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TÍTULO DE LA TESIS

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pueden ser dos líneas.

Saludos

Agradecimientos

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Capítulo 1

background and motivation

1.1. Introduction

Primarly, this document corresponds to the tesis job about The developement of a complete Through the Earth communication system for underground environments. The need for reliable communication systems in underground environments has become increasingly important in recent years, particularly in the mining and construction industries. Specially in certain situations like emergencies in mines, where communication is critical for the safety of workers and the efficiency of operations. Underground environments present unique challenges for communication systems, including the presence of conductive materials, complex geological structures, and limited line-of-sight propagation. These challenges can lead to significant signal attenuation and interference, making it difficult to establish reliable communication links. Traditional communication methods, such as radio and wired systems, can opperate in normal conditions, but they often fail in extreme environments or material collapse. As a result, there is a growing need for innovative communication solutions that can overcome these challenges and provide reliable connectivity in underground environments. For this reason, the Through the Earth (TTE) communication system has been proposed as a potential solution for underground communication. Tipically TTE systems utilize low-frequency electromagnetic waves to transmit data through the earth, allowing for communication over long distances and through various geological materials. This technology has the potential to revolutionize underground communication and improve safety in mining and construction industries. However, the development of a complete TTE communication system for underground environments requires a comprehensive understanding of the underlying principles, challenges, and potential applications of the technology.

1.2. Motivation

The motivation relies on the need for reliable communication system in underground environments without previous infrastructure. The possibility of communicate through centenars of meters of rock and solid material, with a simple system that can be implemented in a short time and with limited resources can be a game changer in the mining and other underground activities. The ability to establish communication links in challenging environments can enhance safety, improve operational efficiency, and facilitate emergency response efforts. Additionally, the development of a complete TTE communication system can contribute to the advancement of communication technologies and provide valuable insights into the challenges and solutions associated with underground environments.

1.3. Hipothesis

Is possible to develop a complete Through the Earth (TTE) communication system for underground environments considering relatively simple hardware and software and limited resources, achieving an useful system to reach text messaging through centenars of meters of rock and solid material.

1.4. Objectives

The objectibes of this thesos are divided in two levels: general and specific objectives.

1.4.1. General Objective

The main objective of this thesis is to develop a complete Through the Earth (TTE) communication system for underground environments, focusing on the design, implementation, and evaluation of the system's components and performance. This includes the development of resonant coils and antennas, signal processing techniques, and communication protocols that are specifically tailored for underground applications. The goal is to create a reliable TTE communication system that can operate effectively in challenging underground conditions, providing a valuable tool for industries such as mining and construction.

1.4.2. Specific Objectives

- Design and implement resonant coils and antennas for TTE communication, optimizing their performance for underground environments.
- Develop signal processing techniques to enhance the reliability and efficiency of the system.
- Compare different modulation and coding schemes for TTE communication.
- Characterization of the underground medium, including the effects of geological materials and environmental factors on signal propagation.
- Evaluate the performance of the TTE communication system in various underground conditions, including different geological materials and environmental factors.
- Investigate potential applications of TTE communication systems in mining and construction industries, focusing on safety and operational efficiency.

1.5. Document Structure

- Chapter 1: Background and Motivation. This chapter provides an overview of the motivation behind the development of a TTE communication system, the challenges associated with underground communication, and the objectives of the thesis.

- Chapter 2: Theoretical Framework. This chapter presents the theoretical principles underlying TTE communication systems, including the physical principles of transmission by magnetic induction, resonant coils and antennas, and fundamentals of digital communication systems.
- Chapter 3: Metodology. This chapter outlines the methodology used in the development of the TTE communication system, including the design and implementation of hardware and software components, as well as the experimental setup for performance evaluation.
- Chapter 4: Analysis and Results. This chapter presents the whole development of the TTE communication system, including design, construction, implementation of software models, simulation snd experimental results, and performance evaluation in various underground conditions.
- Chapter 5: Discussion. This chapter discusses the implications of the results obtained in the previous chapter, including the challenges faced during the development process and the potential applications of TTE communication systems in underground environments.
- Chapter 6: Conclusions and Future Work. This chapter summarizes the main findings of the thesis, highlights the contributions made to the field of TTE communication systems, and suggests potential directions for future research and development in this area.

