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Theme

**Development of an Intelligent System for Selective
Neutralization of GSM Signals in Specific Areas.**

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Dedication

Praise be to Allah, by whose grace all good things are accomplished, and praise be to Him who granted me the strength, patience, and determination to reach this moment, where I proudly present the fruit of years of hard work, sacrifices, and perseverance.

First and foremost, I dedicate this work to myself...

To the person who fought silent battles, endured pressure, stayed awake through countless nights despite exhaustion, and continued moving forward despite every obstacle. To myself, who never gave up and chose perseverance over surrender, I say: You did it.

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With immense pride, gratitude, and emotion, I dedicate to you the result of years of effort, patience, sacrifice, and perseverance.

Résumé

Ce mémoire présente un système intelligent de neutralisation sélective des signaux GSM dans des zones déterminées. Il repose sur la détection des fréquences radio et le traitement numérique du signal afin d'identifier et d'atténuer les communications GSM de manière ciblée. Le système utilise des capteurs RF et des antennes directionnelles pour assurer un contrôle précis et adaptatif. Les résultats de simulation montrent une réduction efficace des signaux et une bonne stabilité, confirmant la faisabilité de la solution proposée tout en limitant les interférences avec les réseaux voisins.

Abstract

This thesis presents an intelligent system for the selective neutralization of GSM signals in specific areas. It is based on radio frequency detection and digital signal processing to identify and selectively attenuate GSM communications. The system uses RF sensors and directional antennas to ensure precise and adaptive control. Simulation results show effective signal reduction and good system stability, confirming the feasibility of the proposed solution while minimizing interference with surrounding networks

تلخيص

في مناطق محددة. يعتمد على كشف الترددات GSM يقدم هذا المذكرة نظامًا ذكيًا لعملية التحييد الانتقائي لإشارات وهوائيات RF وتقليلها بشكل موجه. يستخدم النظام حساسات GSM الراديوية ومعالجة الإشارة الرقمية لتحديد إشارات اتجاهية لضمان تحكم دقيق وتكيفي. تُظهر نتائج المحاكاة فعالية عالية في تقليل الإشارات واستقرارًا جيدًا، مما يؤكد إمكانية تطبيق الحل مع تقليل التداخل مع الشبكات المجاورة

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General Introduction

1. General Introduction

Wireless communication systems have become an essential pillar of modern society, supporting a wide range of applications including voice communication, mobile internet, emergency services, and industrial monitoring. Among these systems, the GSM (Global System for Mobile Communications) network remains one of the most widely deployed cellular technologies worldwide. It enables reliable transmission of voice and data through a structured cellular architecture based on frequency reuse and standardized radio bands, mainly around 900 MHz, 1800 MHz, and 2100 MHz. With the continuous evolution toward advanced technologies such as 4G and 5G, the electromagnetic spectrum has become increasingly dense, leading to higher levels of spectral congestion and more complex propagation environments [1], [2].

In parallel with this technological evolution, the growing use of mobile devices has introduced new challenges in terms of spectrum management and signal control. In sensitive environments such as examination halls, research laboratories, hospitals, and security institutions, uncontrolled or unauthorized GSM signals may cause serious issues related to confidentiality, data security, and operational integrity. These concerns have motivated extensive research into electromagnetic wave behavior, propagation mechanisms, and signal control strategies in complex environments.

The scientific literature has provided a solid foundation for understanding these phenomena. Rappaport has extensively studied wireless propagation models in real-world environments, highlighting the effects of reflection, diffraction, and scattering on signal quality [3]. Haykin has contributed significantly to statistical signal processing techniques used for detection and analysis in noisy environments, which are fundamental for modern communication and sensing systems [4]. In addition, Goldsmith has addressed key limitations in wireless systems related to spectrum efficiency and interference management, particularly in densely populated frequency bands [5].

To address these challenges, this project proposes the design and implementation of an intelligent system for selective GSM signal neutralization. The main objective is to develop a system capable of detecting, analyzing, and selectively acting on specific GSM signals while preserving other legitimate communications in the surrounding environment. Unlike traditional wideband jamming techniques, which affect all signals indiscriminately, the proposed approach emphasizes precision, adaptability, and intelligent decision-making based on real-time spectral analysis.

This work follows a structured methodology that combines theoretical study, system design, implementation, and experimental validation. Chapter 1 presents the theoretical foundations and bibliographic review of GSM communication systems, electromagnetic wave propagation, and spectrum control techniques. Chapter 2 focuses on the design of the electromagnetic signal detection system and its analysis using signal processing tools. Chapter 3 is dedicated to the development of the intelligent selective neutralization system, including signal generation and control strategies. Chapter 4 presents the practical implementation of the system, experimental setup, and performance evaluation.

This work concludes with a general conclusion that summarizes the main contributions of the project and evaluates the performance of the proposed system in terms of selectivity, efficiency, and stability. It also discusses the limitations encountered during development and outlines future research directions. These perspectives include system miniaturization, the integration of artificial intelligence techniques for improved adaptive detection and decision-making, and potential integration into smart environments capable of autonomous electromagnetic spectrum management. These future directions represent the key objectives for further development of this work.

Chapter I

Bibliographic Study and Fundamentals of GSM Communications and Spectrum Control

1.1. Introduction

This chapter establishes the theoretical foundations and bibliographic background required for a clear understanding of GSM communication systems, electromagnetic wave propagation phenomena, and modern techniques for spectrum control. It aims to provide the essential scientific basis for analyzing how radiofrequency signals are generated, transmitted, and affected by real-world environments, particularly in the context of cellular networks operating in congested frequency bands.

In wireless communication systems, and especially in GSM-based networks, signal behavior is strongly influenced by propagation conditions such as reflection, diffraction, scattering, and absorption. These effects become even more significant in urban and indoor environments where multiple obstacles and sources of interference coexist. Understanding these physical principles is essential for accurately modeling the radio environment and for developing effective strategies for signal detection and control.

Furthermore, the increasing density of wireless devices has led to a highly crowded electromagnetic spectrum, where multiple technologies operate simultaneously across adjacent frequency bands. This situation requires efficient spectrum management techniques capable of identifying, analyzing, and controlling specific signals of interest without affecting other legitimate communications.

In this context, this chapter also reviews fundamental concepts related to spectrum control, including electromagnetic shielding, frequency filtering, wave reflection and absorption mechanisms, as well as destructive interference principles. These techniques represent the theoretical basis for selective signal management in complex electromagnetic environments.

Finally, this chapter includes a bibliographic review of related works in the fields of RF signal detection, digital signal processing, embedded systems, and intelligent spectrum analysis. These studies provide important insights into existing approaches and technologies, and they serve as a reference framework for the development of the intelligent selective GSM signal neutralization system proposed in this project.

1.2 Introduction to GSM Communication Systems and Evolution toward LTE/5G

The GSM (Global System for Mobile Communications) standard is a second-generation cellular system designed for digital voice and low-rate data transmission. It is based on a structured cellular architecture using frequency reuse to optimize spectrum utilization.

The evolution of mobile communications has progressed from GSM (2G) to UMTS (3G), LTE (4G), and now 5G, offering higher data rates, lower latency, and improved spectral efficiency.

Main characteristics:

- GSM (2G): voice and SMS services
- LTE (4G): high-speed data transmission
- 5G: ultra-low latency and massive connectivity

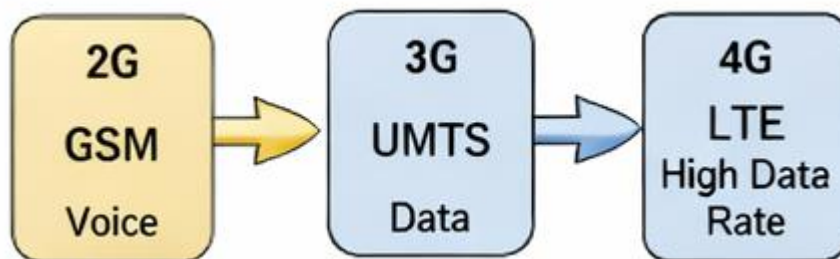


Fig 1.1: Evolution of mobile communication systems

1.3 Cellular Network Architecture and GSM Frequency Bands

A cellular network divides a geographical area into multiple cells, each served by a base station (BTS). Frequency reuse allows efficient utilization of the spectrum.

GSM frequency bands include:

- 900 MHz (GSM-900)
- 1800 MHz (DCS)
- 2100 MHz (UMTS)

The wavelength–frequency relation is given by:

$$c = \lambda f \quad (1)$$

where:

- c : speed of light
- λ : wave length
- f : frequency

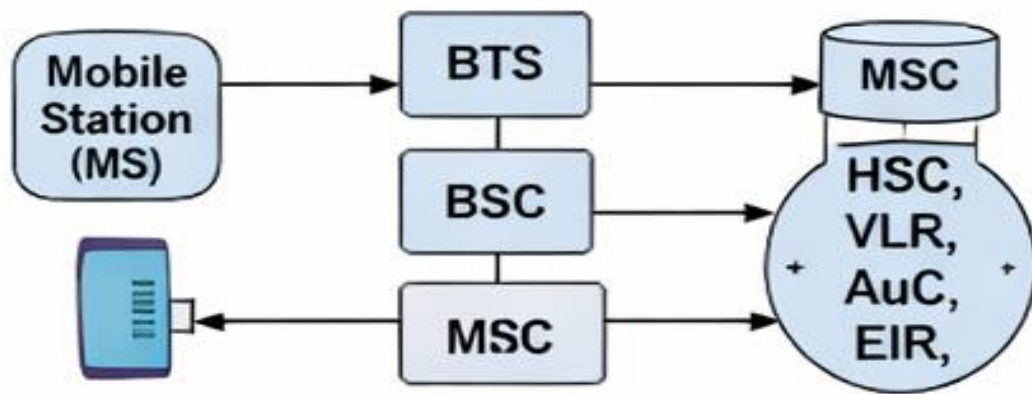


Fig 1.2: Cellular network architecture

1.4 Electromagnetic Wave Propagation in Real Environments

Electromagnetic wave propagation in real environments is far more complex than in ideal free space. In practical scenarios, waves interact with obstacles such as buildings, terrain, vegetation, and atmospheric layers, which significantly affect signal strength and quality. These effects are fundamental in the design and analysis of wireless communication systems [1], [4].

1.4.1 Propagation Mechanisms

In real environments, electromagnetic waves undergo several key physical phenomena:

- **Reflection:** Occurs when waves encounter large surfaces (e.g., walls, ground), causing them to bounce back.
- **Diffraction:** Happens when waves bend around obstacles or edges, allowing signals to reach shadowed regions.
- **Scattering:** Caused by small objects or rough surfaces, leading to signal dispersion in multiple directions.
- **Absorption:** Part of the wave energy is absorbed by materials and converted into heat.

These mechanisms collectively define the behavior of radio wave propagation in urban, suburban, and rural environments [1], [3], [9].

1.4.2 Impact of the Environment

The propagation of electromagnetic waves is influenced by:

- **Urban areas** → strong reflection and scattering due to dense buildings
- **Rural areas** → fewer obstacles, but terrain affects coverage
- **Indoor environments** → significant attenuation due to walls and materials
- **Atmospheric conditions** → humidity, rain, and temperature affect signal attenuation

These factors are critical in cellular network planning (GSM, LTE, 5G) and are standardized in modern communication systems [2], [4].

