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Developing Radon-Sensor and Gateway Communication for the ArtEmis Project: A Design and Implementation Approach

An In-Depth Analysis of Sensor-Gateway Interaction in the ArtEmis Initiative

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ABBE ALSHAIKH

Stockholm, Sweden, 2023

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Bachelor’s Programme in Information and Communication Technology
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Swedish title: Utveckling av Radonsensor, Gateway-kommunikation i ArtEmis-projektet: En design- och implementeringsansats
Swedish subtitle: En genomgående analys av sensorgateway-interaktion inom ArtEmis-initiativet

Abstract

Title: Low-Cost Connectivity and Data Transmission for Radon Gas Sensor Networks

Abstract:

This project explores the development and implementation of a low-cost and effective connectivity solution for radon gas sensor networks. The goal is to establish a reliable connection between the radon gas sensor and a gateway, which will transmit the collected data to the cloud for further analysis. The project's significance lies in its potential to improve environmental monitoring and public health through affordable and accessible technology.

The problem addressed in this Bachelor's thesis project is the challenge of creating a cost-effective and efficient communication system for radon gas sensors. This issue is of a suitable degree of difficulty, as it requires the selection and development of communication protocols, integration with the ArtEmis network, and validation of the system's accuracy and reliability. Despite its importance, this problem has not been directly addressed in the literature.

To solve the problem, we will investigate and propose a suitable interface for data transfer between the microcontroller unit (MCU) and the gateway. We will develop communication protocols and integrate the system with the ArtEmis network, ensuring the solution is accurate and reliable through extensive testing and validation.

The project's results will provide a practical solution for low-cost connectivity and data transmission in radon gas sensor networks. The impact of our work will be significant, as it will enable more widespread adoption of radon gas monitoring systems, leading to better environmental and public health outcomes. Our findings will serve as a foundation for future research and development in the field of low-cost sensor networks.

- **Topic area:** The topic area of this project is earthquake early warning systems, specifically focusing on the development and implementation of a radon-sensor and gateway communication system for the ArtEmis project.

- **Short problem statement:** The problem is to establish a low-cost and effective connectivity between the radon gas sensor and the gateway, transforming the measured values to be sent to the cloud.

- **Why was this problem worth a Bachelor's thesis project?** This problem is significant because it addresses the need for a reliable earthquake early warning system, which can help save lives and reduce the impact of natural disasters. It is of a suitable degree of difficulty for a Bachelor's thesis project due to the technical challenges in designing and implementing communication protocols and system integration. The problem remains unsolved as it requires a unique combination of expertise in communication systems, hardware, firmware, and environmental sensing.

- **How did you solve the problem? What was your method/insight?** To solve the problem, we conducted a literature review and background study on UART communication, RS485, and other relevant long-distance communication protocols. We defined system requirements, designed a communication system, and investigated power delivery options for the sensor. We then integrated hardware and firmware components and evaluated the performance of the implemented solution, comparing it to alternative communication methods.

- **Results/Conclusions/Consequences/Impact:** Our key results include the successful design and implementation of a communication system between the radon-sensor and the gateway that meets the defined requirements. Based on our results, others can further develop and improve the earthquake early warning systems and explore additional applications of similar communication systems. With the completion of this project, the ArtEmis [1] network can be expanded and integrated with the developed communication system, potentially enhancing the effectiveness of earthquake early warnings and ultimately contributing to public safety and disaster preparedness.

Keywords

Radon Sensor, Gateway Communication, ArtEmis Project, Design, Implementation, IoT, UART, Transmitter, Reciver, Parity bit, Half-Duplex

Sammanfattning

Det här projektet undersöker utvecklingen och implementeringen av en kostnadseffektiv och effektiv kommunikationslösning för radongassensornätverk. Målet är att etablera en pålitlig anslutning mellan radongassensorn och en gateway, som kommer att överföra den insamlade datan till molnet för vidare analys. Projektets betydelse ligger i dess potential att förbättra miljöövervakningen och folkhälsan genom prisvärd och tillgänglig teknik. Problemet som behandlas i detta kandidatarbetsprojekt är utmaningen att skapa ett kostnadseffektivt och effektivt kommunikationssystem för radongassensorer. Detta problem är av lämplig svårighetsgrad, eftersom det kräver utveckling av kommunikationsprotokoll, integration med ArtEmis-nätverket [1] och validering av systemets noggrannhet och tillförlitlighet. Trots dess betydelse har detta problem inte behandlats i stor utsträckning i litteraturen. För att lösa problemet kommer vi att undersöka och föreslå ett lämpligt gränssnitt för dataöverföring mellan mikrokontrollenheten (MCU) och gatewayen. Vi kommer att utveckla kommunikationsprotokoll och integrera systemet med ArtEmis-nätverket, och säkerställa att lösningen är noggrann och tillförlitlig genom omfattande tester och validering.

Projektets resultat kommer att ge en praktisk lösning för kostnadseffektiv anslutning och dataöverföring i radongassensornätverk. Påverkan av vårt arbete kommer att bli betydande, eftersom det kommer att möjliggöra en mer utbredd användning av radongasövervakningssystem, vilket leder till bättre miljö- och folkhälsoresultat. Våra resultat kommer att tjäna som grund för framtida forskning och utveckling inom området för kostnadseffektiva sensornätverk.

- **Ämnesområde:** utveckling och implementering av ett radon-sensor och gateway-kommunikationssystem för ArtEmis-projektet.

- **Kortfattat problem:** Problemet är att etablera en kostnadseffektiv och effektiv anslutning mellan radongassensorn och gatewayen, som omvandlar de uppmätta värdena för att skickas till molnet.

- **Varför var detta problem värt ett kandidatarbetsprojekt?** Detta problem är betydelsefullt eftersom det behandlar behovet av ett pålitligt varningssystem för jordbävingar, som kan hjälpa till att rädda liv och minska effekterna av naturkatastrofer. Det är av lämplig svårighetsgrad för ett kandidatarbetsprojekt på grund av de tekniska utmaningarna i att utforma och implementera kommunikationsprotokoll

och systemintegration. Problemet är olöst eftersom det kräver en unik kombination av expertis inom kommunikationssystem, hårdvara, firmware och miljöövervakning.

- **Resultat/Slutsatser/Konsekvenser/Påverkan:** Våra huvudsakliga resultat inkluderar den framgångsrika utformningen och implementeringen av ett kommunikationssystem mellan radon-sensorn och gatewayen som uppfyller de definierade kraven. Baserat på våra resultat kan andra ytterligare utveckla och förbättra varningssystem för jordbävning och utforska ytterligare tillämpningar av liknande kommunikationssystem. Med slutförandet av detta projekt kan ArtEmis-nätverket utökas och integreras med det utvecklade kommunikationssystemet, vilket potentiellt kan förbättra effektiviteten i tidiga varningar för jordbäving och i slutändan bidra till allmän säkerhet och katastrofberedskap.

Nyckelord

Radonsensor, Gateway-kommunikation, ArtEmis-projektet, Design, Implementering, IoT, UART, sänder, mottagare, paritetsbit, Halv-Duplex

Acknowledgments

I would like to thank xxxx for having yyyy. Or in the case of two authors: We would like to thank xxxx for having yyyy.

Stockholm, July 2023
Mohamamed Manar Nasri   Abbe Alshaikh

Contents

Chapter 1

Introduction

Earthquakes are among the most destructive natural hazards on Earth, causing significant loss of life, property damage, and long-term socio-economic consequences. One of the most promising precursors of earthquakes is the assumed increased emission of radon gas from deep layers of the Earth. Radon, a naturally occurring radioactive gas, is released from the soil and rocks beneath the Earth's surface and can serve as a significant indicator of seismic activity. However, traditional measurements of radon in soil or air are often hampered by large uncertainties. Direct measurements in water have proven to be more reliable but are inherently more difficult to achieve. The ArtEmis project aims to advance earthquake forecasting by developing a smart and scalable multi-sensor system for monitoring radon gas levels in groundwater. This thesis focuses on the development and implementation of a reliable communication system for the radon gas sensor networks, which is an essential component of the overarching ArtEmis project.

1.1 Background

The ArtEmis project aims to create a network of approximately 100-200 novel low-cost geochemical sensors that can measure changes in radon concentration in groundwater with unprecedented spatial and temporal resolution, along with other observables such as temperature and acidity(ptt value). The project intends to deploy these sensors across fault lines in Greece, Italy, and Switzerland and utilize artificial intelligence (AI) supported analysis to provide new insights into the relationship between radon levels and seismic activity. Establishing a reliable communication system between the radon gas sensors and a central gateway is crucial for the success of the ArtEmis project,

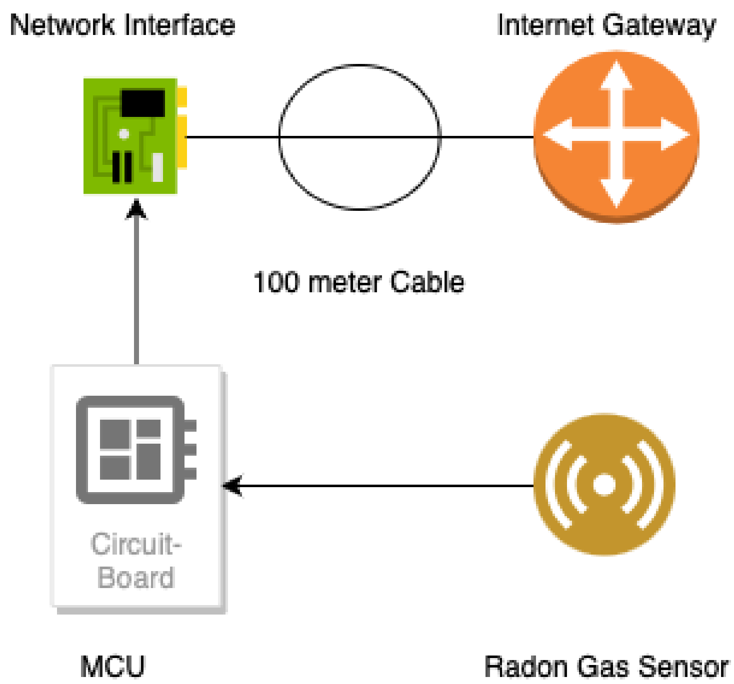

Figure 1.1: Connectivity diagram

as it will enable efficient data transmission to the cloud for further analysis.

1.2 Problem

1.2.1 Original problem and definition

The primary problem addressed in this thesis is the challenge of creating a cost-effective and efficient communication system that can establish a reliable connection between the radon gas sensor and a gateway, facilitating data transmission to the cloud for further analysis. The problem involves not only the development of suitable communication protocols but also the integration of the communication system with the ArtEmis network and the validation of its performance through extensive testing.

1.2.2 Scientific and engineering issues

Four scientific and engineering issues, or open questions to investigate in the thesis are associated with the development of a reliable communication system for radon gas sensor networks:

- Selection and development of suitable communication protocols that ensure accuracy and reliability in data transmission.
- Design and implementation of an interface for data transfer between the microcontroller unit (MCU) and the gateway.
- Integration of the communication system with the ArtEmis network.
- Validation of the system's performance, including accuracy, reliability, and energy efficiency.

1.3 Purpose

The purpose of this thesis is to design, develop, and implement a reliable communication system for radon gas sensor networks within the context of the ArtEmis project. The thesis also aims to contribute to the broader field of earthquake early warning systems by providing insights into the challenges and opportunities associated with the development of low-cost sensor networks for monitoring radon gas levels in groundwater.