Capítulo 2

Theoretical Framework

2.1. Overview of Through-The-Earth (TTE) Magnetic Induction Communication

En este capítulo se presentan los fundamentos teóricos y el marco conceptual para lograr comunicación efectiva a través de la roca. Se abordan los principios físicos de la inducción magnética, las características del medio geológico, el modelado del canal, el diseño de transductores (bobinas), y los fundamentos de la comunicación digital aplicados a sistemas TTE. Además, se discuten técnicas de procesamiento de señales digitales (DSP) relevantes y se identifican los principales desafíos técnicos asociados con la comunicación TTE mediante inducción magnética.

2.1.1. Definition and Scope of TTE MI Communication

2.1.2. System Architecture

2.1.3. Motivation and Application Domains

2.1.4. Key Technical Challenges (Preview)

2.1.5. State of the Art Overview

2.1.6. Comparison with Alternative Underground Technologies

2.1.7. Comparison with Conventional RF in Lossy Media

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2.2.3. Magnetic Flux, Mutual Inductance and Coupling Coefficient

2.2.4. Skin Depth and Frequency-Dependent Attenuation in Rock

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2.6.3. Noise Modeling and Detection Basics

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2.7.1. Rationale for Selecting Non-Coherent FSK

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2.7.3. Demodulation Techniques: Filterbanks, Energy Detectors

2.7.4. BER Performance in AWGN

2.7.5. Impact of Channel Frequency Selectivity and Detuning

2.8. Error Control Coding

2.8.1. Role of FEC in MI Links

2.8.2. Block Codes (Hamming, BCH, Reed–Solomon)

2.8.3. Convolutional Codes and Viterbi Decoding

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2.8.5. Interleaving for Burst Error Mitigation

2.8.6. Coding Gain and Trade-offs

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2.9.1. Preamble Design and Frequency Stabilization

2.9.2. Symbol Timing Recovery

2.9.3. Packet Structure and Overhead

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2.10.6. Uncertainty Analysis and Repeatability

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2.12.4. Coupling Variability and Misalignment

2.12.5. Interference and Regulatory Considerations

2.12.6. Detection System

2.13. Signal Processing (DSP) Techniques in TTE MI Systems

2.13.1. Filtering and Noise Reduction

2.13.2. Adaptive Thresholding and Detection

2.13.3. Channel Estimation / Tracking Approaches

2.13.4. Time/Frequency Synchronization Enhancements

$$z_i(T) = \int_0^T r(t) s_i(t)\, dt, \quad i = 1, \ldots, M \tag{2.1}$$

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2.14. Emerging Enhancements and Research Directions

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Capítulo 3

Methodology

Capítulo 4

Results

4.1. Hardware Developement

El hardware del sistema de comunicación TTE fue diseñado y construido para cumplir con un conjunto específico de requisitos y restricciones. En primer lugar el sistema debe ser capaz de satisfacer la prueba de concepto logrando comunicación a una diatancia media pero significativa en un entorno subterráneo. Asismismo el equipo no debe ser extremadamente voluminoso o pesado para facilitar su transporte y versatilidad en su uso.

4.1.1. Design

El sistema de comunicación TTE está compuesto por varios elementos que trabajan en conjunto para lograr la transmisión y recepción de datos mediante inducción magnética. El elemento principal es la bobina resonante, la cual está diseñada para generar y recibir campos magnéticos en una frecuencia específica. Además de la bobina, el sistema incluye un amplificador para aumentar la potencia del mensaje transmitido y un sistema de switching para intercambiar la conexión de la bobina resonante entre los canales de entrada y salida del sistema.

4.1.2. Coil

La bobina resonante corresponde a al elemento encargado de transmitir el campo magnético variable al circular corriente por su estrcutura (Transmisor) y de entregar la fem inducida en presencia al atravesar por su estructira las líneas de campo magnético transmitido (Receptor). En vista de lograr el objetivo de comunicación a distancia significativa, la bobina debe ser diseñada para maximizar la eficiencia de la transferencia de energía magnética entre el transmisor y el receptor, es por esto que se optó en primera instancia por un diseño simple toroidal, donde las variables de diseño y construcción se reducen a número de vueltas N, diámetro de la estructura D, y el calibre del conductor C.

Para esta primera versión se fijó el diámetro de la bobina en 55 cm, ya que correspondía a un tamaño manejable y portátil. El calibre del conductor se seleccionó en función de su costo, resistencia eléctrica y peso, optando por un cable de cobre esmaltado de 17 AWG. A continuación se muestra una tabla de resistencia eléctrica en función del calibre del conductor, entregada por el fabricante.

Tabla 4.1: Resistencia eléctrica en función del calibre del conductor.