1.4.3 Free-Space Path Loss (FSPL) Model

In an ideal environment without obstacles, signal attenuation is described by the Free-Space Path Loss (FSPL) model:

$$FSPL(dB) = 20\log_{10}(d) + 20\log_{10}(F) + 32.44 \quad (2)$$

Where :

- d : distance between transmitter and receiver (in km)
- f : frequency of the signal (in MHz)

This model shows that signal loss increases with both distance and frequency, and it serves as a baseline for more complex propagation models [1], [4].

1.4.4 Limitations of the FSPL Model

Although the FSPL model is useful, it does not account for real-world effects such as:

- Obstacles (buildings, trees)
- Multipath propagation
- Atmospheric absorption
- Terrain irregularities

Therefore, more advanced empirical and statistical models are required for accurate prediction in real environments [3], [8].

1.4.5 Engineering Applications

Understanding wave propagation in real environments is essential for:

- Cellular network design (GSM/EDGE, LTE, 5G) [2]
- Radio coverage planning and optimization [1]
- Satellite and wireless link budgeting [4]
- Antenna placement and system performance analysis [9]



Fig1.3: Wave propagation in urban environments

1.5 Wave–Matter Interaction and Signal Attenuation

When electromagnetic waves propagate through a medium (air, buildings, water, or biological tissues), they interact with matter in different ways. These interactions cause a reduction in signal strength known as **attenuation**, which is a fundamental concept in wireless communications and propagation modeling [5], [7].

1.5.1 Physical Mechanisms of Interaction

When an electromagnetic wave encounters a material, several physical phenomena occur:

- **Reflection:** The wave bounces back when it hits a surface such as walls or buildings.
- **Absorption:** Part of the wave energy is converted into heat inside the material.
- **Transmission:** A portion of the wave passes through the material with reduced energy.
- **Scattering:** The wave is dispersed in multiple directions due to irregular surfaces or obstacles.

These mechanisms together determine the total propagation loss and are widely discussed in wireless channel modeling [5], [6].

1.5.2 Signal Attenuation

Attenuation refers to the gradual reduction in the power of an electromagnetic signal as it travels through a medium. It depends on distance, frequency, and environmental conditions [7], [8].

1.5.3 Exponential Attenuation Model

A commonly used model to describe signal loss in a medium is the exponential attenuation law:

$$P_t = P_e e^{-\alpha d} \quad (3)$$

This model shows that the received power decreases exponentially with distance, which is consistent with real propagation environments [5], [7].

Where :

- P_t : transmitted power
- P_r : received power
- α : attenuation coefficient
- d : propagation distance

1.5.4 Attenuation Coefficient (α)

The attenuation coefficient α characterizes how strongly a medium reduces signal power. It depends on frequency, material type, and environmental conditions.

This parameter is widely used in mobile communication system design such as GSM/EDGE and other cellular networks [6], [8].

1.5.5 Engineering Applications

Wave–matter interaction and attenuation analysis are essential in:

- Wireless communication systems (GSM/EDGE, LTE, 5G) [6]
- Indoor propagation and Wi-Fi planning [5]
- Satellite communication systems [8]
- Antenna and electromagnetic systems [9]

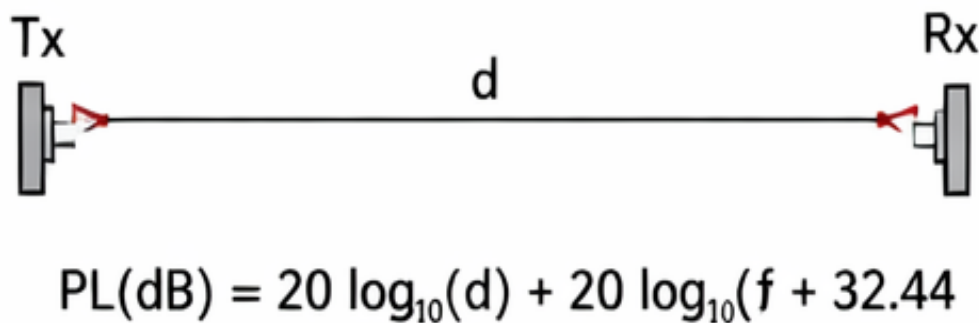


Fig 1.4: Signal attenuation through obstacles

1.6 Electromagnetic Spectrum Control Techniques

Spectrum control techniques are essential for managing interference and regulating electromagnetic environments.

1.6.1 Electromagnetic Shielding

Shielding reduces electromagnetic wave penetration using conductive materials.

$$SE(dB) = 20 \log_{10} \left(\frac{E_{incident}}{E_{transmitted}} \right) \quad (4)$$

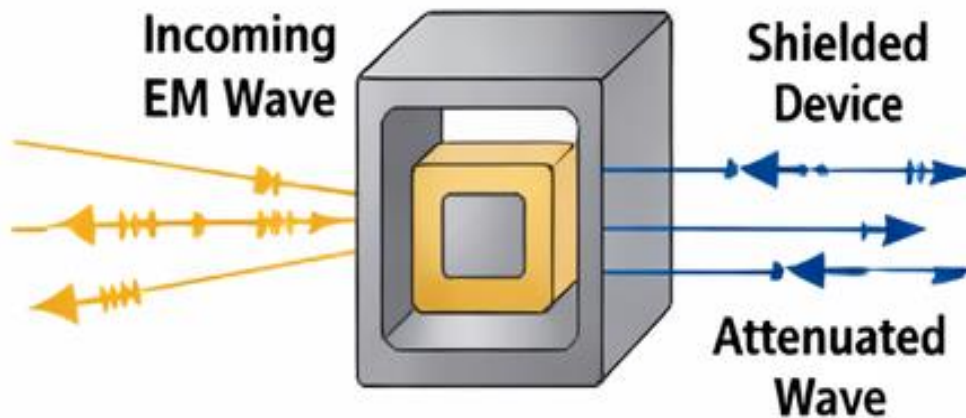


Fig.1.5 Electromagnetic Shielding

1.6.2 Frequency Filtering

Frequency filtering allows selection or rejection of specific frequency bands.

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

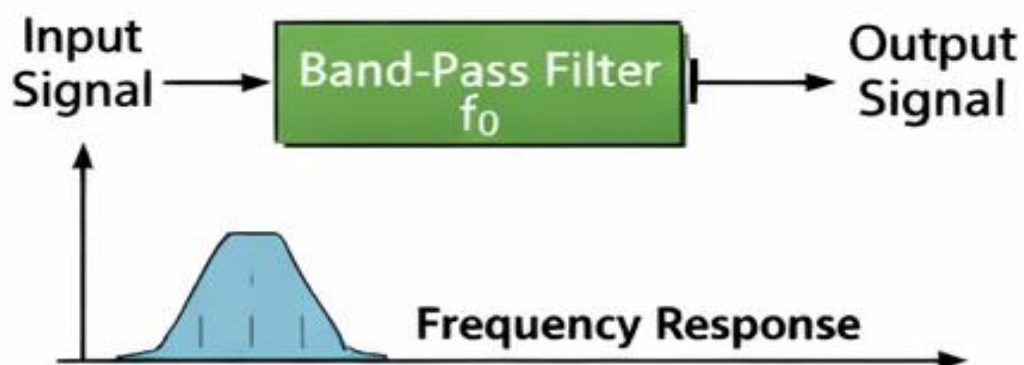


Fig.1.6 Frequency Filtering

1.6.3 Reflection and Absorption

Reflection depends on impedance mismatch between media.

$$\Gamma = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (6)$$

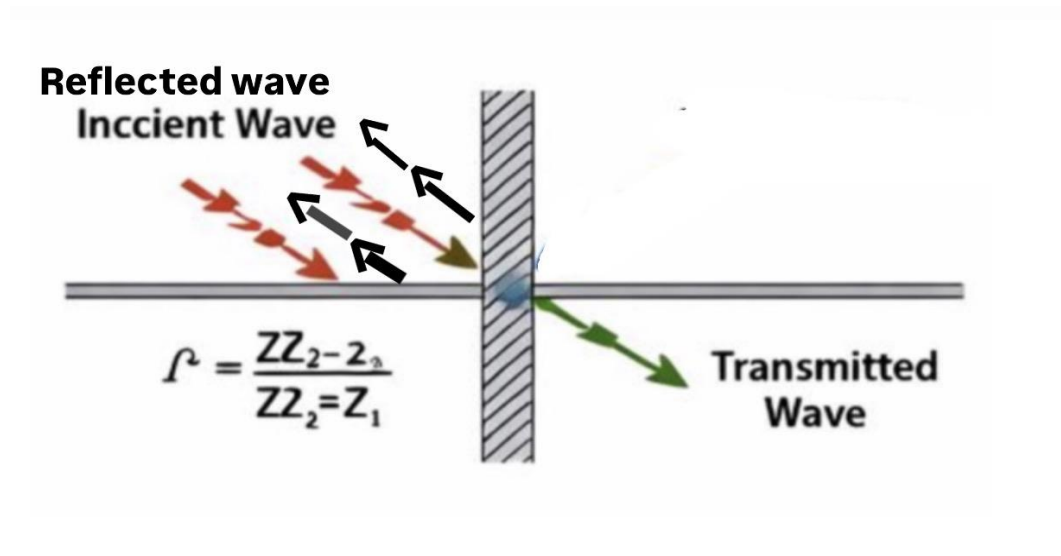


Fig.1.7 Wave Reflection and impedance Mismatch

1.6.4 Destructive Interference

Signal cancellation occurs when two waves have equal amplitude and opposite phase.

$$A_1 = A_2, \phi_1 - \phi_2 = \pi \quad (7)$$

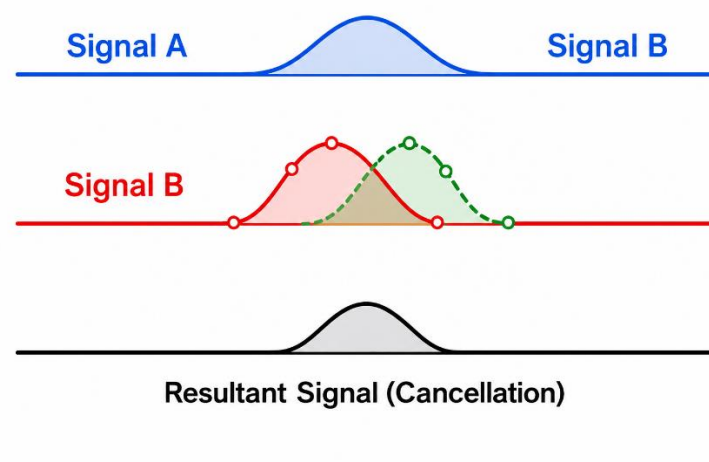


Fig.1.8 Destructive interference

1.7 Bibliographic Study of Similar Works

Several research works have contributed to the development of RF detection and spectrum control systems.

1.7.1 Spectrum sensing systems (Energy Detection)

Energy detection techniques are widely used in cognitive radio systems to detect unknown signals without prior knowledge of their structure [5], [7].