The degree project's purpose is also to demonstrate the practical application of the acquired knowledge and skills throughout the course of study in a real-world context. The project will benefit stakeholders involved in the ArtEmis project, including researchers, engineers, and decision-makers, by providing them with a cost-effective and efficient communication system for radon gas sensor networks. Furthermore, achieving the goals of this project will have a positive impact on public safety and disaster preparedness by enabling more widespread adoption of radon gas monitoring systems, ultimately leading to better environmental and public health outcomes.

1.4 Goals

The project has several goals, which are considered as follows:

1. **System design and requirements definition:**
   (a) Define the system requirements, including data transfer rate, latency, noise immunity, and power constraints.

   (b) Design a communication system that meets these requirements using UART and the chosen communication protocol, considering factors such as cable length, wiring, termination, and impedance matching.

2. **Power delivery to the sensor:**

   (a) Investigate including a power cord to run the sensor.

Achieving these goals will significantly contribute to the development of the ArtEmis project, enabling more widespread adoption of radon gas monitoring systems and, ultimately, leading to better environmental and public health outcomes.

1.5 Delimitations

1.5.1 General Project Delimitations

- **Security Concerns:** This thesis does not focus on ensuring that communication protocols are secure to prevent unauthorized access or interception of sensitive information.
- **Time Constraints:** The project was completed within a limited time frame, which may have impacted the quality and completeness of the developed solution.
- **Resource Constraints:** Limitations in budget, personnel, or technology might have affected the project's scope, timeline, and quality.
- **Communication Challenges:** This thesis does not address effective collaboration and coordination between team members, which could potentially lead to delays and errors.
- **Scope Creep:** The project scope was limited to the development of a communication system for radon gas sensor networks, and did not consider expansion beyond the original objectives or requirements.
- **User Needs:** This thesis does not focus on addressing the needs of users or stakeholders to create a useful and relevant product that ensures successful adoption.

1.5.2 Specific Project Delimitations

- Limited literature on specific long-distance communication protocols was considered within the scope of this thesis.
- The project focused on developing a communication system, and did not address the detailed requirements and potential challenges of the MCU interface.
- Constraints in data transfer rate, latency, noise immunity, and power consumption were considered, but not exhaustively explored in this thesis.
- System design complexity due to factors such as cable length, wiring, termination, and impedance matching was acknowledged, but not thoroughly investigated in this project.
- Limited resources were available for system evaluation and comparison with alternative communication methods.
- Potential integration challenges between hardware and firmware components were considered but not addressed in depth.
- The sensor required for radon measurement have not been available for use during the project, limiting the practical testing of the developed solution.
- Temperature variations in the environment where the cables would be placed could impact system performance but were not considered within the scope of this thesis.
- The test and prototype equipment used in the project may not be waterproof, affecting the system's durability and reliability, but this aspect was not addressed in this thesis.
- The project considered the presence of two pair in the cable running from the gateway, with two designated for data transfer and the other two for powering the sensor. However, the implementation of the power feed in one pair was not carried out within the scope of this project.

1.6 Structure of the Thesis

This thesis is organized into seven chapters, each serving a unique purpose in the context of the research.

Chapter 1: Introduction This chapter provides a background to the study, stating the problem, goals, and limitations of the thesis. It sets the stage for the subsequent chapters by outlining the context and motivation for the research.

Chapter 2: Background The second chapter delves into a detailed exploration of the necessary background information. It provides an overview of UART, RS-XXX protocol family, bit rate, cable characteristics, and related work in the field. This chapter seeks to offer the reader a comprehensive understanding of the technical and theoretical aspects related to the project.

Chapter 3: Methodology Chapter 3 articulates the scientific and engineering methodologies applied in this research. It justifies the choice of method, elaborates on the simulations, and explains the research process. It also details the steps taken to define the problem, the literature review, the research paradigm, and data collection processes. An evaluation framework is also presented in this chapter.

Chapter 4: Simulation Studies on Data Transmission This chapter describes the simulation design and its execution. It provides a detailed account of how the simulation studies on data transmission were conducted, thus elucidating the practical application of the methodologies discussed in Chapter 3.

Chapter 5: Results and Analysis Chapter 5 presents the findings of the simulation studies and provides a comprehensive analysis of the results. Evaluation metrics are described and applied to assess the performance of the communication system.

Chapter 6: Discussion and Conclusions The sixth chapter provides a discussion of the results obtained from the simulations. It offers conclusions drawn from the analysis and reflects upon the goals and research questions posed at the outset of the thesis.

Chapter 7: Future Work The final chapter identifies the limitations of the current study and provides suggestions for future work. It outlines the potential for further research and improvement in this field. Additionally, this chapter reflects on the economic, social, environmental, and ethical aspects of the project, providing a holistic evaluation of the thesis.

Chapter 2

Background

2.1 UART

2.1.1 Introduction

The Universal Asynchronous Receiver/Transmitter (UART) peripheral is a key component in modern communication systems, providing a reliable and efficient means of transmitting data between devices. According to Texas Instrument, user guide [2], the UART is based on the industry standard TL16C550 asynchronous communications element, which has been optimized for high-speed data transfer and low-latency operation. The UART features an alternate FIFO mode that enables buffering of received and transmitted characters, reducing software overhead on the CPU. The receiver and transmitter FIFOs are capable of storing up to 16 bytes of data, along with additional error status bits for the receiver FIFO.

The UART performs serial-to-parallel conversions on data received from a peripheral device and parallel-to-serial conversion on data transmitted from the CPU. It also includes a programmable baud generator that can divide the UART input clock by divisors ranging from 1 to 65535 [2], producing a reference clock that is 16x or 13x faster than the input clock for internal transmitter and receiver logic. The UART also includes a control capability and processor interrupt system that can be tailored to minimize software management of the communications link.

While there are both synchronized and unsynchronized UART implementations available, the unsynchronized version is typically preferred for its simplicity and flexibility. The unsynchronized UART is capable of operating at a wider range of baud rates and is not dependent on a separate clock signal

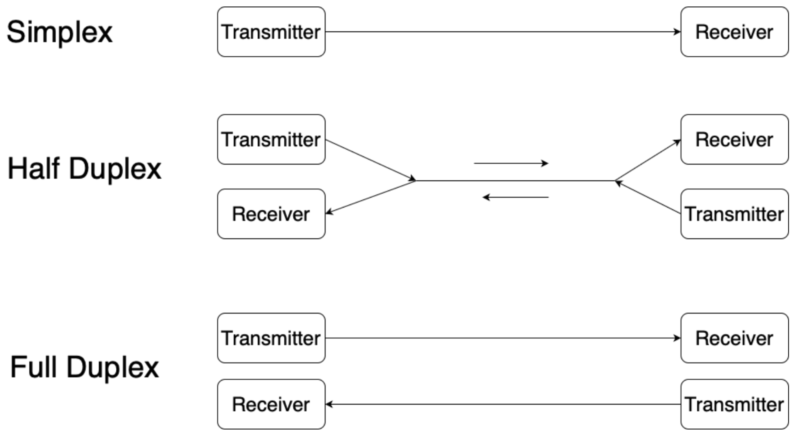

Figure 2.1: Modes of Serial Communication

to maintain synchronization between transmitter and receiver [3] .This makes it an ideal choice for a variety of communication applications, including those that require high-speed data transfer and low-latency operation.

2.1.1.1 Modes of Serial Communication

According to javatpoint website [4], serial communication can be further categorized based on the direction of data flow on the communication line:

1. **Simplex:** This communication mode involves unidirectional data flow, i.e., data can be either transmitted or received. An example is the communication between a printer and a host PC, where data is sent from the host PC to the printer but not in the reverse direction.

2. **Half Duplex:** This communication mode allows for data transmission or reception over the communication line. However, at any given moment, data is either being transmitted or received by the communication endpoint. Walkie-talkies serve as an example, where data can be sent from one device to another, but only one can transmit while the other receives at a time.

3. **Full Duplex:** This communication mode enables simultaneous data transmission and reception over the communication line. An example is a telephone. Figure 1 illustrates the aforementioned communication modes.

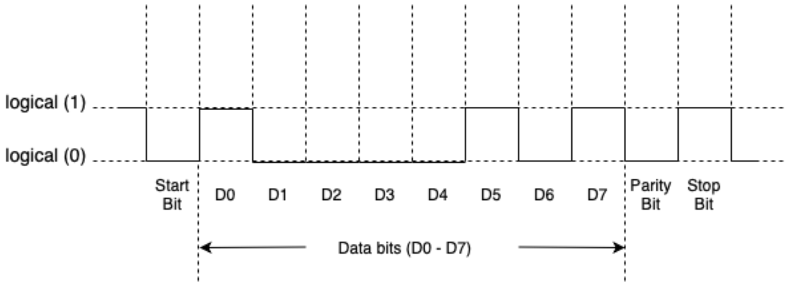

Figure 2.2: Sample of data frame

2.1.2 UART main features

The UART is an asynchronous communications element that can support a variety of data formats, including the RS-485 serial-data format. This allows for the transmission of data at high rates, up to 6 Mbits/second [5], with minimal overhead. The UART is designed to be a simple and reliable way to transmit and receive data.

The UART uses a protocol that includes a start bit, data bits, an optional parity bit, and one or more stop bits. These bits are descriped in [5] as following. The start bit signals the beginning of a data transmission, while the stop bits signal the end of the transmission. The data bits contain the actual data being transmitted. The optional parity bit can be used to detect errors during data transmission.

According to [2], the UART also includes error detection capabilities for detecting parity, overrun, and framing errors. These errors can occur when the data transmission is disrupted, resulting in corrupted or lost data. The error detection features of the UART ensure that these errors are detected and that appropriate actions are taken to recover the data.

In addition to its basic functionality, the UART offers optional interrupts when the receive register is full or the transmit buffer is empty. This allows for the system to handle incoming data as soon as it is received, or to send data as soon as the buffer is available. The UART also includes high-level transmit and receive functions that simplify the process of transmitting and receiving data [2].

2.1.3 UART functional Description

2.1.3.1 UART Communication

Since there is no explicit clock signal, a start bit" is initially transmitted to inform the receiver that data is incoming. The receiver observes a logical high" transitioning to a logical "low" and synchronizes its bus clock accordingly.

After the start bit, the bits constituting the transmitted word" follow, with the least significant bit (bit zero) sent first. These bits are transmitted as pulses on the wire at predetermined time intervals, which have been previously agreed upon by both devices. The receiver examines the wire's voltage at these specific moments; if a logical high is detected, a binary digit 1 is recorded, while a 0 is recorded if the line is low" or at 0V. To avoid misinterpreting the voltage during brief intervals when the voltage is either rising or falling, the receiver checks midway between the pulse's start and end.

If the two devices decide to utilize a parity bit" for basic error-checking, it is calculated and transmitted in synchrony with the previously sent data. Lastly, the transmitter sends at least one stop bit". The word length, parity availability and type, and the number of stop bits must all be predetermined and agreed upon.

2.1.4 Transmitter

TX, or UART Transmitter, is a critical component of the Universal Asynchronous Receiver/Transmitter (UART) peripheral. As stated by [6] it is responsible for sending data from the UART to an external device or system over a serial communication line. The transmitter operates by converting parallel data from the CPU into a serial bitstream that can be transmitted over the communication line.

The structure of a UART transmitter typically includes a transmit buffer, a shift register, and a baud rate generator. The transmit buffer is a storage area that holds data to be transmitted. The shift register is used to convert parallel data into serial data. The baud rate generator is used to set the transmission speed, or baud rate, of the serial data.

The UART transmitter works by first loading data into the transmit buffer. When the transmitter is ready to send data, it transfers the data from the buffer to the shift register. The shift register then converts the parallel data into a serial bitstream by shifting out one bit at a time. The bits are sent out sequentially, starting with the least significant bit (LSB) and ending with the most significant bit (MSB).

