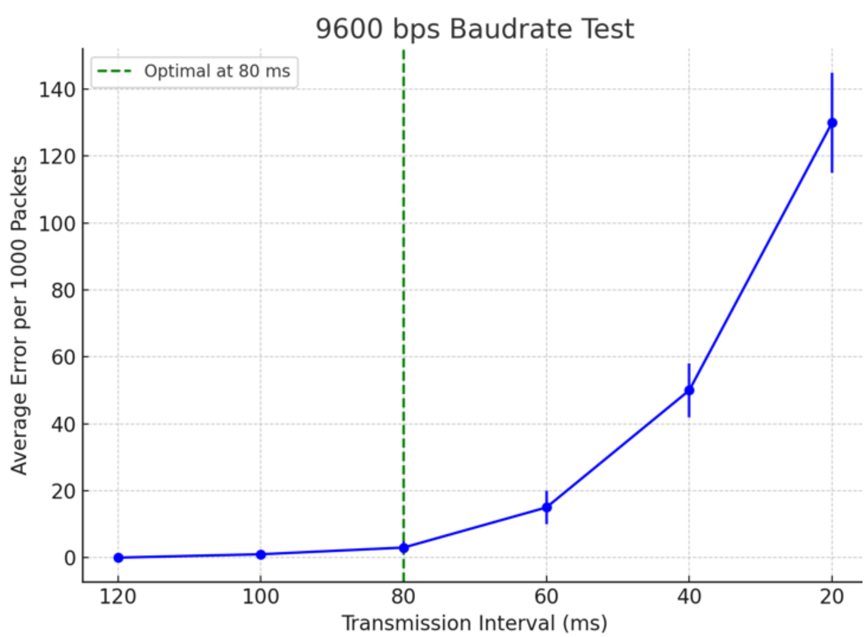

Figure 17. 9600 Baudrate Result Graph

Table 2: 9600 Baudrate Test Results

Baudrate	Transmission Interval (ms)	Average Errors per 1000 Packets	Standard Deviation
9600	120	0	0
9600	100	1	1
9600	80	3	2
9600	60	15	5
9600	40	50	8
9600	20	130	15

Similarly, Figure 18 and Table 3 contain the results of the tests for the baudrate value of 115200 bps. The optimum transmission interval at this speed was determined as 16 ms and timing conflicts and data losses were detected in the system at shorter intervals. The analyses performed for both baudrate levels have clearly revealed the limits of the system's ability to operate while maintaining signal integrity.

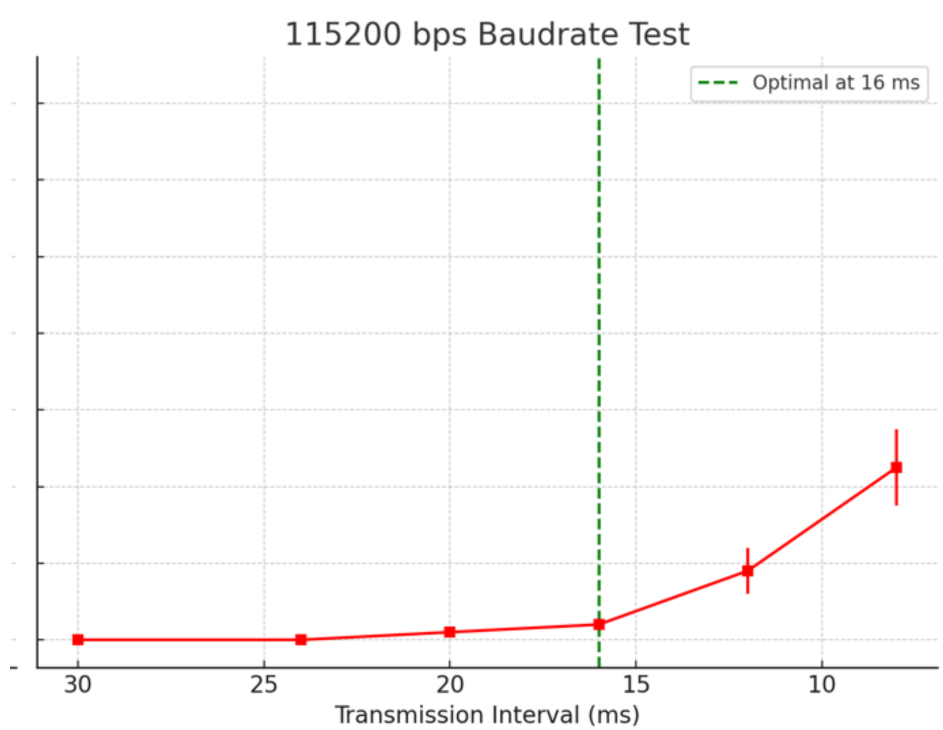

Figure 18. 115200 Baudrate Test

Table 3: 115200 Baudrate Test Results

Baudrate	Transmission Interval (ms)	Average Errors per 1000 Packets	Standard Deviation
115200	30	0	0
115200	24	0	0
115200	20	2	1
115200	16	4	2
115200	12	18	6
115200	8	45	10