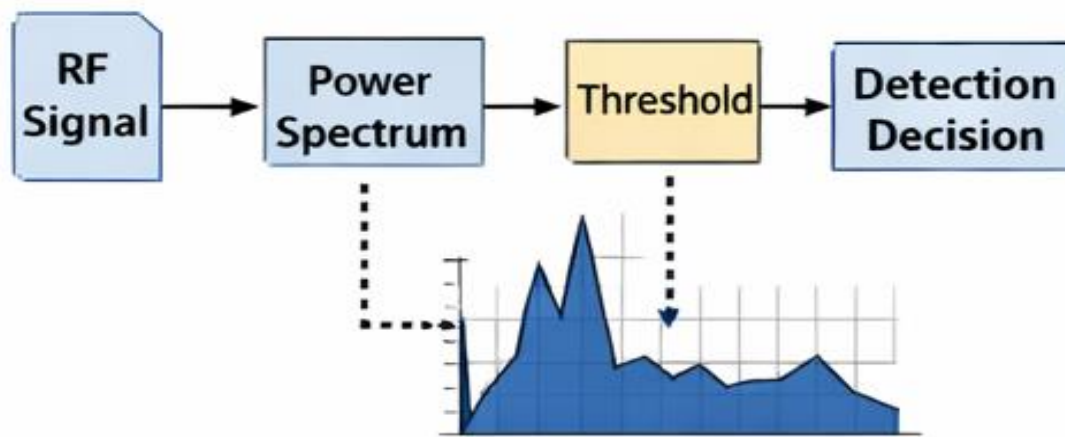


Figure 1.9: Spectrum Sensing Using FFT

Fig.1.9: Spectrum Sensing FFT

1.7.2 FFT and DSP-based spectral analysis

FFT is a fundamental tool for converting signals from time domain to frequency domain, enabling real-time spectral analysis [7].

1.7.3 Embedded RF systems (Arduino / ESP32 / SDR)

Embedded platforms such as Arduino, ESP32, and SDR systems are widely used for real-time RF monitoring and signal processing [6], [8].

1.7.4 Active signal cancellation techniques

Active cancellation aims to generate an inverse-phase signal to reduce unwanted electromagnetic waves [9].

1.7.5 Artificial intelligence in RF detection

Recent studies focus on machine learning techniques for adaptive spectrum sensing and intelligent signal classification [9].

1.8 Conclusion

This chapter has presented the theoretical foundations and bibliographic review of GSM communication systems, electromagnetic wave propagation, and spectrum control techniques. It also highlighted recent developments in RF detection, signal processing, and intelligent spectrum management. These concepts form the basis for the design and implementation of the intelligent selective GSM signal neutralization system presented in the following chapters.

References chapter I

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Chapter II

Intelligent System for GSM Signal Detection and Analysis

2.1 Introduction

This chapter presents the design and conceptual development of an intelligent system for GSM signal detection and analysis. The objective of this system is to capture, process, and analyze radio frequency (RF) signals in the GSM bands, particularly 900 MHz, 1800 MHz, and 2100 MHz, in order to identify active communication sources and characterize their spectral behavior.

The proposed system integrates RF sensing, signal conditioning, digital conversion, and intelligent signal processing techniques. This approach is widely used in modern wireless monitoring, spectrum analysis, and cognitive radio systems [1–3].

The main goal is to transform raw electromagnetic signals into meaningful spectral and temporal information through a structured signal processing chain.

2.2 RF Signal Detection System Architecture

The proposed detection system is based on a modular RF architecture designed to ensure accurate signal acquisition and processing.

The system includes the following main functional blocks:

- RF signal acquisition subsystem
- Directional antenna system
- RF front-end conditioning stage
- Band selection and filtering unit
- Analog-to-digital conversion module
- Digital signal processing (DSP) unit
- Signal classification and decision-making system

This architecture allows real-time monitoring of GSM activity while minimizing interference from non-relevant frequency bands.

The overall system follows a classical RF receiver structure enhanced with intelligent processing capabilities, similar to those used in spectrum monitoring systems [2].

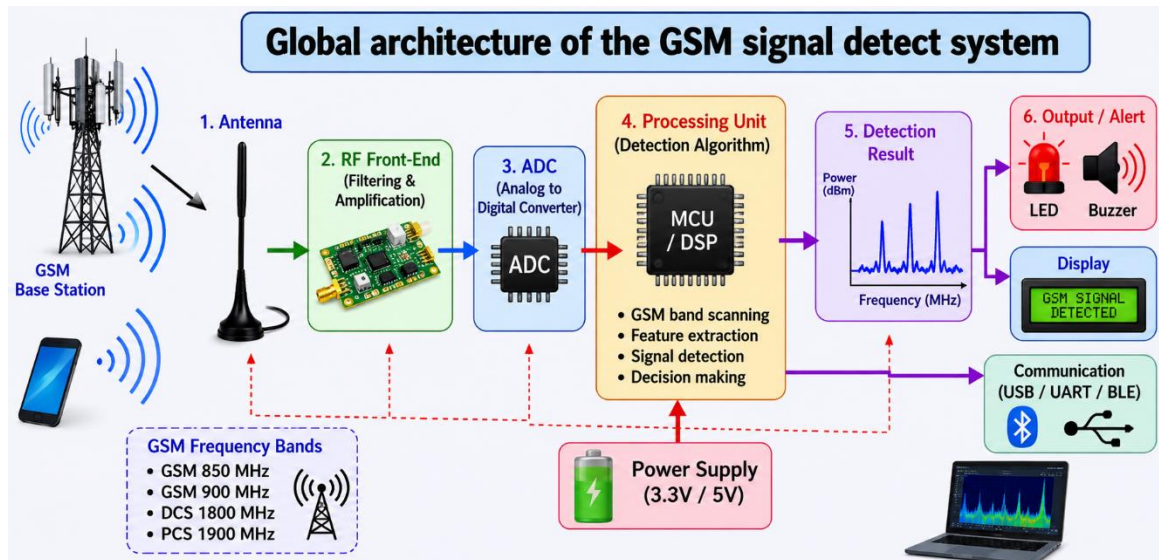


Figure 2.1: Global Architecture of the GSM Signal Detection System

2.3 RF Sensors and Directional Antennas for GSM Signal Capture

The signal acquisition stage relies on **RF sensors and directional antennas** designed to capture electromagnetic waves in specific GSM frequency bands.

2.3.1 RF Sensors

RF sensors are responsible for converting electromagnetic waves into electrical signals. These sensors are characterized by :

- High sensitivity in the GSM frequency range
- Low noise figure
- Wide dynamic range
- Stability under varying environmental conditions

2.3.2 Directional Antennas

Directional antennas are used to improve signal selectivity and spatial resolution. They allow the system to :

- Focus on a specific signal direction
- Reduce interference from unwanted sources
- Improve signal-to-noise ratio (SNR)

Common antenna types used in such systems include Yagi-Uda antennas, patch antennas, and log-periodic antennas [3].

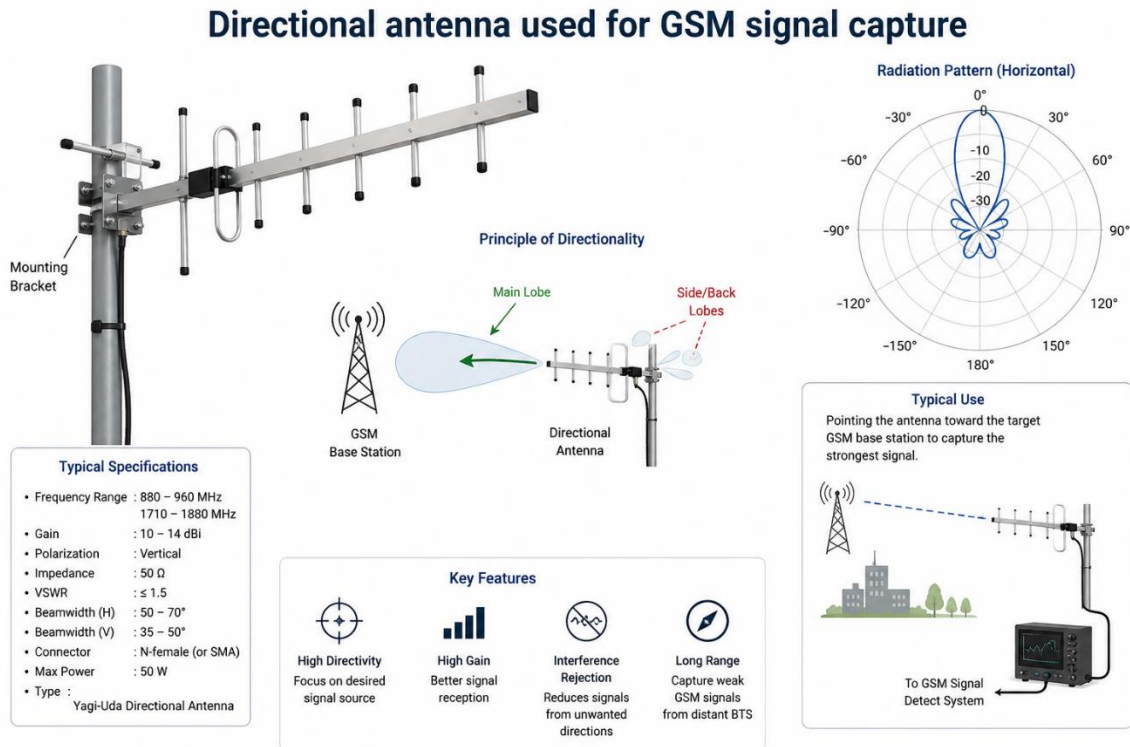


Figure 2.2: Directional Antenna Used for GSM Signal Capture

2.4 Signal Power Measurement and Estimation (dBm)

Once the signal is captured, its power level is measured in **decibel-milliwatts (dBm)**. The received signal power is an essential parameter for evaluating signal strength and link quality.

The power level is defined as:

$$P(\text{dBm}) = 10 \log_{10}(P(\text{mW})) \quad (8)$$

Signal Interpretation

- Strong GSM signal : > -50 dBm
- Moderate signal : -50 dBm to -80 dBm
- Weak signal : < -80 dBm

This measurement allows the system to evaluate signal availability and quality in real time.

2.5 Filtering and Isolation of GSM Frequency Bands

To ensure accurate analysis, the system applies **band-pass filtering** to isolate specific GSM frequency bands:

- GSM 900 MHz
- GSM 1800 MHz
- UMTS 2100 MHz

The filtering stage removes unwanted noise and adjacent channel interference.

This process is based on digital and analog filtering techniques such as:

- Butterworth filters
- Chebyshev filters
- FIR digital filters

The goal is to improve spectral clarity and reduce out-of-band distortions [2].