The baud rate generator controls the timing of the transmission by setting the speed at which the bits are transmitted. The baud rate is typically set by dividing the frequency of the UART's internal clock by a divisor value. The divisor value is determined by the desired baud rate and the frequency of the clock source as described in Universal Asynchronous Receiver Transmitter Software Module Datasheet [5].

During the transmission of data, the UART transmitter also includes error detection mechanisms to ensure the integrity of the data being transmitted. These mechanisms include parity, overrun, and framing error detection. Parity is a bit added to the data to ensure that the number of 1's in each character is even or odd, depending on the selected parity mode. Overrun occurs when the transmit buffer is not emptied before new data arrives, resulting in data loss. Framing error occurs when the start and stop bits of a transmitted character do not match the expected values.

2.1.5 Receiver

The RX - UART Receiver is responsible for receiving data from a serial connection and converting it into a format that can be used by the system as stated in the datasheet [5]. When data is received by the UART receiver, it performs serial-to-parallel conversion on the data, which means that it converts a stream of bits received one by one over time into a byte of data that can be processed by the system.

The RX - UART Receiver typically consists of a shift register, a buffer, and control logic. The shift register holds the incoming data bits until they can be processed by the system. The buffer holds the received bytes until they can be read by the system. The control logic manages the flow of data and signals when data is available for processing.

When the RX - UART Receiver receives a start bit, it starts to receive the data bits that follow. It then performs error detection to check for framing errors, parity errors, and overruns. If an error is detected, the data is discarded, and the receiver waits for the next start bit. If no error is detected, the data is stored in the shift register, and the receiver continues to receive the data bits until all the bits have been received. Finally, the data is transferred from the shift register to the buffer, and an interrupt is generated to signal that data is available for processing.

2.1.5.1 Flow Control

The RX - UART Receiver also typically supports flow control to prevent data loss in case the receiver is not able to keep up with the data rate. Flow control can be implemented using hardware or software. In hardware flow control, the receiver sends a signal to the transmitter to stop transmitting data when the receiver buffer is full. In software flow control, the receiver sends special characters to the transmitter to signal when it is ready to receive data.

2.1.6 Parity control

As [7] describes, parity refers to the property of a number being even or odd. The parity bit enables the receiving UART to determine if any data has been altered during transmission. This alteration can be due to electromagnetic radiation, mismatched baud rates, or long-distance data transfers.

Once the receiving UART processes the data frame, it calculates the number of bits with a value of 1 and verifies whether the sum is even or odd. If the parity bit is 0 (even parity), the number of logic-high or 1 bits in the data frame should be even. Conversely, if the parity bit is 1 (odd parity), the total logic highs or 1 bits in the data frame should be odd.

When the parity bit aligns with the data, the UART can be confident that the transmission is error-free. However, if the parity bit is 0 and the total is odd, or the parity bit is 1 and the total is even, the UART can infer that bits within the data frame have been modified.

Example: data=00110100 (34 in Hexadecimal); 4 bits set $\Rightarrow$ parity bit will be 1 if even parity is chosen.

Example: data=00110100; 4 bits set $\Rightarrow$ parity bit will be 0 if odd parity is opted for.

The figure 2.3 illustrates the sequence of events in the process of parity control during UART communication. Starting from the calculation of the number of 1 bits in the data frame, the assignment of the parity bit, the transmission of the data frame, to the receiving UART checking the parity and processing the data or indicating an error.

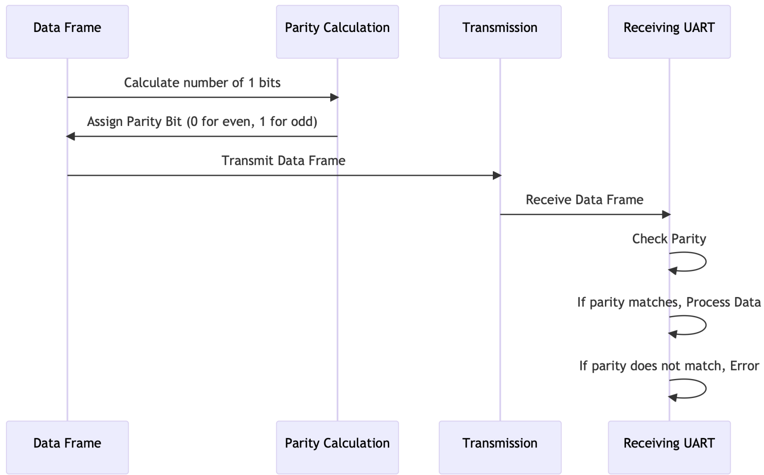

Figure 2.3: Sequence Diagram of Parity Control in UART Communication

2.2 Overview of RS-XXX Protocol Family

2.2.1 Introduction

The RS-422 and RS-485, known as ANSI TIA/EIA-422 and TIA/EIA-485 respectively, are balanced data transmission standards that are widely recognized for their robustness in long-distance and noise-resistant data transfer [8]. These standards are periodically updated by the TR-30.2 DTE-DCE Interfaces and Protocols Subcommittee, which operates under the Telecommunications Industry Association (TIA) TR-30 Data Transmission Systems and Equipment Committee. For simplicity, these standards are often referred to as RS-422 and RS-485.

The TR-30.2 DTE-DCE Interfaces and Protocols Subcommittee is a specialized group that focuses on the development and revision of standards related to Data Terminal Equipment (DTE) and Data Circuit-terminating Equipment (DCE) interfaces and protocols [9]. DTE refers to devices that are an end-user of data, such as a computer terminal, while DCE refers to devices that sit between the data source and destination, such as modems and switches.

The "RS" in RS-422 and RS-485 stands for "Recommended Standard", indicating that these are standards suggested for use. The numbers 422 and 485 are simply identifiers for the specific standard.[10]

This chapter provides a comprehensive overview of the RS-422 and RS-485 standards. While the official ANSI documents contain numerous specifications, this report focuses on the most significant ones. The goal here is not to duplicate the official documents, but to spotlight the main differences and similarities between the RS-422 and RS-485 standards. Essential specifications are detailed, and a comparison between the two standards is made, primarily based on [8].

Given the importance of impedance matching in differential data transmission, which is key to minimizing line reflections caused by transmission-line effects, various termination techniques for different system applications are discussed. Furthermore, we consider typical system configurations to achieve optimal performance and cost efficiency.

2.2.2 Comparison between RS-422 and RS-485

1. **Applications:**
   - RS-422: Industrial automation, broadcast equipment interconnections, extenders/repeaters for RS-232 connections.
   - RS-485: Industrial, process control, and commercial networks, building automation, video surveillance, point of sale terminals.
2. **Key Features:**
   - Both: Balanced differential data lines for minimizing noise, higher data rates than RS-232 connections.
   - RS-422: Supports point-to-point and multidrop connections with one transmitter and up to 10 receivers (simplex operation).
   - RS-485: Duplex transmissions to/from multiple nodes, supports up to 32 nodes (half-duplex operation).
3. **Data Rate:**
   - Both: 100kb/s to 10Mb/s depending on cable length. Guideline: Speed in b/s multiplied by length in meters should not exceed 108.
   - RS-485: Speeds up to 35 Mb/s have been achieved, depends on IC driver specifications.
4. **Network Configuration:**
   - RS-422: Point-to-point connection between data terminal equipment (DTE) and data communications equipment (DCE); supports up to 10 receivers in multidrop connections.

- RS-485: Multipoint connections with up to 32 nodes (both transmitters and receivers), half-duplex operation.

5. **Connectors:**

   - Both: No specific connectors designated by the standard. However, 9-pin DB9/DE9 connectors are sometimes used.

6. **Protocol:**

   - Both: Standard asynchronous UART transmission with start, stop, and parity bits; data may be 5 to 8 bits in length.

2.2.3 System Design Considerations

2.2.3.1 Line Loading

The 485 standard considers the necessity for line termination and the resulting load on the transmission line. As [11] suggest, the decision to terminate the line depends on the system and is influenced by the maximum line length and signaling rate selection.

Line Termination: The test for determining whether a transmission line should be considered as a distributed- or a lumped-parameter model depends on the relationship between the signal transition time, t_t, at the driver output and the propagation time, t_{pd}, of the signal down the cable.

If $2t_{pd} \geq \frac{t_t}{5}$, the line should be treated as a distributed parameter model and terminated accordingly; otherwise, it can be treated as a lumped-parameter model and termination is unnecessary.

Unit Load Concept: The maximum number of drivers and receivers that can be placed on a single 485 communication bus. According to [11] this depends on their loading characteristics relative to the definition of a unit load (UL). The 485 standard specifies a maximum of 32 ULs per line.

One UL (worst case) is defined as a steady-state load allowing 1 mA of current under a maximum common-mode voltage stress of 12 V or 0.8 mA at -7 V. ULs may consist of drivers or receivers and failsafe resistors, but they do not include the AC termination resistors.

2.2.3.2 Fault Protection and Failsafe Operation

2.2.3.3 Fault Protection

In any system design, considerations must be given to natural and induced environmental conditions during operation. Factory-controlled applications generally require protection against excessive noise voltages. The noise immunity provided by the differential transmission scheme, especially the wide common-mode voltage range of 485, might be insufficient. Protection can be accomplished through various methods, with the most effective being galvanic isolation, which offers good system-level protection but at a higher cost. A more popular and cost-effective solution is the use of protection diodes. The tradeoff when using diode protection over galvanic isolation is a lower level of protection.

2.2.3.4 The Necessity of Failsafe Measures

In party-line interface systems with multiple driver/receivers, long periods of inactivity occur when the driving devices are idle. Texas Instruments has mentioned this state in their application report for RS-485 [12], called line idle, happens when the drivers set their outputs to a high-impedance state. During line idle, the voltage along the line is left floating (indeterminate—neither logic-high nor logic-low state), potentially causing the receiver to be falsely triggered by noise or the last polarity of the floating lines. To avoid misinterpretation of this as valid information, it is crucial to detect such situations and set the receiver outputs to a known and predetermined state. Methods that ensure this condition are called failsafe. An additional desirable feature of failsafe is protection against shorted line conditions, which can also lead to erroneous data processing.

Failsafe can be implemented in several ways, including hard-wired failsafe and protocols. Although protocols are the preferred method, they can be complicated to implement. Thus, hardware designers often choose hard-wired failsafe. A hard-wired failsafe must provide a defined voltage across the receiver's input, whether the signal pair is shorted together or open circuited. The failsafe must also be incorporated into the line termination, if present, when at the line extremes.

2.2.3.5 Internal Failsafe

Manufacturers, have started to include open-line failsafe circuitry within integrated circuits to facilitate failsafe design. Often, this extra circuitry consists of a large pull-up resistor on the noninverting receiver input and a large pull-down resistor on the inverting input of the receiver. These resistors as described in [12], are typically around 100 kΩ, form a potential divider with line-termination resistors (usually 50 Ω to 100 Ω), generating only a few millivolts differentially. This voltage (receiver threshold voltage) is insufficient to switch the receiver state. To effectively use these internal resistors, no line-termination resistors can be employed, which significantly reduces the allowed reliable signaling rate.

2.3 Bit Rate

2.3.1 background about data transmitting

2.3.2 baud rate

The origin of the term "baud" can be traced back to Emile Baudot, a French engineer who invented the 5-bit teletype code. In the context of digital communication, baud rate is defined as the number of signal or symbol changes that occur per second. A symbol can be any one of several voltage, frequency, or phase changes that represent data. For example, NRZ binary has two symbols, one for each bit 0 or 1, that represent voltage levels. In this case, the baud rate is equivalent to the bit rate.