Calibre (AWG)	Diámetro (mm)	Resistencia (ohm/m)
10	2.588	0.00328
12	2.053	0.00521
14	1.628	0.00829
16	1.291	0.01317
17	1.150	0.01660
18	1.024	0.02100
20	0.812	0.03340

De esta manera al escoger tal calibre, el cual corresponde a 1.15 mm de diámetro y considerando una masa total cercana a los $1.5Kg$, se logra una extensión total de 156 metros, lo que se traduce en $N = 90$, con esta extensión la resistencia total de la bobina resulta en 2.6 ohmios. Sin embargo al ser medida de forma experimental el valor de resistencia total es de 3Ω, un valor ideal considerando la resistencia a la cual opera el amplificador clase D seleccionado para el proyecto.

Ya definida la geometría y características de la bobina, se procede a calcular los parámetros eléctricos asociados a la misma. En primera instancia se calcula la inductancia de la bobina utilizando la fórmula para una bobina toroidal:

$$L = \frac{\mu N^2 A}{l} \tag{4.1}$$

Donde:

- L es la inductancia en Henrios (H).
- μ es la permeabilidad del núcleo (para aire, $\mu_0 = 4\pi \times 10^{-7} H/m$).
- N es el número de vueltas.
- A es el área de la sección transversal del toroide en metros cuadrados (m^2).
- l es la longitud media del camino magnético en metros (m).

Considerando un área de sección transversal aproximada de $A = 0.2375m^2$ y una longitud media del camino magnético de $l = 1.7m$, se obtiene una inductancia teórica de $L \approx H$. Sin embargo, al medir la inductancia de la bobina construida utilizando un medidor LCR, se obtiene un valor experimental de $L_1 = 10.67mH$ y $L_2 = 10.55mH$. Esta discrepancia puede atribuirse a factores como la distribución no uniforme del campo magnético, las pérdidas en el conductor y las tolerancias en la construcción de la bobina.

Finalmente, se calcula la capacitancia necesaria para sintonizar la bobina a la frecuencia de resonancia deseada, que en este caso es de 3.2 kHz. La frecuencia de resonancia f_0 de un circuito LC está dada por la fórmula:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{4.2}$$

Despejando para la capacitancia C, se obtiene:

$$C = \frac{1}{(2\pi f_0)^2 L} \tag{4.3}$$

De esta menera la capacitancia necesaria para sintonizar la bobina a $\approx 3.2kHz$ resulta en $C \approx 237\mu F$ para L_1 y $C \approx 240\mu F$ para L_2. Se seleccionaron capacitores cerámicos de 470 μF dispuesto en serie para alcanzar el valor deseado, considerando la tolerancia de los componentes. A continuación se muestra una figura de la bobina construida:

Figura 4.1: Bobina resonante construida para el sistema TTE.

Al medir la función de transferencia para en un sistema donde se tiene una de las bobinas sintonizadas y otra más pequeña sin sintonizar puede observarse en la figura 4.2 para L_1 y L_2 que la frecuencia de resonancia se encuentra cercana a los 3.2 kHz, cumpliendo con el diseño inicial.

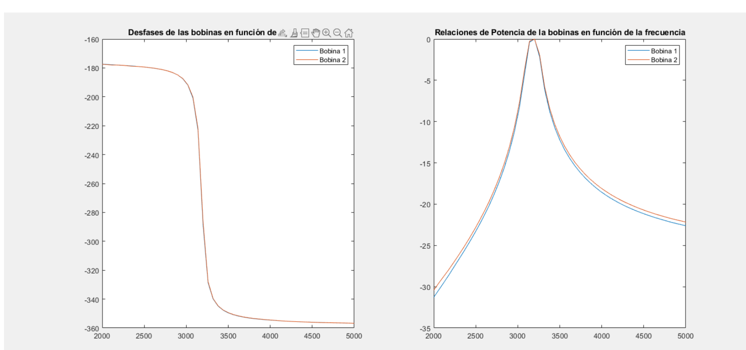

Figura 4.2: Función de transferencia del sistema de bobinas resonantes.

Se muestra a continuación la función de transferencia del sistema completo medido a una distancia de 2 metros entre las bobinas.

4.1.3. Amplifier

El amplificador escogido para la aplicación corresponde a un amplificador de audio clase D basado en los chips TPA3116D2 y NE5532 de Texas Instruments. Este amplificador es capaz de entregar una potencia máxima de 150W Mono, considerando una tensión de 26 V.