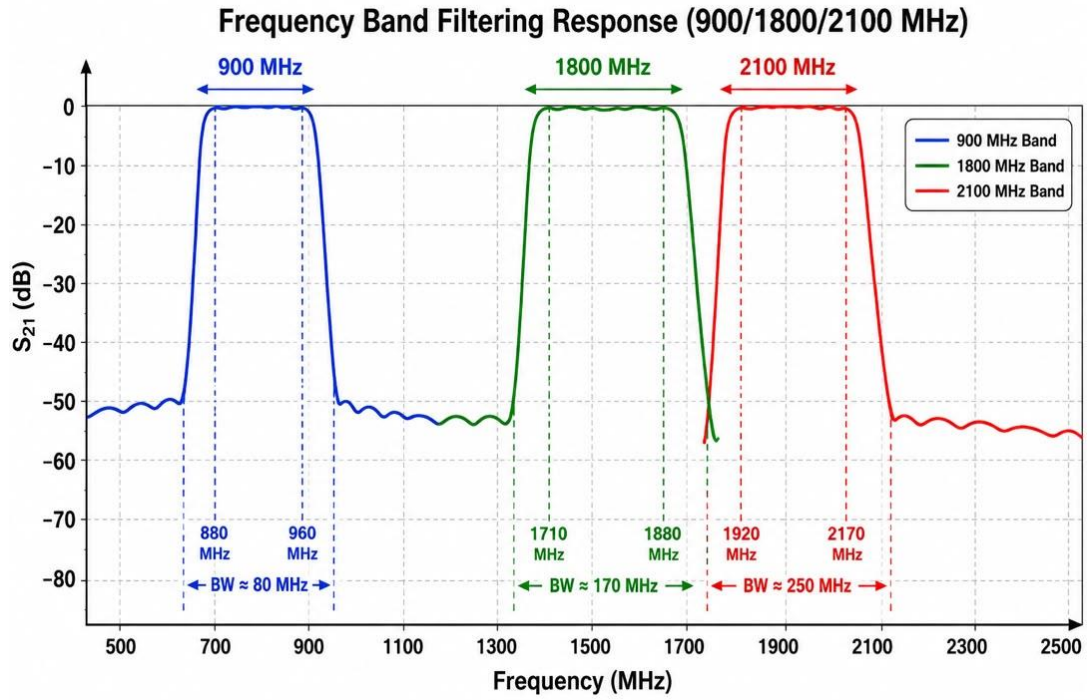


Figure 2.3: Frequency Band Filtering Response (900/1800/2100 MHz)

2.6 Analog-to-Digital Conversion (ADC)

After filtering, the analog RF signal is converted into a digital form using an **Analog-to-Digital Converter (ADC)**.

The ADC process includes:

- Sampling of the continuous signal
- Quantization of amplitude levels
- Binary encoding of the signal

The sampling frequency must satisfy the Nyquist criterion:

$$f_s \geq 2f_{max} \quad (9)$$

where:

- (f_s) is the sampling frequency
- (f_{max}) is the highest signal frequency component

High-resolution ADCs are preferred to ensure accurate spectral reconstruction.

2.7 Spectral Analysis of GSM Signals (FFT and DSP)

Once digitized, the signal is processed using Digital Signal Processing (DSP) techniques.

2.7.1 Fast Fourier Transform (FFT)

The FFT is used to convert the time-domain signal into the frequency domain, enabling spectral analysis.

$$X(f) = \sum_{n=0}^{N-1} x(n)e^{-j2\pi fn/N} \quad (10)$$

This transformation allows identification of:

- Carrier frequencies
- Signal bandwidth
- Interference components

2.7.2 DSP Processing

Additional DSP techniques include:

- Noise reduction filtering
- Windowing functions (Hamming, Hanning)
- Peak detection algorithms

These methods improve the accuracy of spectral interpretation [1].

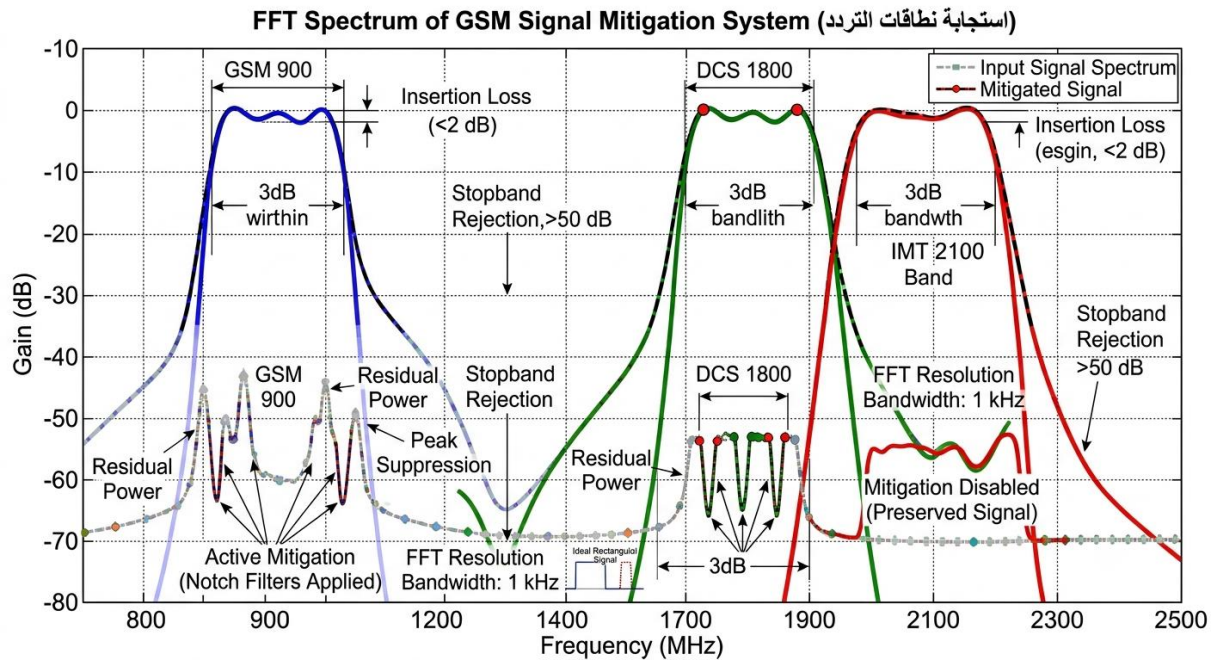


Figure 2.4: FFT Spectrum of GSM Signal

2.8 Identification and Classification of Active GSM Signals

The final stage of the system involves **signal identification and classification**.

The system analyzes spectral features such as:

- Frequency location
- Signal amplitude
- Bandwidth characteristics
- Temporal variation

Based on these parameters, signals are classified into:

- GSM 900 MHz signals
- GSM 1800 MHz signals
- UMTS 2100 MHz signals
- Noise or interference signals

Classification can be implemented using:

- Threshold-based detection
- Machine learning classifiers (optional extension)
- Pattern recognition techniques

This process is essential for intelligent spectrum monitoring systems and cognitive RF networks [3].

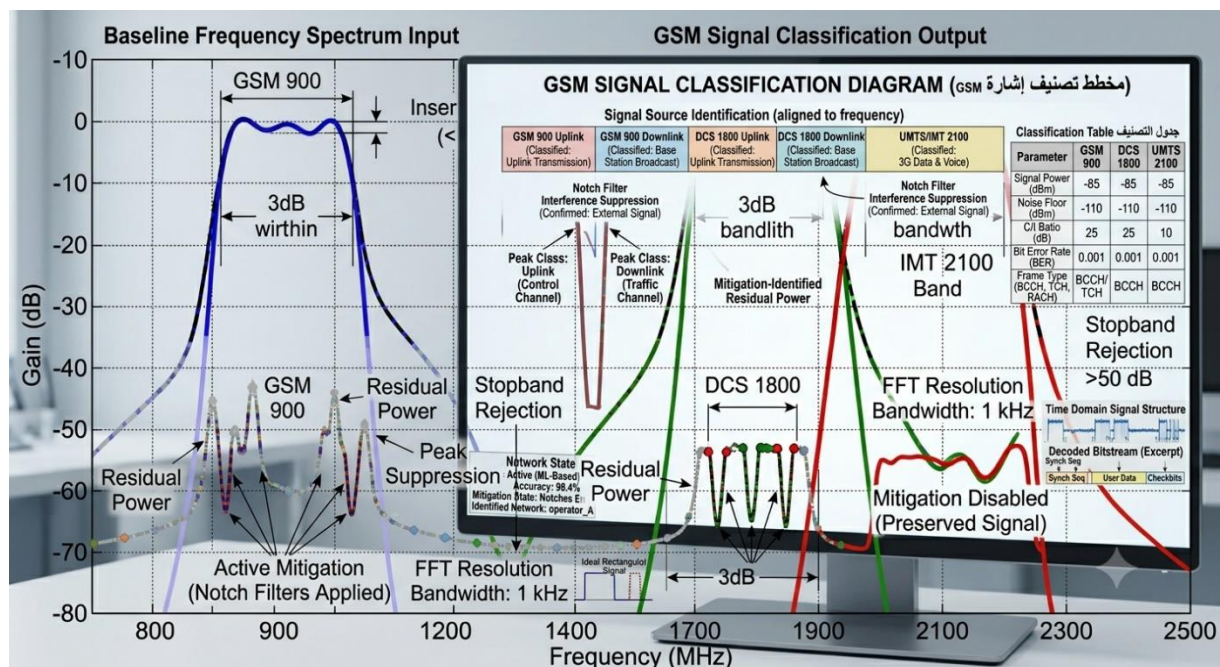


Figure 2.5: GSM Signal Classification Output

2.9 Conclusion

This chapter presented the design of an intelligent GSM signal detection and analysis system. The proposed architecture integrates RF acquisition, directional antennas, filtering stages, ADC conversion, and digital signal processing techniques.

The system enables accurate detection and classification of GSM signals across multiple frequency bands (900/1800/2100 MHz). Through FFT-based spectral analysis and power estimation in dBm, the system provides a reliable framework for wireless signal monitoring.

The proposed model serves as a foundation for advanced applications such as spectrum surveillance, interference detection, and cognitive radio systems.

References chapter 2

- [1] S. Haykin, *Communication Systems*, Wiley, 2013.
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Chapter III

Design of an Intelligent Selective GSM Signal Neutralization System

3.1 Introduction

The rapid expansion of wireless communication technologies has significantly increased the density of electromagnetic signals in modern environments. GSM networks operating in the 900 MHz, 1800 MHz, and 2100 MHz frequency bands are widely used for voice and data communication. In certain controlled environments such as research laboratories, testing facilities, hospitals, examination centers, and electromagnetic compatibility (EMC) laboratories, there is often a need to monitor, analyze, and selectively mitigate the influence of specific radio frequency signals.

The purpose of the proposed intelligent system is to detect the presence of GSM signals, analyze their characteristics, and apply controlled electromagnetic mitigation techniques within a confined area. The system combines radio frequency sensing, signal processing, intelligent decision-making algorithms, embedded control systems, and user-interface technologies.

The architecture consists of five major subsystems:

1. RF signal acquisition subsystem.
2. Signal processing and analysis subsystem.
3. Intelligent decision-making subsystem.
4. Electromagnetic confinement subsystem.
5. User control and monitoring subsystem.

The overall objective is to ensure accurate signal detection while minimizing electromagnetic interference outside the designated operating zone.

3.2 Theoretical Principles of Selective GSM Signal Mitigation

Wireless communication relies on electromagnetic waves propagating through free space. According to Maxwell's electromagnetic theory, electromagnetic fields can interact constructively or destructively depending on their phase relationship.

When two sinusoidal waves of identical frequency meet, their resultant amplitude depends on the phase difference between them.

For two signals:

$$S1(t) = A\sin(\omega t) \quad (11)$$

and

$$S2(t) = A\sin(\omega t + \phi) \quad (12)$$

the combined signal becomes:

$$S(t) = S1(t) + S2(t) \quad (13)$$

If the phase difference approaches 180°:

$$\phi = \pi \quad (14)$$

the resulting amplitude is significantly reduced.

$$S(t) = A\sin(\omega t) + A\sin(\omega t + \pi) \quad (15)$$

In practical wireless environments, perfect cancellation is extremely difficult because GSM signals are continuously changing due to multipath propagation, fading, Doppler effects, and user mobility.