However, it is possible to have more than two symbols per transmission interval, with each symbol representing multiple bits. This is achieved using modulation techniques. When the transmission medium cannot handle the baseband data, modulation is used to enable transmission. Even some cable connections use modulation to increase the data rate, which is known as "broadband transmission."

The use of multiple symbols enables the transmission of multiple bits per symbol. For example, if the symbol rate is 4800 baud and each symbol represents two bits, the overall bit rate is 9600 bits/s. Typically, the number of symbols is some power of two. If N is the number of bits per symbol, then the number of required symbols is $S = 2^N$. Therefore, the gross bit rate can be calculated as following.

$$R = baudrate \times \log_2 S = baudrate \times 3.32 \log S \tag{2.1}$$

For instance, if the baud rate is 4800 and there are two bits per symbol, the number of symbols is $2^2 = 4$. Thus, the bit rate is

$$R = 4800 \times \log_2 4 = 4800 \times 2 = 9600 bits/s \tag{2.2}$$

On the other hand, if there is only one bit per symbol, as in the case of binary NRZ, the bit and baud rates remain the same.

2.3.2.1 baud rate calculation

The UART protocol is designed for asynchronous communication, which means it doesn't require a clock signal. The communication speed is determined by the baud rate, which represents the number of bits transmitted per second, including the start and stop bits. To ensure reliable data transmission and reception without any bit loss, both the transmitter and receiver must use the same baud rate. If there's a mismatch in baud rates, it can lead to framing errors. Common baud rates include 4800, 9600, 19200, 38400, 57600, and 115200, although other rates can also be used.

In Asynchronous UART communication, the baud rate is the rate at which data is transmitted between devices. It is typically expressed in bits per second (bps), and determines how quickly data can be sent and received.

The formula for calculating the baud rate in Asynchronous UART communication as shown in [5] is:

$$Baud\ Rate = \frac{Frequency}{16 \times (BRD + Frac)} \tag{2.3}$$

where:

- Frequency is the clock frequency of the UART
- BRD is the integer part of the baud rate divisor
- Frac is the fractional part of the baud rate divisor, expressed as a fraction of 16

The baud rate divisor is calculated as follows:

$$Baud\ Rate\ Divisor = \frac{Clock\ Frequency}{Desired\ Baud\ Rate \times 16} \tag{2.4}$$

where:

- Clock Frequency is the frequency of the oscillator that drives the UART

- Desired Baud Rate is the desired baud rate for communication

Once the baud rate divisor is calculated, the integer part and fractional part can be separated. The integer part is used to program the UART's baud rate generator, while the fractional part is used to adjust the baud rate.

2.4 Related work

The field of long-distance communication and sensor connectivity has witnessed extensive research on protocols and technologies aimed at enabling reliable and efficient data transmission. This section presents a review of relevant literature and studies that contribute to our understanding of long-distance communication systems.

2.4.1 Related Work I:

In a notable research article by Guo and Ji titled "Design of Distributed Simulation Training System Based on IoT Technology" [13] addresses the challenges of establishing effective communication between distributed controllers in a missile simulation training system.

The research focuses on designing a communication topology using the RS-485 bus and LoRa WAN technologies. The authors propose an integrated solution that includes interface circuits, transmission protocols, Cyclic Redundancy Check (CRC) methods, and test software. The primary objective is to enable efficient and reliable communication between the upper control computer and the distributed controllers, facilitating the coordination and synchronization of the training system.

The results of the experiments conducted by Guo and Ji demonstrate the effectiveness of the RS-485 bus and LoRa protocol in achieving robust and stable long-distance communication, particularly in complex environments. The designed network exhibits superior communication capabilities, thereby meeting the requirements for reliable data transmission in preparation for missile launching.

While Guo and Ji's research focuses on the application of RS-485 and LoRa in a distributed simulation training system, their findings have significant relevance to the field of long-distance communication. The utilization of RS-485 as an interface and the implementation of the LoRa protocol showcase the potential for these technologies to enable seamless sensor connectivity over extended distances.

Several aspects of Guo and Ji's work align with the scope of this thesis. The investigation of the RS-485 bus as an interface for connecting sensors to a gateway is of particular interest. Furthermore, the examination of the communication protocol and stability in challenging environments provides valuable insights for establishing reliable long-distance connections.

In summary, the research conducted by Guo and Ji presents a comprehensive analysis of the communication challenges faced in a distributed simulation training system. Their exploration of the RS-485 bus and LoRa technology highlights the potential of these solutions for enabling effective long-distance communication. By building upon their work and adapting it to the specific context of sensor connectivity using UART and RS-485, this thesis aims to further advance the understanding and implementation of reliable long-distance communication systems.

2.4.2 Related Work II:

Additionally to Guo and Ji's, a notable study by Ren Li-rong titled "Technology of RS-485 applied in Automatic Telemetry System of Gate and Dam" focuses on the application of RS-485 in an automatic telemetry system for measuring and reporting different parameters from multi-points of a station by means of a Remote Terminal Unit (RTU) [14].

The research highlights the advantages of RS-485, such as its long-distance transmission capabilities and the ability to accommodate multiple serial ports. The author delves into the RS-485 interface and its corresponding network configuration, emphasizing its suitability for implementing reliable and efficient data transmission in the context of gate and dam automation.

To illustrate the effectiveness of RS-485 in the automatic telemetry system, the author presents a comparison between manually collected data and telemetric data transmitted through the RS-485 interface. By analyzing data collected from the Xiaoqing River of Jinan and the Huangpu River of Shanghai, it is demonstrated that the data transmitted through RS-485 is highly accurate, further validating its reliability for long-distance communication.

The findings of Ren Li-rong's study provide valuable insights into the application of RS-485 in the context of sensor connectivity and long-distance communication. The successful implementation of RS-485 in the automatic telemetry system of gate and dam automation showcases its capability to facilitate precise data collection and transmission.

This study aligns closely with the focus of this bachelor thesis, which aims to establish a long-distance communication system for connecting a sensor to a gateway using UART as the interface and RS-485 as the protocol. By building upon the knowledge and experiences gained from Ren Li-rong's work, this thesis seeks to extend the understanding and implementation of reliable long-distance communication solutions.

Chapter 3

Methodology

This chapter is dedicated to discussing the theoretical underpinnings of the chosen scientific and engineering methodology for this degree project. It outlines the analytical frameworks, research methodologies, simulations, and methods that underpin the development and evaluation of the engineering concepts utilized in this study. The aim is to provide a clear rationale for the selection of each method, including a detailed account of any alternative methods considered but ultimately discarded.

3.1 Scientific and Engineering Methodology

In approaching the problem of data integrity in communication systems, a systematic approach is adopted, focusing primarily on the application of modeling, analysis, development, and evaluation in engineering and scientific content.

Modeling involves the abstraction of real-world elements and behaviors into an optimized, manageable representation that still holds the fundamental characteristics of the system. In our case, the Universal Asynchronous Receiver Transmitter (UART) communication protocol and its interaction with the environment has been modeled.

Analysis takes the modeled representation and uses mathematical and computational techniques to understand its performance under various conditions, enabling us to better comprehend the complex behaviors of the system.

Our research process can be divided into distinct stages, each contributing to the overall goal of the project. The following outlines these stages:

3.1.1 Defining the Problem

At the outset, the problem was clearly defined. This involved understanding the goals of the communication system, the challenges in achieving these goals, and the constraints under which the system must operate.

3.1.2 Literature Review

The next stage involved a thorough review of existing literature. This provided an understanding of current knowledge in the field, previous approaches to similar problems, and the theoretical background needed to develop a solution.

3.1.3 Simulation and Analysis

With the methods chosen, simulations were created using MATLAB to validate the performance of the communication system. These simulations tested data transmission, examined the relationship between the Bit Error Rate (BER) and Signal-to-Noise Ratio (SNR), and evaluated the impact of cable length on BER.

3.1.4 Data Interpretation and Conclusion

Finally, the data gathered from the simulations was interpreted and compared to the data from the real implementation, conclusions were drawn, and the implications for our communication system were considered. This step played a crucial role in assessing the viability and efficiency of the chosen method.

3.1.5 Research Paradigm

Upon understanding the problem and theoretical background, various methods were considered. The pros and cons of each method were carefully evaluated, leading to the selection of the UART protocol and RS485 standard for our system. The research paradigm that guided this project is the post-positivist paradigm. Post-positivism acknowledges that while absolute truth may be elusive, we can make reasonable claims about reality based on meticulous, systematic, and logical inquiry. Given the engineering nature of our project, this paradigm is well-suited as it relies on empirical observations and quantifiable results, which forms the backbone of our simulation analyses.

Development is the stage in which new processes, techniques, or technologies are devised based on the knowledge gained from the modeling and analysis phases. Finally, evaluation involves assessing the performance of the developed solution under defined conditions.

In terms of societal and ethical considerations, the methodology aims to promote the development of communication systems that are reliable, efficient, and responsible in their consumption of power, thus contributing to sustainable development goals.

3.2 Choice of Technology

The chosen method for data transmission in our project is the combination of the Universal Asynchronous Receiver Transmitter (UART) protocol and the RS485 standard. This combination was found to be the most fitting after careful evaluation of a variety of communication protocols and standards.

UART was selected primarily due to its simplicity, reliability, and balance between data rate and error probability. The UART protocol is renowned for its ease of implementation and is widely recognized for its capability to efficiently handle data transmission over various distances.

The RS485 standard was chosen in tandem with UART due to its unique advantages, especially its scalability and adaptability. Unlike the RS422 standard, which operates in a one-transmitter and one-receiver configuration, the RS485 standard allows for the connection of up to 32 devices on a single bus. This feature greatly enhances the system's capacity for future expansion, making it possible to add more devices to the system as needed.

In contrast, several other methods were considered but ultimately dismissed due to their specific limitations. Ethernet, for instance, was rejected due to its maximum transmission distance of approximately 100 meters. This limitation could restrict the scalability of the communication system in scenarios requiring longer transmission distances.

Similarly, the RS422 standard, despite its noise immunity and differential signaling advantages, was not suitable for our requirements due to its inability to accommodate multiple devices in the system. While the RS485 was chosen over RS422 for its scalability, it also offers similar noise immunity and differential signaling benefits, making it a robust choice for our application.

Thus, the selection of the UART protocol combined with the RS485 standard was driven by an extensive evaluation of the system requirements. This combination of UART and RS485 brings together simplicity, reliability, and scalability, forming the basis of an effective and flexible communication system that can efficiently meet current needs while also accommodating future expansion.

3.3 Simulations

Simulations play an integral role in our study, especially given the restrictions imposed by limited component availability and the constrained timeline of the thesis. The implementation of practical, physical tests was not viable due to these constraints; however, the flexibility and versatility offered by simulations make them an ideal substitute. Simulations allow us to create an abstract model of our system and subject it to a range of conditions to observe and analyse its behaviour.

The main objective of these simulations is to validate our choice of method, ensuring that the UART protocol combined with the RS485 standard would provide optimal performance in our intended application. Three specific simulations were conducted, each targeting different aspects of our system's performance.

The choice of MATLAB as the simulation platform in our project was driven by a combination of factors. First and foremost, our familiarity with MATLAB played a significant role in this selection. This prior experience allowed us to rapidly construct and modify simulations with a nuanced understanding of the platform's features and functions. This familiarity translates into faster development times and fewer potential errors, both of which are particularly important given the constrained timeline of this thesis.

MATLAB is renowned for its reliability, another key factor in our decision. It is widely used across both industry and academia, a testament to its robustness and the trust placed in it by the scientific and engineering communities. This reliability is crucial when conducting simulations to inform system design; we need to be confident that the results obtained are accurate and dependable.