It was observed that the tests were repeated not only in the air environment, but also in more complex dielectric environments such as water and soil, and similar results were obtained. This situation shows that the RS-485 based communication infrastructure can operate without being affected by dielectric changes caused by the environment and that the system has a high immunity to external conditions. Thus, it has been concluded that the TDR system can provide secure and consistent data transmission in field applications.

7.6 The Testing and Verification Process of the Power Distribution System

Three-stage tests were carried out in order to verify the applicability and functionality of the designed power distribution system in real life:

7.6.1 Test 1: Power Switching and Energy Continuity Experiment

In this test, the Arduino Nano microcontroller was connected to the computer via USB, both energized and sending commands via the serial port. Three commands are defined in the software running on Arduino:

- PON1: By applying 12V to the OUT1 pin of the motor drive and 0V to the OUT2 pin, positive energy is provided to the EU line.

- PON2: Energy transfer was performed again by applying 0V to the OUT1 pin and 12V to the OUT2 pin. In both cases, it was observed that energy was transmitted to the EU line, during which it was confirmed that the LED was lit.

- POFF: The power on the EU line has been cut off by turning off the OUT pins. It has been observed that when the power is cut off, the LED continues to burn through the capacitors for about 4-5 seconds more. This situation shows that capacitors used as energy storage units can provide energy for long enough for the system to take measurements.

7.6.2 Test 2: Communication Test with Capacitive Battery Network

In the second test, the Arduino connected to the capacitive battery network is programmed to send a "Hello" message via the UART protocol. In this scenario, the Arduino is positioned to be powered only from capacitors instead of a power supply.

Arduino communicated via UART with RS-485 TTL converter; the message transmitted at 9600 baud rate was successfully displayed on the computer screen through the ZK-U485 module. This test has proven that the system is able to perform communication without interruption and correctly when working with capacitive energy.

7.6.3 Test 3: TDR Measurement Security and Distance Accuracy Test

In the last test, although the TDR device was supplied with an external power supply, energy and communication operations were carried out over the same line. The purpose of this test was to check the measurement accuracy of the TDR system on the A-B line, which was isolated by coils. In the measurements made, the distance along the 100 meter cable was determined without error and the TDR system worked successfully. This, in turn, revealed that the coil insulation guarantees measurement accuracy by protecting the TDR signals.

This structure shows that the system has been tested both in terms of energy transmission continuity, communication stability and integration with TDR and has given successful results. The power management network is shown in Figure 19. In Figure 20, the measurement network is shown.