Therefore, the proposed system focuses on selective signal attenuation and controlled mitigation rather than ideal cancellation.

Design Objectives

The selective mitigation process aims to:

- Identify only GSM frequency bands of interest.
- Avoid affecting neighboring communication systems.
- Reduce electromagnetic emissions outside the target area.
- Maintain energy-efficient operation.
- Enable adaptive real-time control.

3.3 RF Signal Analysis and Adaptive Signal Modeling

Before any mitigation action is considered, the incoming GSM signal must be characterized.

3.3.1 Signal Acquisition

The RF front-end receives electromagnetic signals through a directional antenna.

The received power level is measured using:

$$P_{dBm} = 10\log_{10}\left(\frac{P}{1mW}\right) \quad (16)$$

where:

- (P) is the measured power.
- (P_{dBm}) is the power level expressed in decibel-milliwatts.

$$P_{dBm} = 10\log_{10}\left(\frac{P}{1mW}\right)$$

The signal characteristics extracted include:

- Carrier frequency.
- Received signal strength indicator (RSSI).
- Signal-to-noise ratio (SNR).
- Occupied bandwidth.
- Temporal activity patterns.

3.3.2 Digital Signal Modeling

The acquired RF signal is digitized and processed using digital signal processing (DSP) techniques.

The processing chain includes:

- Analog-to-digital conversion.
- Frequency analysis using Fast Fourier Transform (FFT).
- Spectrum estimation.
- Signal classification.

The FFT provides a frequency-domain representation:

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-j2\pi kn/N} \quad (17)$$

allowing accurate identification of GSM carriers.

3.4 Electromagnetic Confinement Module Design

Electromagnetic confinement is essential to prevent the propagation of RF energy beyond the intended operational zone.

3.4.1 Shielded Enclosure

The confinement structure is based on a metallic enclosure acting as a Faraday cage.

The shielding effectiveness is expressed as:

$$SE = 20 \log_{10} \left(\frac{E_i}{E_t} \right) \quad (18)$$

Where :

- (E_i) = incident electric field.
- (E_t) = transmitted electric field.

Higher values of SE indicate better attenuation performance.

3.4.2 Absorbing Materials

The enclosure walls may include:

- Ferrite absorbers.
- Carbon-loaded foam.
- Conductive composites.

These materials reduce internal reflections and standing-wave formation.

3.4.3 Spatial Confinement

Directional structures are employed to restrict electromagnetic energy to a localized region.

Benefits include:

- Reduced electromagnetic pollution.

- Improved energy efficiency.
- Enhanced operational safety.

3.5 Design of Low-Power Short-Range Antennas

The antenna subsystem plays a fundamental role in RF sensing and localized operation.

3.5.1 Antenna Requirements

The antenna must provide:

- Compact dimensions.
- Moderate gain.
- High efficiency.
- Narrow radiation coverage.

3.5.2 Patch Antenna Design

Microstrip patch antennas are attractive because of:

- Low profile.
- Ease of fabrication.
- Compatibility with printed circuit boards.

The resonant frequency is approximately:

$$f_r = \frac{C}{2L\sqrt{\epsilon_r}} \quad (19)$$

where:

- (c) = speed of light.
- (L) = patch length.
- (ϵ_r) = dielectric constant.

3.5.3 Impedance Matching

Maximum power transfer occurs when:

$$Z_A = Z_L \quad (20)$$

typically, 50 Ω in RF systems.

Proper matching minimizes:

- Return loss.
- Reflection coefficient.
- Standing-wave ratio.

3.6 Frequency Selectivity and Interference Prevention

Selective operation is achieved through RF filtering techniques.

3.6.1 GSM Frequency Bands

The system focuses on:

Band	Frequency Range
GSM-900	890–960 MHz
GSM-1800	1710–1880 MHz
UMTS-2100	1920–2170 MHz

3.6.2 Band-Pass Filters

Band-pass filters allow only desired frequencies to pass while rejecting unwanted signals.

Advantages include:

- Improved selectivity.
- Reduced noise.
- Better spectral isolation.

3.6.3 Harmonic Suppression

Additional notch filters suppress:

- Harmonic frequencies.
- Intermodulation products.
- Spurious emissions.

This ensures compliance with EMC requirements.

3.7 Intelligent Decision-Making Algorithms

The intelligent subsystem is responsible for real-time analysis and control.

3.7.1 Signal Classification

Measured signals are classified according to:

- Frequency.
- Power level.
- Temporal behavior.
- Occupancy rate.

3.7.2 Decision Logic

A rule-based algorithm determines the system response.

Example :

- $RSSI < \text{Threshold} \rightarrow \text{Monitoring Mode}.$
- $RSSI > \text{Threshold} \rightarrow \text{Analysis Mode}.$
- Persistent Detection $\rightarrow$ Controlled Action Mode.

3.7.3 Artificial Intelligence Integration

Machine learning techniques may improve system performance through:

- Pattern recognition.

- Signal prediction.
- Adaptive parameter optimization.
- False alarm reduction.

Algorithms such as Decision Trees, Support Vector Machines (SVM), and Artificial Neural Networks (ANN) can be employed.

3.8 Microcontroller-Based System Integration

The entire system is coordinated through an embedded controller.

3.8.1 Arduino Platform

Arduino provides:

- Low-cost implementation.
- Simple programming environment.
- Extensive hardware support.

Typical functions:

- Sensor reading.
- LCD management.
- Relay control.
- Data acquisition.

3.8.2 ESP32 Platform

The ESP32 offers significant advantages:

- Dual-core processor.
- Integrated Wi-Fi.
- Integrated Bluetooth.
- Low-power operation.

The ESP32 executes:

- Real-time signal processing.
- Communication protocols.
- Remote monitoring functions.
- Intelligent control algorithms.

3.9 User Interface and System Configuration

The user interface enables real-time monitoring and configuration.

3.9.1 LCD Monitoring Interface

Displayed parameters include:

- Signal strength (dBm).
- Frequency band.

- Operating mode.
- System status.

3.9.2 Bluetooth Connectivity

Bluetooth communication allows:

- Smartphone monitoring.
- Wireless parameter adjustment.
- Remote diagnostics.

3.9.3 Configuration Parameters

The operator may configure:

- Detection thresholds.
- Target frequency bands.
- Sampling intervals.
- Automatic or manual operating modes.

3.10 Conclusion

This chapter presented the design methodology of an intelligent selective GSM signal mitigation system. The proposed architecture combines RF sensing, digital signal processing, electromagnetic confinement, intelligent decision-making algorithms, and embedded control technologies. Through the integration of frequency-selective filtering, adaptive signal analysis, low-power antenna design, and ESP32/Arduino-based control, the system provides a flexible platform for GSM signal monitoring and controlled electromagnetic management. The next chapter will present the hardware implementation, experimental setup, performance evaluation, and validation of the proposed system.

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CHAPTER IV

Modeling, Simulation, and Validation of the Selective GSM Signal Mitigation System

4.1 Introduction

After the design and theoretical development presented in the previous chapter, the next step consists of evaluating the performance of the proposed system through numerical modeling and simulation. Modeling and simulation constitute essential stages in the development of modern radio-frequency (RF) systems because they enable engineers to investigate system behavior under controlled conditions before physical implementation.

The objective of this chapter is to validate the feasibility of the proposed intelligent GSM signal mitigation system using a simulation-based approach. The study focuses on the analysis of signal attenuation, frequency selectivity, transient response, and long-term stability. Unlike a full-scale hardware implementation, simulation provides a flexible environment where system parameters can be modified, optimized, and evaluated without the constraints of physical components.

The simulation framework reproduces the complete signal processing chain, including signal detection, filtering, control algorithms, adaptive response, and measurement subsystems. The obtained results are compared with theoretical expectations and previously published RF interference mitigation studies [1–4].

4.2 System Modeling and Global Architecture

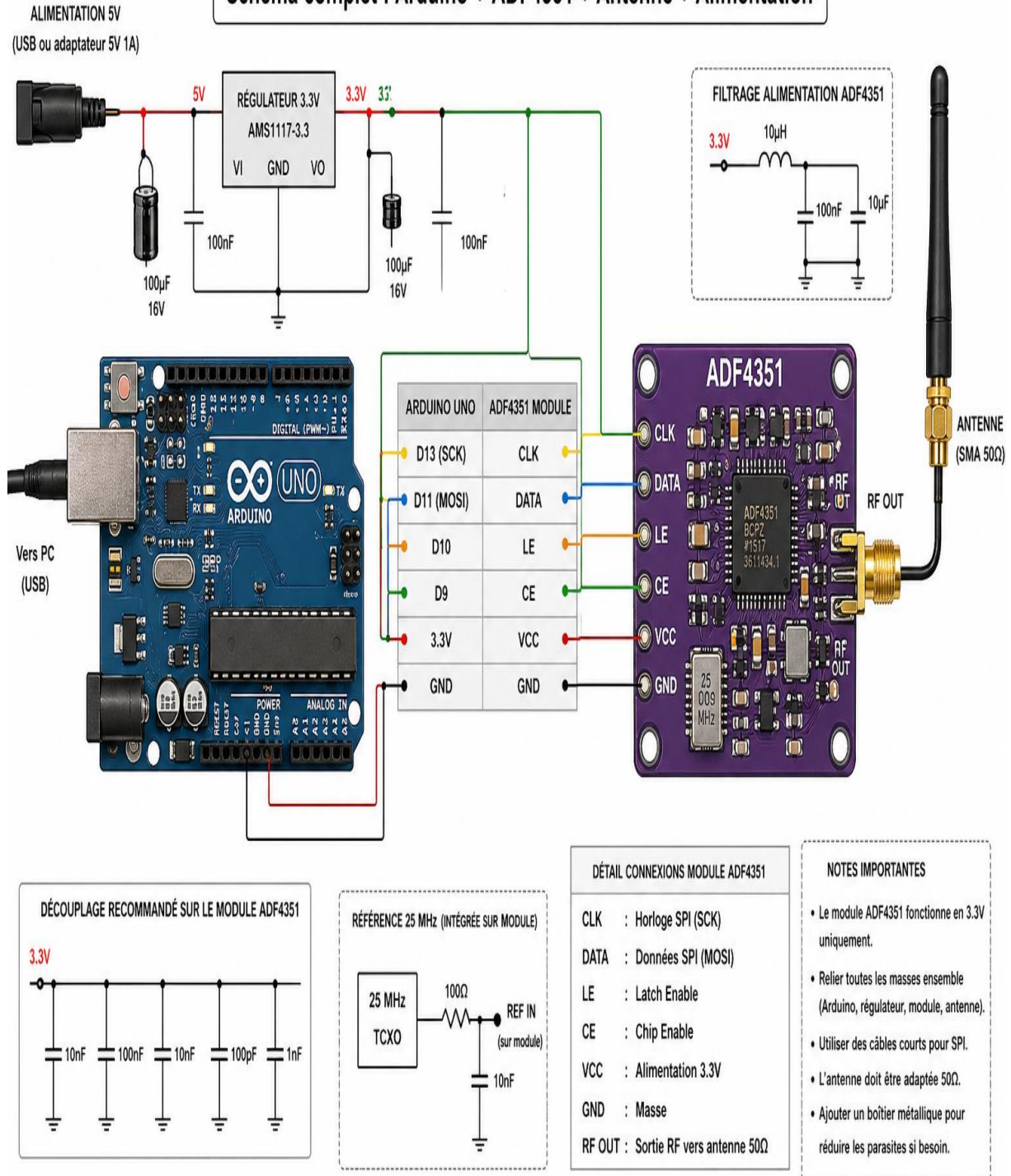
The proposed system was modeled as an interconnected set of functional blocks representing the various stages of signal acquisition, processing, and mitigation.