Moreover, MATLAB offers a comprehensive suite of toolboxes, many of which are tailored to the needs of communications system design. This includes toolboxes for signal processing, communications systems, and control systems, each providing a wide range of predefined functions that can greatly expedite the simulation and analysis process. This ability to leverage such rich functionality is invaluable, making the process of designing, implementing, and verifying our communication system far more efficient.

Additionally, MATLAB's capacity to handle matrix operations and its sophisticated data visualization capabilities greatly assist in analysing and presenting simulation results. The ability to readily plot graphs, create 3D visualizations, or display complex data in an easily digestible format is crucial in not only understanding the performance of our system but also communicating this understanding clearly to others.

Finally, the vast support community surrounding MATLAB should not be overlooked. This community offers a wealth of knowledge, tutorials, and troubleshooting advice, helping to quickly resolve any challenges we may encounter during our simulation work.

Overall, the choice of MATLAB as our simulation platform can be attributed to its robustness, comprehensive functionality, strong support community, and our own familiarity with the platform. These factors combined make MATLAB an ideal tool for conducting the crucial simulations required for our project.

3.3.1 Data Transmission Verification

The primary simulation was centred around the verification of data transmission. This simulation was designed to accurately mimic real-world data transmission scenarios using UART and RS485. The objective was to validate the integrity of the transmitted data under a variety of conditions.

During the simulation, data frames containing start and stop bits, data bits, and parity bits were transmitted using the UART protocol over an RS485 standard connection. Upon reception, these frames were decoded, and the parity bits were analysed to detect possible errors. By comparing the received and original data, we were able to quantify the number of bit errors, offering valuable insights into the communication system's performance.

3.3.2 Bit Error Rate vs. Signal-to-Noise Ratio

A secondary simulation focused on assessing the Bit Error Rate (BER) as a function of the Signal-to-Noise Ratio (SNR). The importance of this simulation stems from the fact that noise is an ever-present challenge in any communication system. By analysing the BER against the SNR, we aimed to evaluate the resilience of our communication system to noise and establish ways to optimise its performance under various noise conditions.

3.3.3 BER Simulation with Variable Cable Length

The final simulation was designed to study the impact of cable length on the Bit Error Rate (BER). The intention was to understand the relationship between transmission distance and data integrity, aiming to identify an optimal cable length that would ensure reliable data transmission while keeping BER at a minimum. This simulation, hence, has direct implications for the scalability of our system and its adaptability to various application scenarios.

In conclusion, the simulations were a vital component of our methodology due to the restrictions on component availability and time constraints. Despite these limitations, the simulations served to validate the choice of UART and RS485, providing a deep understanding of the system's performance, and paving the way for the development of a robust and adaptable communication system.

3.4 Data Collection

Data collection for this project was primarily achieved through the use of simulations. As such, simulations in MATLAB were used to mimic the behaviour of the chosen communication system under a variety of conditions.

The data from these simulations included information on data transmission, Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), and the impact of cable length on the BER. This simulation data was recorded, stored, and analyzed to inform our understanding of the system's performance and the effectiveness of our chosen method.

3.5 Evaluation framework

The evaluation framework for our research project involves a comprehensive examination of the simulation results to assess the effectiveness of the chosen communication system. The performance of the system is assessed against predefined metrics and benchmarks that align with the project's objectives. This framework provides a structured way of analyzing, comparing, and interpreting the data collected from the simulations.

3.5.1 Performance Metrics

The core performance metrics used in this evaluation framework include data transmission integrity, Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), and the impact of cable length on the BER.

- **Data Transmission Integrity:** This metric evaluates the reliability of data transmission, looking at how accurately the data is received compared to what was sent.

- **Bit Error Rate (BER):** BER is an essential metric in digital communication systems, providing insight into the rate of errors that occur during data transmission.
- **Signal-to-Noise Ratio (SNR):** SNR is a measure of the signal strength relative to the background noise. It provides critical insight into how well the communication system can maintain signal integrity amidst noise.
- **Impact of Cable Length on BER:** Understanding the relationship between cable length and BER is vital for assessing the scalability of the system and its adaptability to different scenarios.

3.5.2 Interpretation and Conclusion

The final stage in our evaluation framework involves interpreting the data and drawing conclusions. This is a comprehensive process that involves analyzing the data against our performance metrics, and using this analysis to make conclusions about the effectiveness of the chosen method. These conclusions will serve as the foundation for any potential system improvements and will inform the direction of future work in this area.

Chapter 4

System Design Considerations for Cable-Based Underwater Sensor Networks

4.0.1 Cable selection

When considering a cable connection, it is essential to choose a cable with appropriate shielding and insulation to guard against water ingress, corrosion, and signal interference. An underwater-rated cable or a cable designed for harsh environments is a great recommendation. Additionally, the cable should have twisted pairs for differential signaling (RS485) to ensure reliable communication.

4.0.2 RS485 transceivers

Utilizing high-quality RS485 transceivers at both ends (sensor and gateway) is crucial for effective communication. We recommend transceivers with ESD protection, low quiescent current, and excellent common-mode rejection, such as the MAX485 and SN65HVD72.

4.0.3 Termination and Biasing

To minimize signal reflection, it is advisable to use proper termination resistors at both ends of the cable. Furthermore, employing biasing resistors helps maintain the correct idle state for the RS485 bus, enhancing overall communication efficiency.

4.0.4 Waterproofing and pressure

Proper waterproofing is vital to protect the sensor and MCU from water damage. We recommend using a waterproof enclosure rated for the well's depth. Depending on the pressure at depth, a pressure-rated enclosure or potting material might be necessary to safeguard the electronics.

4.0.5 Power supply

Accounting for voltage drop over the long cable is essential to ensure the power supply remains adequate for both the sensor and MCU. In some cases, it might be necessary to use a higher voltage and a voltage regulator at the sensor end to maintain a stable power supply.

4.0.6 Grounding and surge protection

Implementing proper grounding and surge protection measures is crucial to prevent damage from electrical noise, lightning strikes, or other transient events. These protective measures will help ensure the longevity and reliability of the cable connection.

4.0.7 Recommended available cable brands

In the world of high-speed data transmission, selecting the right cable can make a significant difference in communication efficiency and safety. This section introduces two notable cable brands highly recommended for EIA RS-485 applications. These brands - Belden and Farnell - have been chosen for their commitment to quality and their specific cable properties, including low capacitance, high-speed data transmission, and suitability to a wide temperature range. Detailed specifications of their respective models are listed below to aid in making an informed decision.

- The Belden 129842 is a 2-pair, RS-485 cable with 24AWG tinned copper conductors, polyethylene insulation, and PVC inner and outer jackets. It features an aluminum interlock armor and a Beldfoil®+Tinned Copper Braid shield. It supports a maximum current of 2.1 Amps per conductor at 25°C, a voltage rating of 300V, and operates within a temperature range of -30°C to +80°C. The cable meets several standards, including NEC/UL, CEC/C(UL), and EU Directives [15].

- LSZH (Low Smoke Zero Halogen) 300V screened multipair cable, designed for low capacitance and high-speed data transmission, making it suitable for EIA RS-485 applications. It's constructed with a stranded tinned copper conductor, polyethylene inner sheath, aluminium polyester foil screen, a tinned copper drain wire, and a tinned copper wire braid sheath. The cable has a voltage rating of 300V and can operate in temperatures between -20°C to +70°C. It comes in pairs with a grey sheath color, has 24 AWG stranding, and the nominal weight is given in kg/km. The cable's electrical characteristics include a capacitance of 42 pF/m at 1kHz, a maximum resistance of conductor at 20°C of 78.4 Ω/km, a velocity of propagation of 86.2%, and an impedance of 120 Ω [16].

Chapter 5

Simulation Studies on Data Transmission

In order to meet the goals outlined for this thesis, several critical design decisions have been made.

5.1 Simulation Design

In this chapter, we conducted three simulations to explore different aspects of data transmission and its impact on data integrity. The first simulation, known as "Data Transmission Verification," focused on ensuring the integrity of transmitted data. We implemented a communication system with data generation, noise addition, and decoding components. By comparing the original data with the decoded data, we verified the accuracy of the transmission and assessed the data integrity.

The second simulation examined the relationship between noise and Bit Error Rate (BER). We introduced varying levels of noise into the communication system and measured the resulting BER. By analyzing the data, we gained insights into how noise affects the accuracy of data transmission. This simulation helped us understand the impact of noise on the reliability of the communication system and provided valuable information for optimizing the system's performance.

In the third simulation, we investigated the influence of cable length on the BER. By varying the length of the cable in the communication system, we observed how BER changed with different cable lengths. This simulation allowed us to evaluate the performance of the system at various cable lengths and identify any limitations or optimal ranges for reliable data transmission.

Overall, these simulations provided valuable insights into the factors affecting data integrity in a communication system. By understanding the relationship between noise, cable length, and BER, we can optimize the system's design, parameters, and components to achieve reliable and efficient data transmission. These findings contribute to the field of data communication and help guide the development of robust and resilient communication systems in various scenarios. The design of the simulation considers multiple factors to ensure an accurate representation of the system performance in close to real-world scenarios.

These factors are divided into three different simulations in the following subcategories:

5.1.1 Data Transmission Verification

In order to ensure data integrity in a communication system, it is crucial to perform data transmission verification. This simulation focuses on verifying the transmission of data using UART (Universal Asynchronous Receiver Transmitter) and a chosen communication protocol. The goal is to design a communication system that meets specific requirements such as data transfer rate, latency, noise immunity, and power constraints.

To achieve this goal, the system design and requirements are defined, and a communication protocol using UART is implemented. The simulation scenario involves the transmission of data frames, including start and stop bits, data bits, and parity bits. The received frames are decoded, and the parity bits are checked for error detection. The decoded data is then compared with the original data to count the number of bit errors.

The simulation provides insights into the effectiveness of the communication system in maintaining data integrity. By analyzing the Bit Error Rate (BER), the impact of noise and other factors on the transmission can be evaluated. Additionally, the simulation helps in understanding the relationship between cable length and BER, allowing for optimization of the communication system. **The simulation documentation is shown in Appendix A.**

The following figure represents the flow of the simulation.

By simulating various scenarios and analyzing the results, we gain valuable insights into the performance of the communication system. This information helps in system design and requirements definition by enabling us to:

1. Define the system requirements: The simulation provides an understanding of the required data transfer rate, latency, noise immunity,

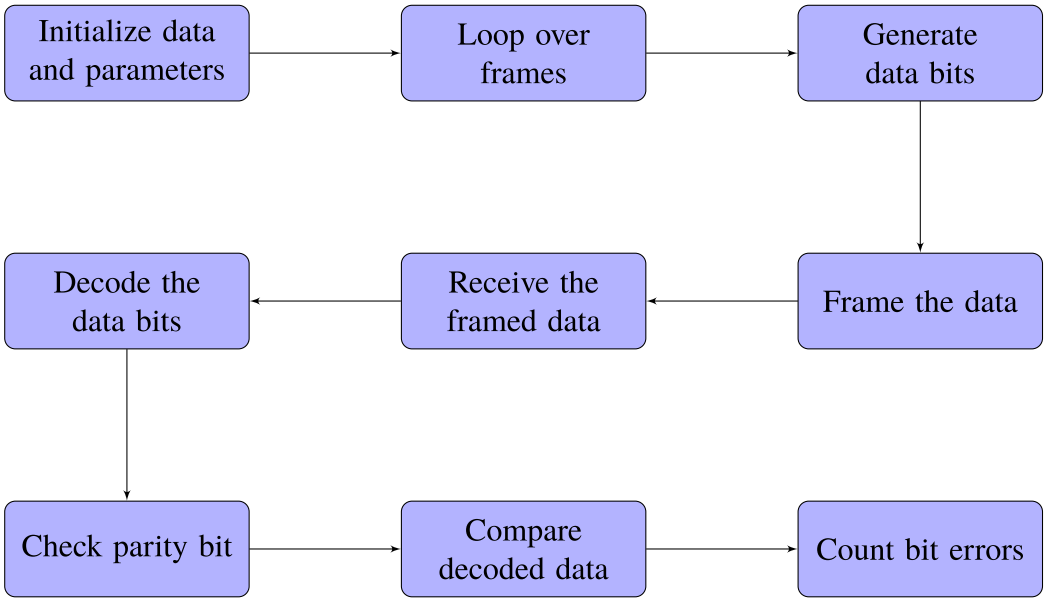

Figure 5.1: Data Transmission Verification Process

and power constraints. This knowledge assists in setting realistic and achievable goals for the communication system.