La elección de este amplificador se basa en su bajo costo, disponibilidad en el mercado y su alta eficiencia al corresponder a un amplificador conmutado, lo que minimiza las pérdidas de potencia y la generación de calor. Además como se enunció anteriormente el sistema operará en un rango de frecuencia en torno a los 3.2 kHz, dentro del espectro audible. A continuación se muestra una figura del amplificador utilizado:

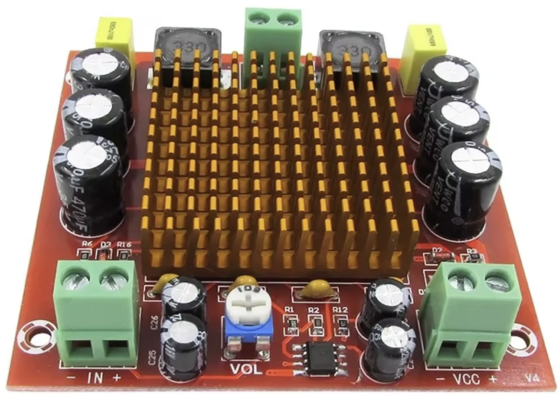

Figura 4.3: Amplificador de audio clase D TPA3116D2.

4.1.4. Switching Circuit

4.1.5. Other Considerations

4.2. Software Developement

4.2.1. Modulation system

4.2.1.1. Non-coherent FSK

The detection system works as a typical non-coherent FSK receiver. The incoming signal is filtered at the beggining to reduce the noise influence in terms os operations in the time domain. Then, the signal is sampled by an ADC and processed digitally to extract the information. A model of thw whole system is presented in Figure 4.4.

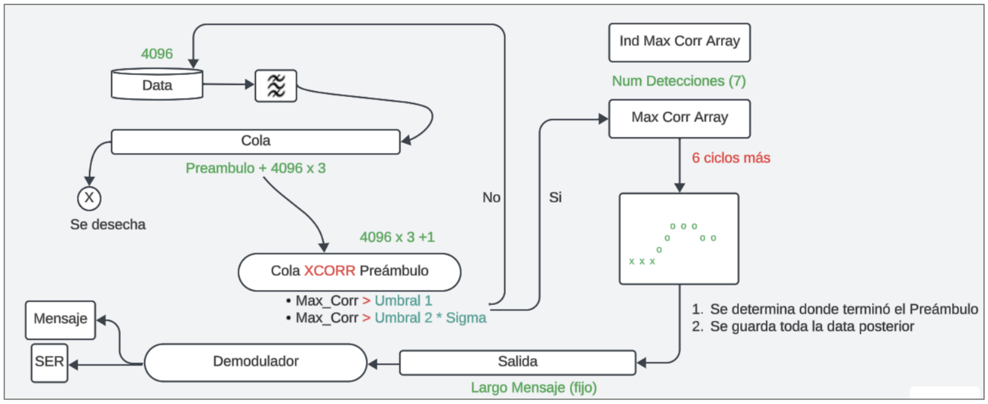

Figura 4.4: Block diagram of the non-coherent FSK detection system.

Why a Non coherent FSK system? The non-coherent FSK system is selected due to its robustness to phase variations and frequency offsets In comparisson for example models based on PSK or QAM, that are more sensitive to phase noise and frequency offsets. FSK modulation allows the receiver to detect the transmitted symbols based on energy detection in specific frequency bands, without requiring precise phase synchronization. This characteristic makes non-coherent FSK particularly suitable for TTE communication systems, where the channel conditions can be highly variable and unpredictable. Here is a diagram of the non-coherent FSK modulation and demodulation process in Figure 4.5.

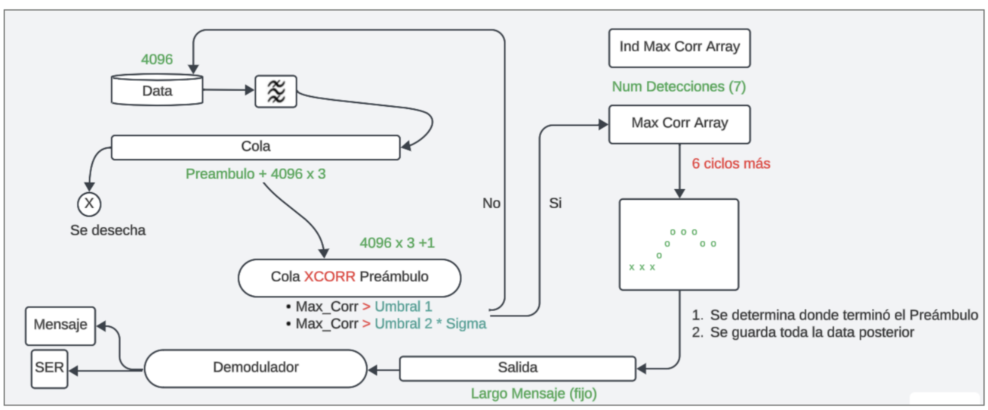

Figura 4.5: Block diagram of the non-coherent FSK modulation and demodulation process.