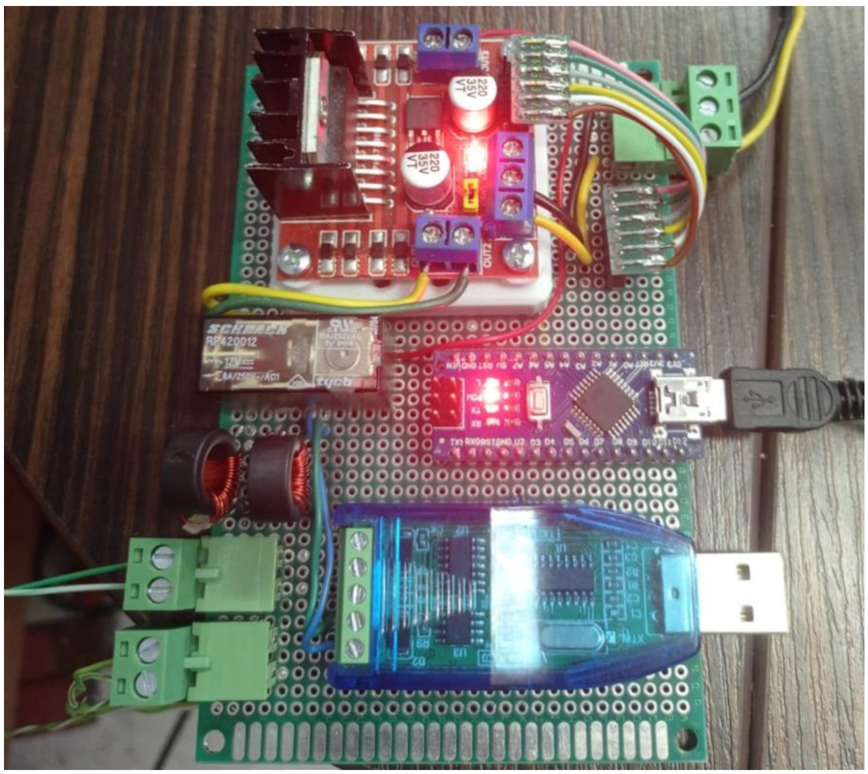

Figure 19: Power Management Network

Figure 20: Measurement Network

8.PROJECT PLAN

The implementation of the TDR-based leak detection system developed in this study has been carried out with a multi-stage engineering process. The goals, contents and progress statuses of each work package are described in detail below.

8.1 Work Package 1: Literature Review and Technical Review

At the beginning of the project, the literature on the basics of TDR (Time Domain Reflectometry) technology and its previous use in underground pipelines was extensively scanned. Existing methods, system architectures and challenges have been evaluated. In this context, how TDR signals are analyzed on the basis of damping, reflection coefficient and electromagnetic properties have been examined; in addition, existing RS-485 communication methods and power transmission strategies have been investigated. The direction of the system design was given with the information obtained from the literature.

8.2 Work Package 2: Material Supply

The electronic components required for the installation of the hardware (ZK-U485, MAX490, STM32 microcontroller, TDR module, communication cables, etc.) have been determined and provided. In addition, an underground cable line infrastructure of about 100 meters has also been prepared for long-distance tests. At this stage, material quality, compliance with the communication standard and signal integrity have been taken into account.

8.3 Work Package 3: Test Circuit Installation

The basic circuit structure has been created for the tests performed. The system is configured as PC– ZK-U485–RS485–MAX490–STM32. The circuit has allowed tests to be performed to analyze errors that may occur in data transmission and to evaluate communication security.

8.4 Work Package 4: Circuit Development and Microcontroller Programming

After the circuit installation, a special software based on the UART protocol was developed on the STM32 microcontroller. This software reads the UART data from the PC on a byte basis and understands that the packet has been completed when it sees the \n character and sends the received data back to the PC for verification purposes. Error control mechanisms have also been put into operation during this process. Software details will be included extensively in the Software section.

8.5 Work Package 5: Interface Development and Baudrate Tests

Due to the fact that terminal-based tests are insufficient and troublesome, a special Python-based test interface has been developed. The interface allows you to define COM port selection, baudrate value, amount of data to be sent and meter start values in a user-friendly way. In this way, data transmission was tried at different baudrates, and baudrate interval was determined where the system could work safely on the 100-meter RS-485 line. The details about the interface will be explained in the Software title; the methodology and findings of the tests will be discussed in the Experiments section.

8.6 Work Package 6: Tests Performed in the Air with the TDR Device

The first TDR tests were carried out in the air in order to evaluate the system's ability to detect basic reflection signals. In this way, the connection and operating accuracy of the TDR device has been verified and reference signals have been obtained.

8.7 Work Package 7: TDR Tests - In the Water Environment

In the next stage, the TDR device was tested in an aquatic environment. In these tests, the effect of the conductive medium on the signal was observed and the characteristic reflection behavior caused by the high dielectric constant of water was analyzed.

8.8 Work Package 8: TDR Tests - In the Soil Environment

At a later stage of the project, the TDR device was tested integrated with pipes buried under the ground. In these tests, damping and reflection curves were obtained in soil environments with different dielectric properties. Thus, it has been evaluated how the device performs in real field conditions.

8.9 Work Package 9: Power Distribution Network Installation

One of the main goals of the project is to enable underground sensor units to operate without external batteries or energy sources. For this purpose, it is aimed to conduct time-division energy transmission via the RS-485 line and store this energy in capacitive batteries (for example, supercapacitors). It is planned that each unit will become active and take measurements when it reaches a sufficient energy level. Although this structure has not yet been implemented, the system architecture has been designed with flexibility that can be integrated into this structure.