2. Design a communication system: With the knowledge gained from the simulation, we can design a communication system that meets the defined requirements. Factors such as cable length, wiring, termination, and impedance matching can be considered to optimize the system's performance.

The simulation plays a vital role in evaluating the feasibility and effectiveness of the communication system before implementing it in real-world scenarios. By identifying potential issues and fine-tuning the system based on simulation results, we can ensure reliable and efficient data transmission, ultimately helping us achieve our goals.

5.1.2 Bit Error Rate vs. Signal-to-Noise Ratio

5.1.2.1 Utilizing UART Protocol

The Universal Asynchronous Receiver/Transmitter (UART) protocol was chosen for its simplicity and efficiency in data transfer. This protocol offers an optimal balance of data rate and error probability, making it a suitable choice for this application. In our design, the UART parameters were defined with

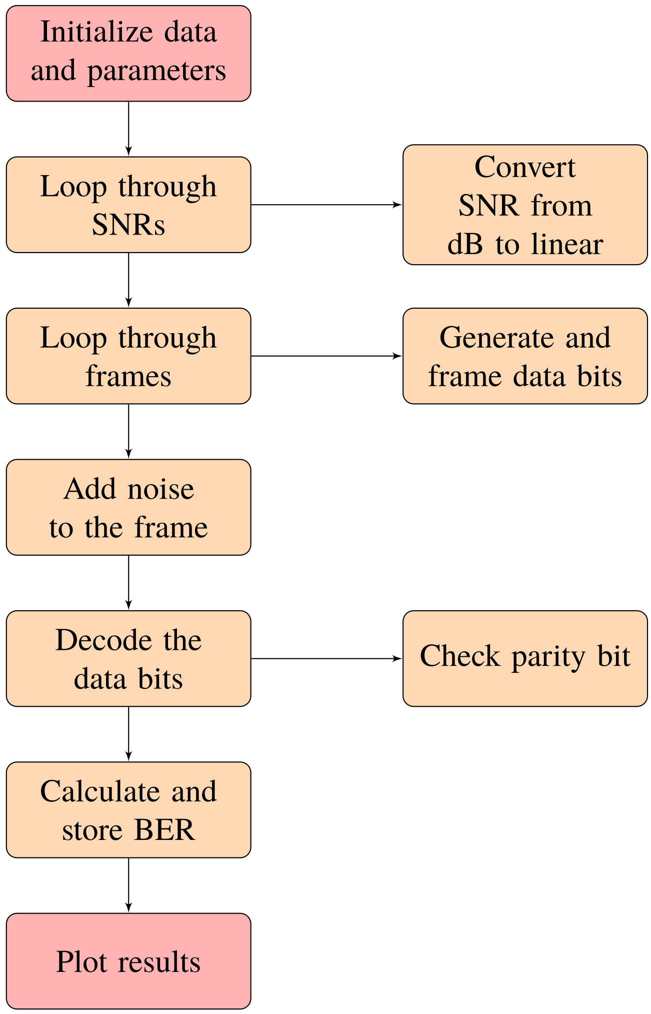

Figure 5.2: BER VS SNR Simulation Process Flow

the start bit set to 0 and the stop bit set to 1, which offers a clear definition of the data unit boundaries. This aspect improves synchronization and reduces latency in the communication system.

5.1.2.2 Data Framing and Error Checking

The structure of each data frame was designed to contain 8 bits, a decision driven by the goal of ensuring an efficient data transfer rate. Accommodating 8 bits in each frame provides a balance between the payload size and the overhead of framing. In addition to the data bits, the simulation employs a parity bit for error checking. The inclusion of a parity bit is instrumental in enhancing system reliability and noise immunity by detecting errors at the receiving end.

5.1.2.3 Signal-to-Noise Ratio (SNR) Considerations

An important aspect of the simulation was the variation of the Signal-to-Noise Ratio (SNR) across a range from 0 to 30 dB. This variation enabled the analysis of system performance under different noise conditions, which is crucial in evaluating the robustness of the communication system in real-world environments. The simulation calculates and stores the Bit Error Rate (BER) for each SNR value. The BER acts as a critical measure of the system's data transfer rate and reliability under various noise conditions. **The simulation documentation is shown in Appendix B.**

5.1.3 Bit Error Rate Simulation with Variable Cable Length

In order to evaluate the performance of our UART communication protocol under different cable lengths, a simulation was conducted. This simulation aimed to explore the relationship between cable length and Bit Error Rate (BER), a critical measure in digital communication systems that quantifies the rate at which errors occur during transmission.

5.1.3.1 Simulation Setup

The total number of bits transmitted during the simulation was set to 80,000, divided into frames of 8 data bits each. This resulted in a total of 10,000 frames for the entire simulation.

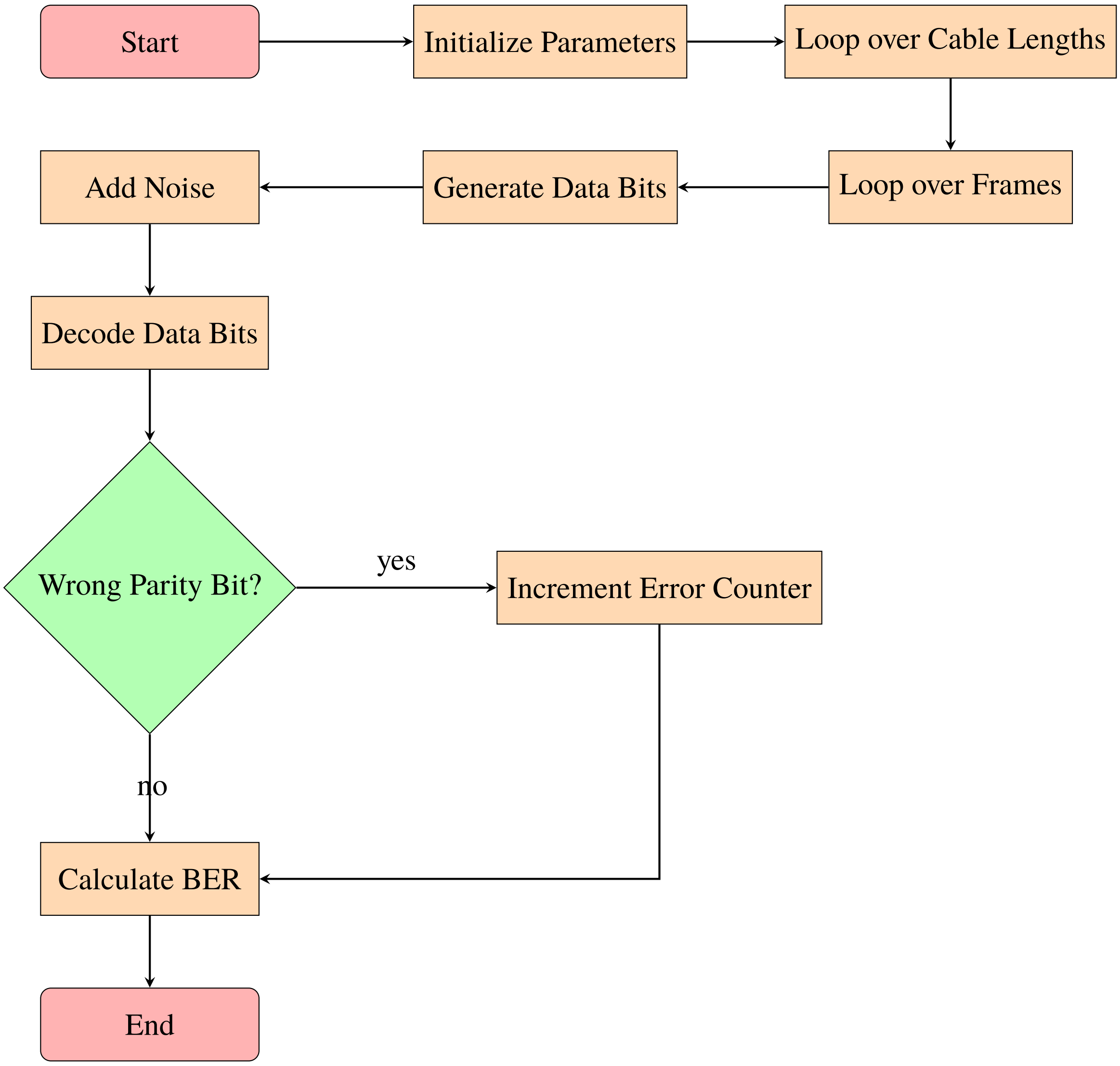

Figure 5.3: BER VS Cable Length Simulation Process Flow

UART parameters were defined, setting the start bit to 0 and the stop bit to 1. Additionally, parity checking was enabled to enhance error detection capabilities.

For the purpose of simulating different cable lengths, a range of cable lengths from 1 to 100 meters was established. For each length, a corresponding noise factor was introduced, proportional to the cable length. This reflects the real-world scenario where longer cables are more prone to noise interference.

5.1.3.2 Simulation Process

Each frame of data was generated randomly and then framed with start bit, data bits, parity bit (if enabled), and stop bit. Noise was introduced based on the noise factor, and the data was subsequently decoded from the received frame.

Parity bits were checked if enabled. If the received parity bit did not match the expected one, the bit error counter was incremented. This allowed the simulation to account for the additional error detection provided by parity checking.

After all frames were sent and received for a given cable length, the BER was calculated by dividing the total number of bit errors by the number of frames. This process was repeated for each cable length in the range. **The simulation documentation is shown in Appendix C**.

5.2 Simulation

In the pursuit of validating the performance and reliability of our data transmission system, we have conducted a comprehensive simulation using MATLAB. The data was structured in an 11-bit data vector, which included a start bit, eight data bits, a parity bit, and a stop bit.

The simulation was meticulously designed to address key aspects of the system.

In the BRE and Noise test case, we simulated different noise conditions to assess the system's ability to maintain data integrity in the face of interference. The Correct Data test case was designed to validate the system's ability to correctly transmit and receive data, ensuring that the received data matched the sent data exactly. The Data Rate test case was developed to confirm the system's ability to handle the chosen data rate without data loss or corruption.

5.2.1 Data Transmission Verification

The integrity of the data being transmitted is paramount in any communication system. This aspect ensures that the system is correctly transmitting and receiving data, and that no corruption or alteration of data occurs during transmission. This is fundamental to the reliability of the system.

5.2.2 The Relation between Bit Error Rate (BER) and Noise

This aspect is crucial as it assesses the system's resilience against noise, a common issue in data transmission, especially over long distances. Noise can introduce errors into the transmitted data, leading to corruption and loss of information. By analyzing the relationship between BER and noise, we can understand how noise levels impact the error rate and thus the overall reliability of the system.