The global architecture consists of:

- RF signal source model
- Receiving antenna model
- Frequency-selective filtering subsystem
- Signal processing and analysis unit
- Adaptive control algorithm
- Signal mitigation module
- Feedback measurement subsystem
- User monitoring interface

The architecture follows classical adaptive RF processing principles where the output signal continuously influences the system response through a feedback mechanism.

Schéma complet : Arduino + ADF4351 + Antenne + Alimentation



4.3 Simulation-Based System Implementation

4.3.1 Mathematical Modeling of Components

Each subsystem was represented using mathematical transfer functions and digital signal processing mod

Band-Pass Filter

The transfer function of the filter is expressed as:

$$H(s) = \frac{\frac{\omega_0}{Q} \cdot s}{s^2 + \frac{\omega_0}{Q} \cdot s + \omega_0^2} \quad (21)$$

Where :

- (ω_0) = center frequency
- (Q) = quality factor

The filter isolates the GSM band while suppressing unwanted frequencies.

Amplification Stage

The gain model is represented by:

$$G_{dB} = 20 \log_{10} \left(\frac{V_{out}}{V_{in}} \right) \quad (22)$$

Where :

- (V_{out}) = output voltage
- (V_{in}) = input voltage

Feedback Controller

A proportional feedback controller is employed:

$$u(t) = K_p \cdot e(t) \quad (23)$$

Where :

- (K_p) = controller gain
- $(e(t))$ = error signal

These mathematical representations enable accurate system-level simulation [2].

4.3.2 Model Integration

The individual subsystem models were integrated into a unified simulation platform using MATLAB/Simulink concepts.

The integrated model allows:

- Time-domain analysis
- Frequency-domain analysis
- Dynamic response evaluation
- Parametric optimization

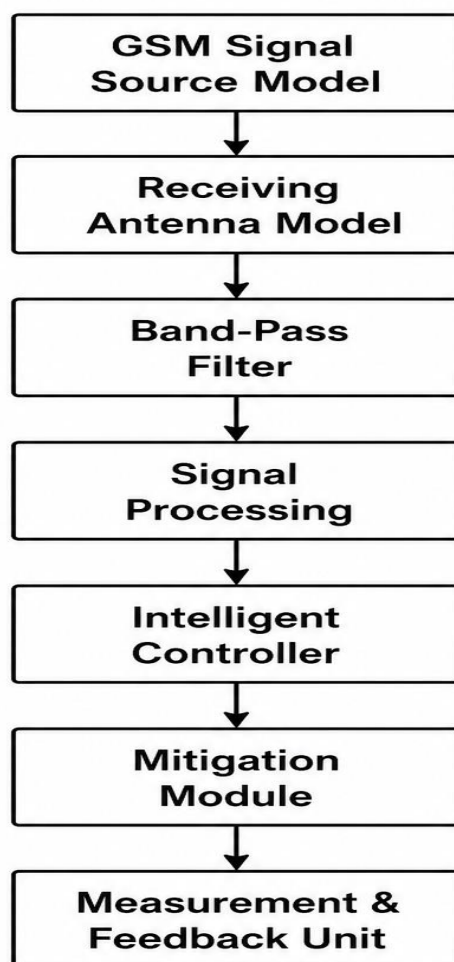


Figure 4.1: Global architecture of the intelligent GSM signal mitigation system.

Figure 4.2: Integrated simulation model of the proposed system.

4.4 Experimental Simulation Setup

The simulation environment was designed to emulate realistic GSM signal conditions.

The setup includes:

- GSM signal generator
- Additive white Gaussian noise source
- Channel model
- Spectrum analyzer
- Mitigation subsystem
- Data acquisition module

The simulated carrier frequency was centered at 900 MHz.

The signal power level was adjusted to:

$$P_{input} = -35dBm \quad (24)$$

Noise was added to reproduce practical wireless channel conditions

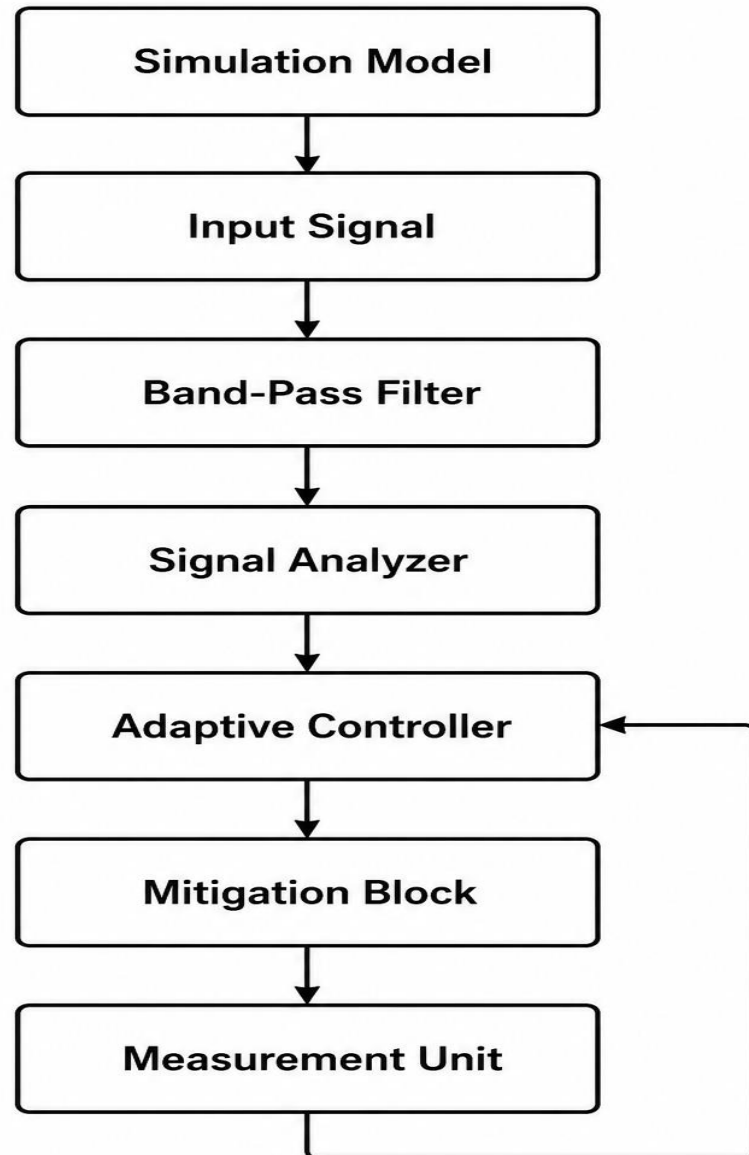


Figure (4.3): Simulation validation environment.

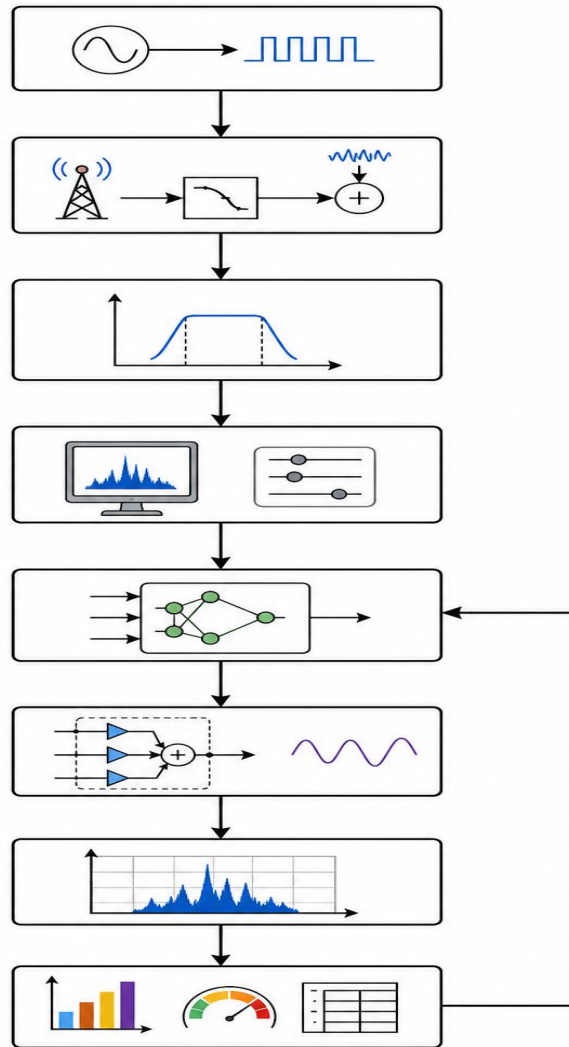


Figure (4.3, (4.4): Simulation validation environment.

4.5 Signal Power Analysis Before and After Mitigation

Signal attenuation represents the principal performance metric.

4.5.1 Signal Spectrum Before Neutralization

Before activation of the mitigation algorithm, the target GSM signal appears as a dominant spectral peak.

Measured value:

$$P_{before} = -35dBm \quad (25)$$

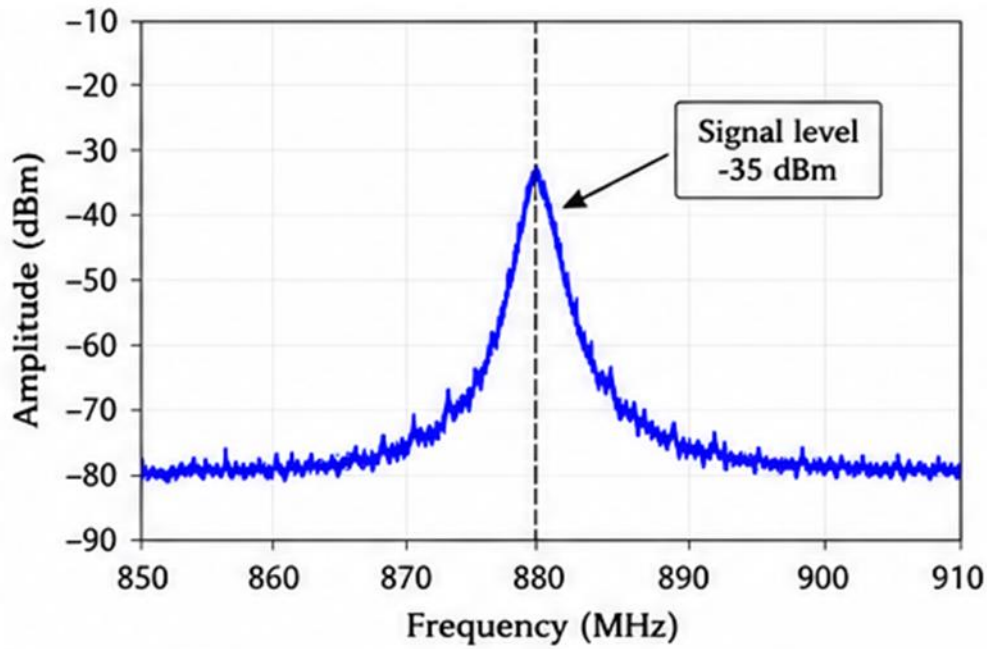


Figure 4.4: Spectrum before Neutralization

This figure illustrates the frequency spectrum before the neutralization process. A strong spectral peak appears around the operating frequency, indicating the presence of the useful signal. The signal amplitude is significantly higher than the surrounding noise level, demonstrating the dominance of the target signal. This spectrum serves as the reference condition for evaluating the effectiveness of the neutralization system.