Table 4: Resource assignments for work packages

Work Package	Resource	Duration (weeks)
1	Batuhan, Mert, Alper, Emre	3
2	Batuhan, Mert, Alper, Emre	2
3	Batuhan, Mert, Alper, Emre	2
4	Mert, Emre	1
5	Batuhan, Alper	2
6	Batuhan, Mert, Alper, Emre	1
7	Batuhan, Mert, Alper, Emre	1
8	Batuhan, Mert, Alper, Emre	1
9	Batuhan, Mert, Alper, Emre	3
PROJECT COMPLETITION TIME		16

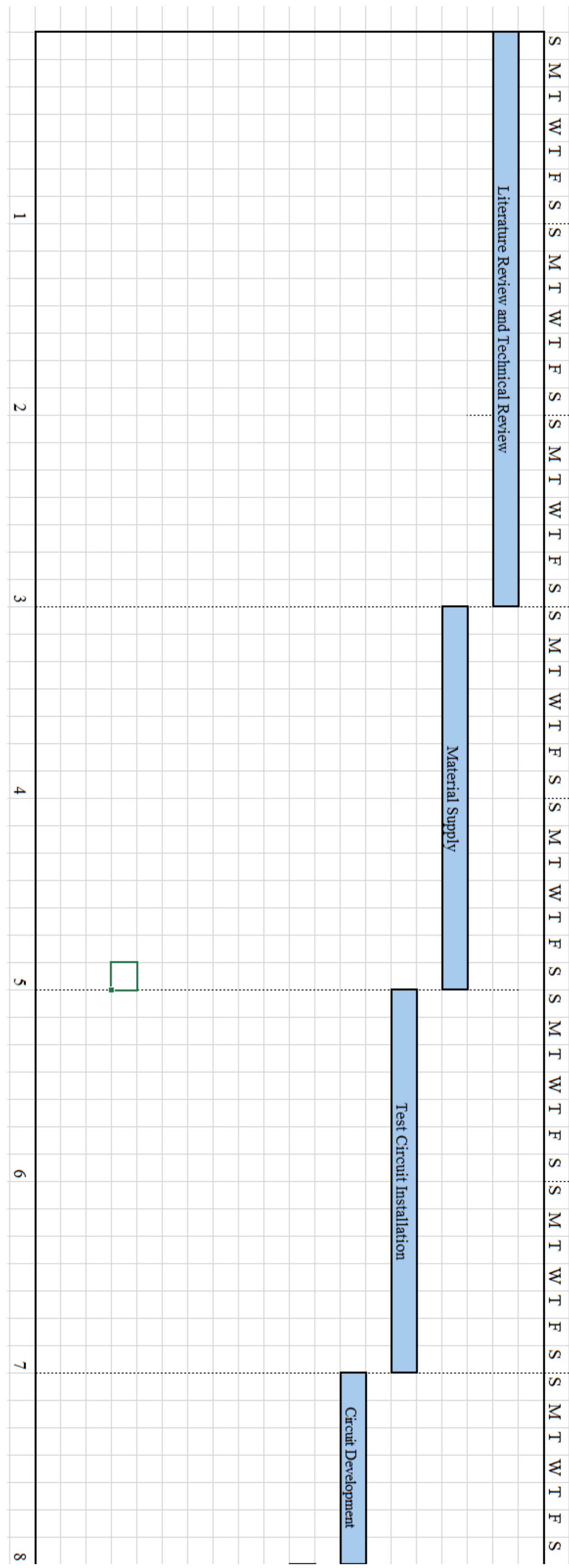

Figure 21 Gantt Diagram first 8 week

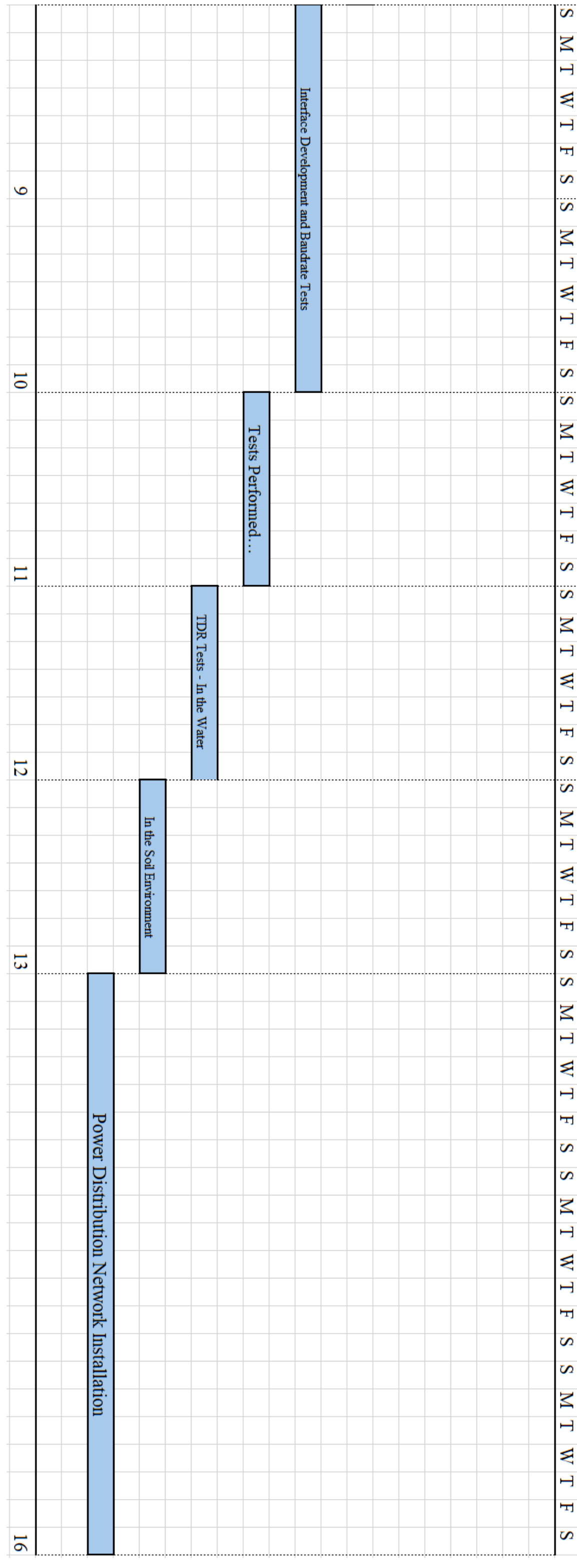

Figure 22 Gantt Diagram last 8 week

9. CONCLUSION

In this Project, successfully designed, implemented and evaluated a scalable, low-cost Time Domain Reflectometry (TDR) sensor network for underground pipeline leak detection. By integrating multiple TDR units along a single sensor cable, shown that high-frequency pulse signal transmission, power distribution and bidirectional data communication can exist on a common RS-485 line. Laboratory experiments confirmed that in air, water and soil environments, the system is able to accurately detect impedance changes corresponding to leaks at distances up to 100 m, meeting the physical and performance requirements specified in Section 2.

9.1 Achievements and Design Evaluation

Integrated Sensor Network: A modular architecture in which each embedded node consists of an STM32 microcontroller, a TDR module and a MAX490 transceiver. Communication and power are multiplexed over time over the same differential pair, eliminating the need for separate energy cables and reducing infrastructure complexity.

Energy Management Strategy: Through scheduled energy transmission and supercapacitor storage, each node charges independently during the “power control unit", and then performs measurements and data loading during the “sensor network". Initial bench tests confirmed uninterrupted operation without external batteries in line with economic and sustainability requirements.

Reliable Data Connection: Baud rate tests of RS-485 cable over 100 m using PyQt5/PySerial GUI have identified stable serial communication up to 2 Kbps with packet error rates close to zero, fulfilling our communication integrity specification.