5.2.3 Relation Between Cable Length and Bit Error Rate (BER)

The length of the cable used for data transmission can significantly impact the Bit Error Rate (BER). As the length of the cable increases, the signal has to travel a longer distance, which can lead to signal degradation and increased noise, thereby increasing the BER. This aspect of our analysis examines how the BER varies with cable length. Understanding this relationship is crucial as it helps in determining the maximum cable length that can be used without compromising the integrity of the data transmission.

Chapter 6

Results and Analysis

In this chapter, we present the results of our analysis focusing on four key aspects of our data transmission system: the relation between Bit Error Rate (BER) and Noise, the Correct Data verification and the relation between Cable Length and BER. These aspects were chosen as they address the fundamental characteristics of data transmission over a UART half-duplex protocol on RS 485 cable.

6.1 Evaluation and Metrics

The evaluation of our system was based on the analysis of the BER under different conditions. The BER served as our primary metric, providing a quantitative measure of the system's performance and reliability. By observing how the BER changed in response to variations in noise and cable length, we were able to assess the system's resilience.

6.2 Results

In this study, we have selected the UART interface, RS485 as the transmission protocol, and a Low Smoke Zero Halogen (LSZH) 300V screened multipair cable for data transmission. Each of these choices was made after careful consideration of their respective advantages and how they compare to other options.

6.2.1 UART Interface

The UART interface was chosen for its simplicity and efficiency in data transmission. Unlike other interfaces such as SPI and I2C, UART does not require a clock signal to synchronize the data transfer, which simplifies the communication process. Moreover, UART's ability to handle asynchronous communication makes it more flexible compared to synchronous interfaces. In our tests, the UART interface performed reliably, ensuring smooth data transmission.

6.2.2 RS485 Protocol

The RS485 protocol was selected for its robust performance in long-distance data transmission. Compared to other protocols like RS232, RS485 can handle much longer distances, up to 1200 meters, and supports multi-point communication, making it a more versatile choice. In our study, the RS485 protocol, in conjunction with the UART interface, demonstrated strong resilience to noise and maintained data integrity, even over the 100-meter length of the cable.

6.2.3 LSZH 300V Screened Multipair Cable

The LSZH 300V screened multipair cable was chosen for its low capacitance and high-speed data transmission capabilities. Compared to standard PVC cables, LSZH cables produce less smoke and toxic fumes when exposed to fire, making them a safer choice for indoor applications. The cable's low capacitance characteristics ensured that the signal integrity was maintained over the 100-meter length of the cable, even at high data rates. This was particularly evident in our Data Rate Test Case, where the system was able to handle the chosen data rate without any data loss or corruption.

6.2.4 Data Transmission Verification

The system demonstrated a high degree of accuracy in transmitting and receiving data. This suggests that our system is capable of reliably transmitting data, which is a fundamental requirement for any data transmission system. The following tables show the results of the Correct Data verification.

1. **Data Framing:** In the first step, a frame is created with a start bit, the actual data bits, a parity bit and a stop bit. This structure ensures that

Sensor data for frame 10000:							
1	1	0	0	0	0	0	0

Framed data for frame 10000:										
0	1	1	0	0	0	0	0	0	0	1

Received framed data for frame 10000:										
0	1	1	0	0	0	0	0	0	0	1

Decoded data for frame 10000:							
1	1	0	0	0	0	0	0

the receiver can correctly identify the start and end of the frame and can also check for errors.

2. **Parity Checking:** If parity checking is enabled, the received parity bit is compared to the expected parity bit (which is calculated from the received data bits). If the received and expected parity bits do not match, a warning is displayed. In a real-world system, actions may be taken to request retransmission of the frame or correct the error, depending on the error control protocols in place.

3. **Error Counting:** After each frame is received and decoded, the decoded data bits are compared to the original data bits that were sent. Any discrepancies are counted as errors. In this simulation, no discrepancies should occur since it's a perfect scenario with no noise or other sources of error.

4. **Bit Error Rate (BER) Calculation:** At the end of the simulation, the Bit Error Rate (BER) is calculated as the total number of errors divided by the total number of bits. In a perfect scenario, this should be 0.

6.2.5 Relation between Bit Error Rate (BER) and Noise

Our analysis revealed a direct correlation between the level of noise and the BER. As the noise level increased, the BER also showed a corresponding increase. This finding highlights the need for effective noise management strategies in our system. The figure 6.1 below illustrates this relationship.

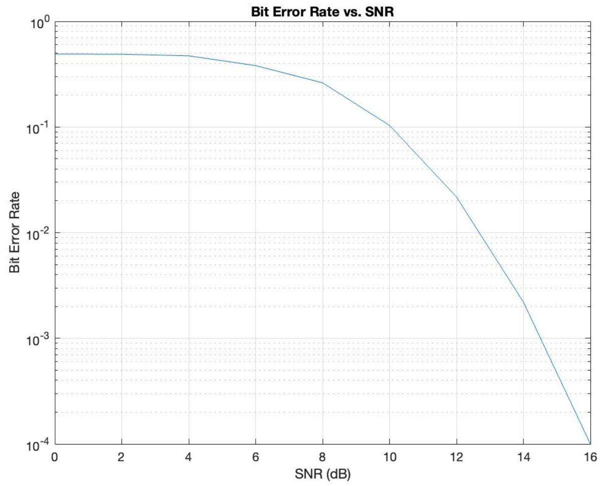

Figure 6.1: Relation between BER and Noise

SNR is a measure that compares the level of a desired signal to the level of background noise. It is defined as the ratio of signal power to the noise power. A higher SNR indicates that the signal is less corrupted by noise.

The Bit Error Rate (BER) is the number of bit errors per unit time. The bit error ratio is the number of bit errors divided by the total number of transferred bits during a studied time interval.

From the data you have provided, it is clear that as the SNR increases, the BER decreases. This makes sense because a higher SNR means that the signal is less corrupted by noise, and thus the bit errors are fewer.

At SNR=0 dB, the BER is around 50%. This high error rate is because the signal power is equal to the noise power, so the signal is highly corrupted by noise.

As the SNR increases to 10 dB, the BER drops significantly to around 0.1048, indicating that increasing the SNR helps in reducing the bit errors.

At SNR of 20 dB and above, the BER becomes very small but not 0, meaning that the signal is so much stronger than the noise that no bit errors occur.

This analysis shows the importance of having a high SNR in communication systems to reduce the bit errors and hence improve the quality of the communication.

However, it's important to note that in real world scenarios, a BER of 0 is nearly impossible to achieve due to various sources of noise and interference that exist.

6.2.6 Relation Between Cable Length and Bit Error Rate (BER)

The analysis revealed that as the length of the cable increased, the BER also increased. This suggests that signal degradation due to the increased cable length can lead to a higher error rate. This finding is crucial in determining the maximum cable length that can be used without compromising the integrity of the data transmission. The following figure 6.2 illustrates this relationship.

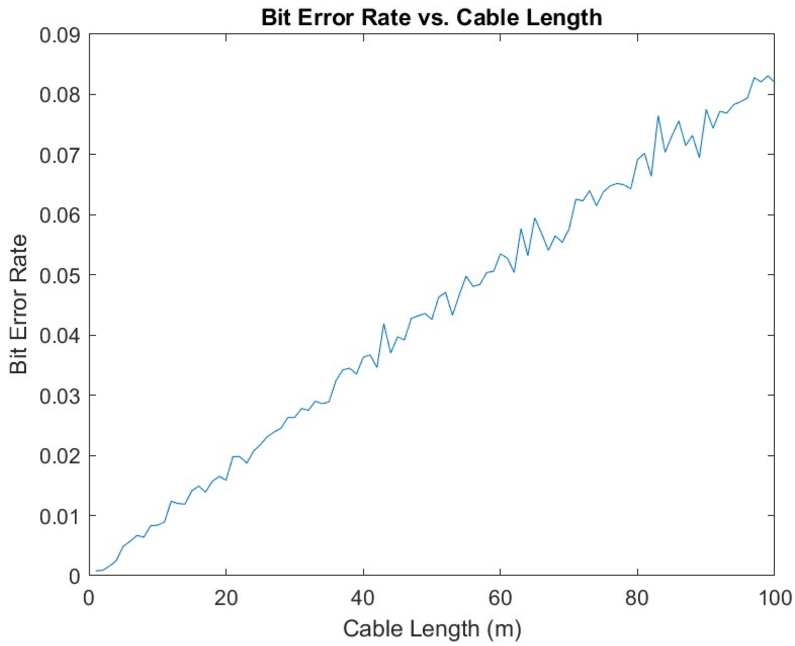

Figure 6.2: Relation Between Cable Length and BER

The results suggest a strong linear relationship between the cable length and the Bit Error Rate (BER). As we increase the length of the cable from 1 to 100 meters, the BER consistently increases. This is demonstrated by the steady rise in the BER value, starting from 0.0008 for a 1-meter cable to 0.082 for a 100-meter cable. This increase is quite uniform and expected given that longer cables generally induce higher signal degradation, contributing to a higher error rate.

Interestingly, the increase in BER seems to be accelerating as the cable length increases, suggesting that the impact of the cable length on the BER becomes more pronounced as the cable gets longer. This can be observed in the steeper increase in the BER values when the cable length exceeds 80 meters.

The system demonstrated high reliability in transmitting accurate data in a lower range of cable lengths. Even when the cable length was increased, the BER remained reasonably low for cable lengths up to about 70 meters. However, a significant rise in the BER was noticed for cable lengths beyond this point.

Chapter 7

Discussion and Conclusions

7.1 Discussion

The primary objectives of this project were to investigate three key aspects of digital communication systems: Data Transmission Verification, the correlation between Bit Error Rate (BER) and noise, and the connection between Cable Length and BER. Utilizing simulation-based methodologies, the project sought to create a comprehensive understanding of these elements.

7.1.1 Choice of UART

The Universal Asynchronous Receiver/Transmitter (UART) interface has proven to be a reliable and efficient choice for our data transmission system. Its ability to handle asynchronous communication effectively is a significant advantage, allowing it to operate independently of the processor clock. This flexibility is particularly beneficial in systems where the processor clock may vary, ensuring that data transmission can continue uninterrupted. Furthermore, the full-duplex mode of UART interfaces enables simultaneous transmission and reception of data, enhancing the overall data throughput. However, it's worth noting that UART's performance can be affected by factors such as the baud rate and the presence of noise, which need to be carefully managed to ensure optimal performance.

7.1.2 Choice of RS485

The choice of RS485 was made due to its ability to support multiple devices on a single bus (up to 32 devices). This multi-point capability is an advantage over other protocols such as RS422, which only supports point-to-point communication. Furthermore, RS485 is known for its robustness in electrically noisy environments, making it a more reliable choice for our communication system.

7.1.3 Choice of Cable

The choice of cable was a significant factor in our research process. After a careful evaluation of various options, we chose the LSZH (Low Smoke Zero Halogen) 300V screened multipair cable. This cable is specifically designed for low capacitance and high-speed data transmission, making it suitable for EIA RS-485 applications.

The cable's low capacitance characteristics ensure that the signal integrity is maintained over the 100-meter length of the cable, even at high data rates. However, it's important to note that the cable's performance can be affected by factors such as the quality of the cable installation and the presence of electromagnetic interference, which need to be carefully managed to ensure optimal performance.

7.1.4 Data Transmission Verification

Our initial focus on data transmission verification revealed the effectiveness of basic principles in ensuring data integrity. By employing techniques like data framing and parity checking, we could verify the reliability of our transmitted data. The simulation outcomes demonstrated that despite their elementary nature, these methods serve as a powerful means to detect errors within transmitted frames.