As I mentiones brewly the last paragraph, at the beggining the digital signal in filtered and then passes to a Window of len N, that is an important number, the dimensions of this Window determine the cost of the processing process, that's because the bigger the window is, the main process that's comes right after is the correlation.

4.2.1.2. Correlation Process

Correlation is a mathematical operation that measures the similarity between two signals as a function of the time-lag applied to one of them In the context of signal processing, correlation is often used to detect the presence of a known signal (template) within a received signal that may be corrupted by noise. In the non-coherent FSK detection system, the correlation process is used to compare the received signal with predefined reference signals corresponding to each of the FSK frequencies. The correlation here is performs between the received signal (or a portion of it) and a known preamble. This preamble is a specific sequence of symbols that is transmitted at the beginning of each data packet. The purpose of the preamble is to help the receiver synchronize with the incoming signal and accurately detect the start of the data transmission. Here we have several main design parameters: an optimar lenght of preamble, its structure, and optimal use of our computation resources, thats because as bigger the lenght of correlation inputs, more calculus to do in each earing time. The size of the window is key of the times that the function *Correlation by parts* is called. The output of the correlation process is a correlation coefficient that indicates the degree of similarity between the received signal and the reference signal at different time lags. A high correlation coefficient at a specific time lag suggests that the known signal is present in the received signal at that time. The correlation formula (2.1), given in previous chapter, is used as a the main operation of correlation IQ System.

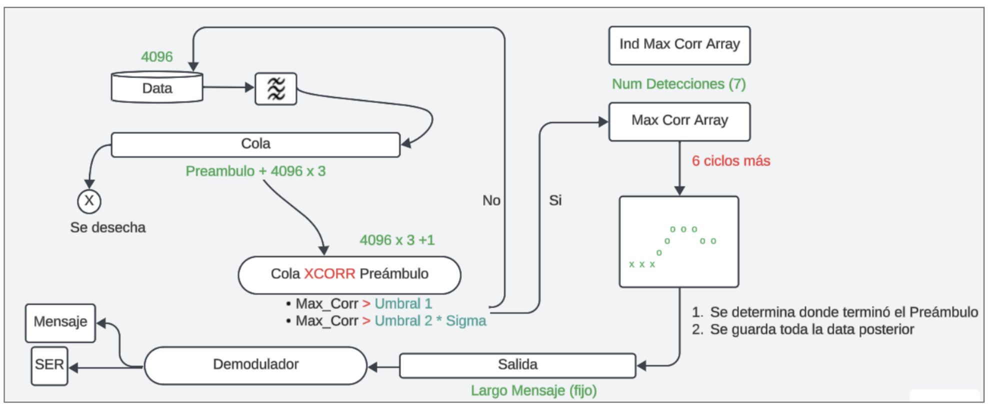

Figura 4.6: Block diagram of the correlation by parts process.

In the last diagram is clear that the incoming signal is partitioned in several parts M, where M is the dimension of the preamble in terms of symbols quantity. Each section named S_N in correlationed with the "N" symbol of the preamble. The structure of S_N is defined as the size of a symbol M plus the sample difference of between preamble (P) and the window size (S). As greater is this difference , the peak of the correlation (the point that the whole structure of the preamble is detected with the system) can be detected with correlation a bigger instance of earing. That means that we are working with a major amount of data and real-time signal chunks. That could work for example if the criteria of detection del preamble are multiple identifications of these peaks levels. In our model we try to minimize the amount of data to process, to reduce time of calculation of time domain chunks, If we exceed the time that ,

4.2.1.3. Ortogonality and Bandwidth

4.2.1.4. Preamble design

4.2.1.5. Decimation?

4.2.2. Performance metrics

4.3. Testing and Validation

4.3.1. Radiolink simulation

4.3.2. Induction Pattern

4.3.3. Measurements underground

4.4. Results Summary

Capítulo 5

Analysis

Capítulo 6

Discussion and Conclusions

6.1. Discussion