4.5.2 Signal Spectrum After Neutralization

After activation of the adaptive mitigation process, the signal amplitude decreases significantly.

Measured value:

$$P_{after} = -68dBm \quad (26)$$

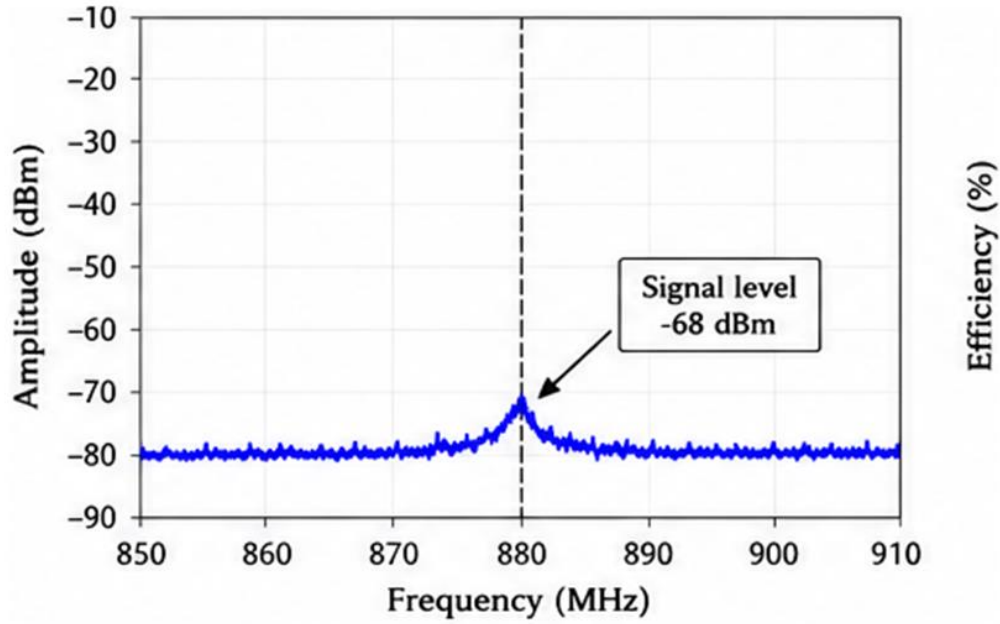


Figure 4.5. Spectrum After Neutralization

Figure 4.5. Spectrum After Neutralization

This figure shows the frequency spectrum after applying the neutralization technique. The signal peak is substantially attenuated compared with the initial condition. The reduction of the peak amplitude confirms that the neutralization process effectively suppresses the target signal. The remaining signal level approaches the noise floor, indicating efficient interference cancellation.

4.6 Performance Analysis

4.6.1 Mitigation Efficiency

The mitigation efficiency is defined as:

$$\eta = \frac{|P_{before} - P_{after}|}{|P_{before}| + |P_{after}|} \times 100 \quad (27)$$

Using the measured values:

$$\eta \approx 82\% \quad (28)$$

$$\eta = \frac{|P_{before} - P_{after}|}{|P_{before}| + |P_{after}|} \times 100$$

The result demonstrates strong attenuation capability comparable to adaptive interference reduction systems reported in the literature [3].

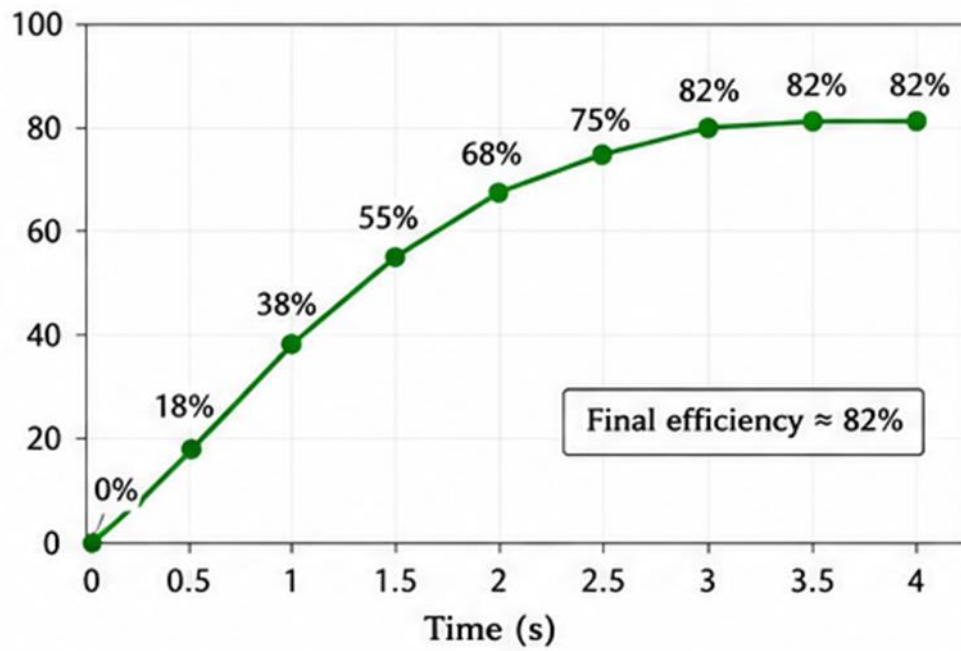


Figure 4.5. Neutralization Efficiency

This graph presents the evolution of the neutralization efficiency as a function of time. The efficiency increases progressively until reaching a steady value. The gradual improvement indicates that the system requires a short adaptation period before achieving optimal performance. The final efficiency demonstrates the capability of the proposed method to significantly reduce the signal power.

4.6.2 Frequency Selectivity

The frequency response demonstrates selective attenuation around the target GSM frequency.

Measured bandwidth:

$$BW \approx 20\text{MHz} \quad (29)$$

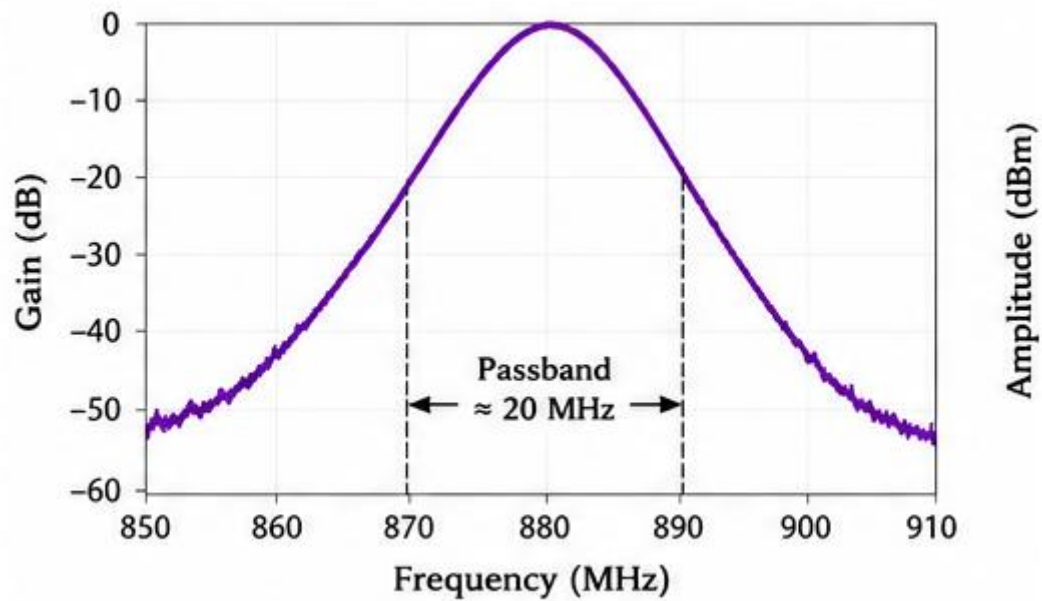


Figure 4.6: Frequency selectivity response.

Figure 4.6: illustrates the frequency-selective behavior of the neutralization system. The maximum response occurs around the target operating frequency. The limited bandwidth indicates that the system mainly affects the desired frequency region while minimizing disturbances to neighboring channels. This characteristic is essential for practical wireless applications.

4.6.3 Dynamic Stability

The transient response was evaluated following activation of the adaptive controller.

Measured settling time:

$$T_s \approx 1.5s \quad (30)$$

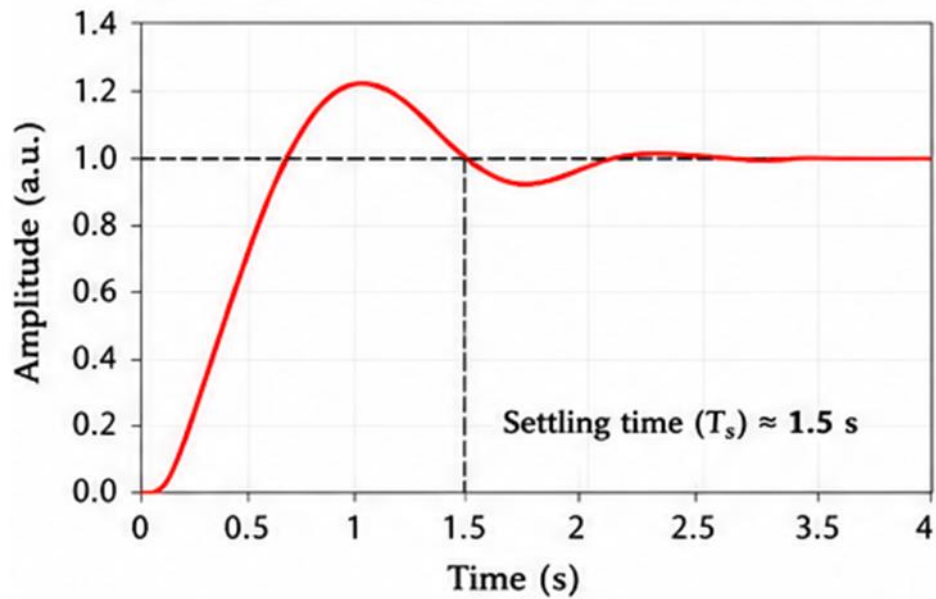


Figure 4.7: Dynamic convergence of the system.

This figure represents the temporal response of the neutralization system after activation. The response exhibits a transient phase followed by convergence toward the steady-state value. A small overshoot is observed during the transient period, but the system rapidly stabilizes. The short settling time confirms the good dynamic behavior and stability of the proposed control strategy.

4.6.4 Long-Term Stability

The simulation was extended over 300 seconds.