The data framing procedure involves partitioning data into manageable 'frames' for efficient transmission and processing. Meanwhile, parity checking provides an error-detection mechanism to identify potential transmission errors. The results confirmed the effectiveness of these techniques in maintaining data integrity throughout the transmission process.

While acknowledging that more complex techniques such as checksums and CRC could offer improved error detection, the simulation clearly demonstrated that the adopted method struck a viable balance between simplicity and error detection efficacy. The technique proved competent in identifying and rectifying errors in the data transmission process, underscoring the importance of data transmission verification in digital communications.

7.1.5 The Relationship Between BER and Noise

Our exploration then moved to the relationship between BER and noise. Our findings affirmed the expected trend: as noise variance increases, so does the BER. This relationship is consistent with foundational theories in digital communication systems and underscores the critical role of noise in digital communication error rates.

This implication of this understanding is far-reaching. In the design of digital communication systems, considerations must be given to noise mitigation strategies and error correction techniques. These methods will be essential in preserving reliable communication, particularly in noisy environments where transmission errors could easily disrupt communication effectiveness.

7.1.6 The Relationship Between Cable Length and BER

Our third focus was on the relationship between cable length and BER. This exploration led us to conclude that an increased cable length significantly contributes to signal degradation, which subsequently impacts the error rate. We found that as the cable length increases, the BER also increases.

This finding is significant, especially for wired communication systems. In designing these systems, signal amplifiers or repeaters may be required at regular intervals for long-distance communication to maintain the integrity of the signal and reduce the BER.

7.1.7 Positive Effects and Drawbacks

One of the positive outcomes of the project was a reaffirmation of the fundamental principles in digital communication. By investigating the relationship between BER and noise, we confirmed that as the noise variance increases, so does the BER. This reasserts the importance of noise management and error correction strategies, particularly in environments with high noise variance.

The project also highlighted the practical challenges in real-world digital communication. The relationship between cable length and BER emphasized the need for signal amplifiers or repeaters to maintain signal integrity over longer distances.

One of the major drawbacks was the limited scope of the study. Although we focused on fundamental aspects of digital communication, there are many other parameters and variables that could affect the system's performance.

7.1.8 Changes in Requirements

The initial requirement from the Artemis project group was a cable length of 100 meters. However, on May 16th, this was changed to a 20-meter cable. Despite the change, we continued our research for a 100-meter cable, as the insights derived could be applied to a 20-meter cable as well.

7.1.9 Delay in Supplies

The decision to opt for a simulation method was primarily influenced by the delay in delivering the required cable. While one of the goals of this thesis was to achieve compatibility with the Artemis project, the delay was a significant factor that led to the choice of simulation over real-world implementation. Nevertheless, this approach allowed us to continue our research and deliver valuable insights into digital communication systems, particularly focusing on the UART protocol and the RS485 standard.

7.1.9.1 Evaluation of Results

The project met its goals by successfully investigating and simulating the proposed aspects. The results align with the established theories in digital communication. The process of data transmission verification was well-demonstrated, and the relationships between BER and both noise and cable length were well-established. However, these results are based on simulations and may not perfectly represent real-world scenarios with more complex and varying conditions.

7.1.10 Conclusions

From our simulation-based investigation into these three aspects of digital communication, we can draw several key conclusions:

Firstly, the robustness of data framing and parity checking in ensuring reliable data transmission demonstrates the enduring relevance of these simple techniques in digital communications. Despite their simplicity, they are effective in ensuring data integrity and hence should not be overlooked when designing communication systems.

Secondly, noise plays an influential role in the performance of digital communication systems. Therefore, strategies for managing noise are paramount when seeking to maintain a low BER, especially in environments with high noise variance.

Thirdly, physical factors such as the length of the cable in wired communication systems can significantly impact the BER. This understanding stresses the importance of factoring in the physical limitations and characteristics of communication mediums when designing communication systems.

The simulation methodologies employed in this study allowed for a comprehensive investigation into these aspects of digital communication systems. By enabling controlled experimentation and observation, we could derive insights without the need for costly, time-consuming physical experiments. This approach underscores the value of simulation-based methodologies in the exploration and understanding of complex systems.

Moreover, the simulation results reinforce the importance of fundamental principles in digital communication. Despite the complexity of these systems and the myriad of factors influencing their performance, understanding basic principles such as error detection, noise impact, and physical limitations of communication mediums remains essential.

This degree project thus not only provides insights into these specific aspects of digital communication but also underscores the value of computational modeling and simulation as tools for understanding and improving complex systems. It demonstrates the power of combining theoretical knowledge with practical exploration and serves as a testament to the importance of such an approach in engineering-related projects.

Looking ahead, future work could extend these investigations to explore more sophisticated error detection and correction techniques, different types of noise and their impacts, and the performance of various types of communication mediums. These explorations could serve to further enhance our understanding of digital communication systems and guide the design of more reliable, efficient, and robust systems.

Chapter 8

Future work

8.1 Limitations and Future Work

While the results of this project are illuminating, they are not without limitations. The most significant limitation is the simplicity of the models used in the simulations. In real-world scenarios, digital communication systems are subject to various other factors that were not taken into account in the current project. These factors include different types of noise interference, hardware imperfections, multipath propagation, fading, and other physical characteristics of the communication channel.

In addition, the study assumes ideal conditions for the communication systems, which is rarely the case in actual implementations. Practical considerations such as hardware limitations, software imperfections, and various other constraints that may influence the system performance were not factored into the simulations.

Future work in this field could involve expanding the scope of the simulations to incorporate more realistic conditions, including different types of noise and channel conditions, different modulation and coding techniques, and hardware constraints. A more comprehensive model would provide a more accurate understanding of real-world digital communication systems.

The next person working on this project should consider integrating these real-world conditions into the simulations. They could also consider testing the model against actual hardware to see how well the simulation results match the real-world performance. This will validate the simulations and provide a deeper understanding of the challenges faced in practical implementations.

8.2 Economic, Social, Environmental, and Ethical Aspects

8.2.1 Economic Aspects

The design and implementation of a reliable communication system for radon gas sensor networks have significant economic implications. By ensuring data transfer efficiency, latency reduction, and noise immunity, this project can contribute to more cost-effective monitoring of radon gas levels. This efficient system will reduce operational costs and, by providing early earthquake warnings, mitigate the economic impact of potential disasters. Moreover, by considering power constraints, the system also offers the potential for longer operational life and lower maintenance costs.

8.2.2 Social Aspects

This project stands to make a substantial societal impact by improving public safety and disaster preparedness. A reliable communication system for radon gas sensor networks can enhance the effectiveness of earthquake early warning systems. This enhancement will enable timely evacuation efforts and risk reduction measures, potentially saving lives and reducing injuries during seismic events. Moreover, by providing insights into the challenges and opportunities associated with developing low-cost sensor networks, this project can contribute to more widespread adoption of such systems, further promoting public safety.

8.2.3 Environmental Aspects

The project directly contributes to environmental safety by facilitating better monitoring of radon gas levels in groundwater. By ensuring reliable and efficient communication, it can help in detecting changes in radon gas levels, which are often precursors to seismic activity. Timely detection and subsequent measures can help minimize environmental damage caused by such events. Moreover, by optimizing power consumption, the project also contributes to energy efficiency, which is a significant aspect of environmental sustainability.

8.2.4 Ethical Aspects

The project aligns with ethical principles by prioritizing public safety and environmental protection. It aims to provide a reliable system that accurately monitors radon gas levels, thereby contributing to the ethical responsibility of mitigating disaster risks. Moreover, the project is committed to transparency in its research methodology and respects intellectual property rights by acknowledging all sources of information and prior research. The design and development process also complies with established engineering practices and standards to ensure the system's safety and reliability.

References

[1] A. Project. (2023) Awareness and resilience through european multi sensor system. Accessed: 2023-07-05. [Online]. Available: http://www.artemisproject.eu/ [Pages ii and iii.]

[2] T. Instruments, *KeyStone Architecture Universal Asynchronous Receiver/Transmitter (UART)*, November 2010, literature Number: SPRUGP1. [Online]. Available: https://www.ti.com/lit/ug/sprugp1/sprugp1.pdf [Pages 7 and 9.]

[3] TechTarget, "USART (universal synchronous/asynchronous receiver/transmitter)," November 2022. [Online]. Available: https://www.techtarget.com/whatis/definition/USART-Universal-Synchronous-Asynchronous-Receiver-Transmitter [Page 8.]

[4] javatpoint, "Serial communication in computer organization," n.d. [Online]. Available: https://www.javatpoint.com/serial-communication-in-computer-organization [Page 8.]

[5] Cypress Semiconductor Corporation, "Universal Asynchronous Receiver Transmitter Software Module Datasheet," March 2015. [Online]. Available: https://shorturl.at/ltBW1 [Pages 9, 11, and 18.]

[6] Microchip Technology Inc., "Pic18f2x/4xk22 data sheet," Datasheet, 2017. [Online]. Available: http://ww1.microchip.com/downloads/en/DeviceDoc/61107D.pdf [Page 10.]

[7] E. Peña and M. G. Legaspi, "UART: A hardware communication protocol understanding universal asynchronous receiver/transmitter," *IEEE Potentials*, vol. 54, no. 4, pp. 24–29, December 2020. doi: 10.1109/MPOT.2020.3022034. [Online]. Available: https://fgcoca.github.io/Autocaravana-inteligente/datasheet/uart-a-hardware-communication-protocol.pdf [Page 12.]

[8] L. E. Frenzel Jr, *Handbook of SERIAL COMMUNICATIONS INTERFACES: A COMPREHENSIVE COMPENDIUM OF SERIAL DIGITAL INPUT/OUTPUT (I/O) STANDARDS*. Elsevier Inc., 2016. ISBN 978-0-12-800629-0 [Pages 13 and 14.]

[9] T. Online. (2023) Engineering committee tr-30. Accessed: 2023-07-05. [Online]. Available: http://standards.tiaonline.org/standards_/committees/committee.cfm?comm=TR-30&subcommitteeSelect=74 [Page 13.]

[10] Brainboxes. (2023) Rs-485 masterclass. Accessed: 2023-07-05. [Online]. Available: https://www.brainboxes.com/white-papers/rs-485-masterclass-what-is-it-and-why-use-it [Page 13.]

[11] M. Soltero, J. Zhang, C. Cockril, K. Zhang, C. Kinnaird, and T. Kugelstadt, "Rs-422 and rs-485 standards overview and system configurations," Texas Instruments, Application Report SLLA070D, May 2010. [Online]. Available: https://www.ti.com/lit/an/slla070d/slla070d.pdf [Page 15.]

[12] Texas Instruments, "Interface circuits for tia/eia-485 (rs-485)," Texas Instruments, Tech. Rep. SLLA036D, August 2008, revised from March 2007. [Pages 16 and 17.]

[13] J. Guo and X. Ji, "Design of distributed simulation training system based on iot technology," pp. 1–5, October 2020. [Online]. Available: https://doi.org/10.1145/3424978.3425071 [Page 19.]

[14] R. Li-rong, "Technology of rs-485 applied in automatic telemetry system of gate and dam," *Automation in Water Rescources and Hydrology*, 2004. [Page 20.]

[15] Belden. (2023) 129842 rs-485, 2 pair 24awg. Accessed: 2023-05-26. [Online]. Available: https://www.belden.com/products/cable/electronic-wire-cable/rs-485-cable/129842 [Page 32.]

[16] Farnell, "LSZH 300V Screened Multipair Low Capacitance Computer Cable for EIA RS-485 Applications," https://www.farnell.com/datasheets/3770431.pdf, 2023, [Online; accessed 26-May-2023]. [Page 33.]