Environment: Air, water and soil experiments showed clear reflection signatures at known discontinuities, confirmed the system's resistance to environmental noise, and confirmed compliance with health and safety standards (no harmful emissions).

User Interface: A dedicated GUI allows for real-time configuration, monitoring of transmitted/received packets, error logging and dynamic adjustment of test parameters, meeting functional availability requirements.

9.2 The Requirements

All physical (≤100 m, underground interoperability), performance (power and simultaneous communication, ≥100 m pulse-access), economic (9000 TL budget) and security (emissions not extreme) it was observed that.

The manufacturability requirement is met by using ready-to-use components (STM32, ZK-U485, MAX490) and standard PVC, providing easy replacement and repair.

9.3 Outstanding Tasks and Improvements

Field Deployment of the Power Grid: Although our timed multi-storey power strategy has been successful in the laboratory, field-tested supercapacitor charging under real underground conditions has not yet been performed. Soil resistance and long-term stability tests are ongoing. Instead of using a relay in the system, a system that consumes less power and faster than a relay can be designed using BJT.

Central Control Unit Integration: The final integration and automatic timing logic for multi-node coordination under a single PC controller, including fault tolerance routines, are planned for future work.

Extended Range and Scalability: The sensor network is designed intended to be repeated with lengths of 100 meters to create a huge network. Thanks to this network, it is intended to serve a neighborhood or a large campus. Taking into account the weakening of the TDR pulse with increasing range, more healthy measurements can be made at a long distance by increasing the pulse size by integrating amplifier circuits into the output of the TDR.

Automatic Leak Classification: Adding machine learning algorithms to analyze reflection waveforms for leak severity estimation is a planned development.

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