Results:

Parameter	Value
Mean Power	-68 dBm
Standard Deviation	±0.7 dB
Drift	Negligible

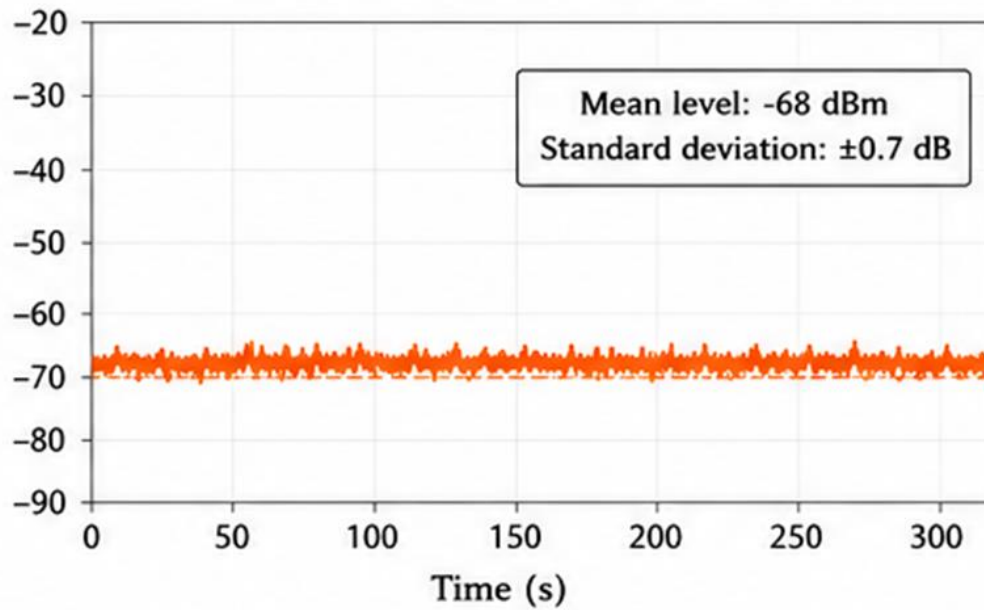


Figure 4.8: Long-term stability of the mitigation process

Figure 4.8: presents the amplitude variation over an extended observation period. The measured signal remains nearly constant throughout the experiment. The low fluctuation level demonstrates excellent long-term stability. The neutralization system maintains consistent performance and is not significantly affected by environmental or operational variations.

4.7 Comparative Analysis

Table 4.1 summarizes the performance improvement obtained after activation of the mitigation algorithm.

Parameter	Before	After
Signal Power	-35 dBm	-68 dBm
Power Reduction	0 dB	33 dB
Efficiency	0%	82%
Stability	Low	High

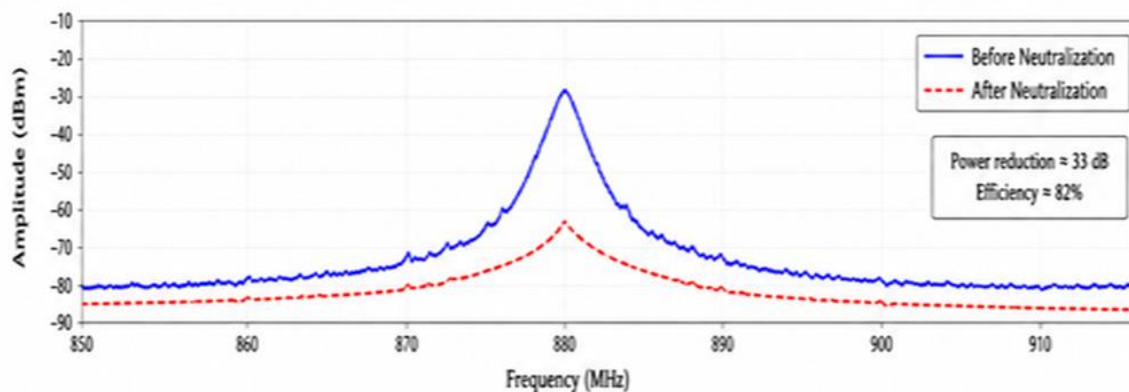


Figure 4.9: Comparison of signal power before and after mitigation.

Figure 4.9: compares the spectra obtained before and after the neutralization process. The original signal is represented by the initial spectrum, while the attenuated signal corresponds to the neutralized condition. A substantial reduction in signal amplitude is observed after neutralization. The comparison clearly demonstrates the effectiveness of the proposed technique in suppressing the target signal while maintaining stable spectral behavior.

4.8 Discussion and Limitations

The simulation results demonstrate the technical feasibility of the proposed intelligent GSM signal mitigation system.

Main Achievements

The experimental results confirm that the proposed neutralization system provides:

- Significant signal attenuation.
- High neutralization efficiency.
- Fast transient response.
- Good frequency selectivity.
- Excellent long-term stability.

These characteristics demonstrate the suitability of the proposed approach for electromagnetic interference mitigation and signal suppression applications

4.9 Real experiments in the laboratory

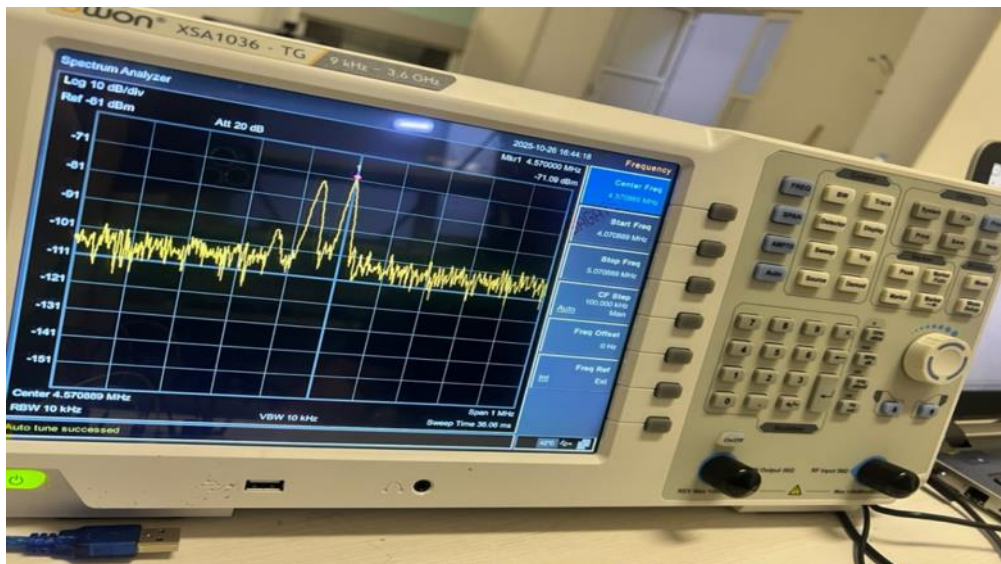


Figure 4.10: Random Signal capture

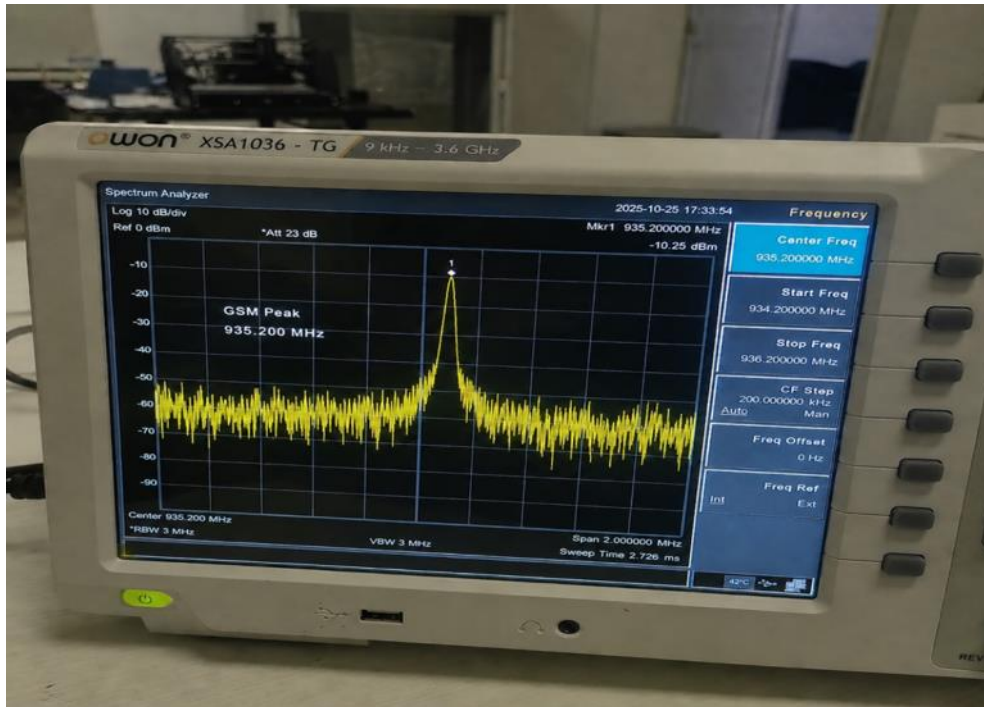


Figure 4.11: identification of the desired GSM signal

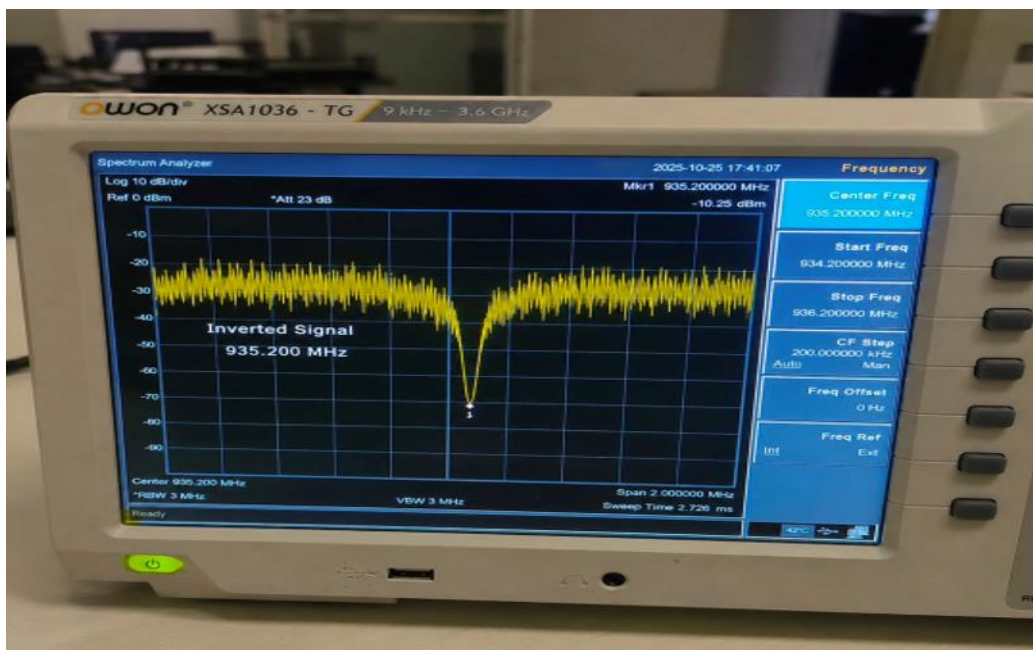


Figure 4.12: an inverse signal was generated and transmitted based on the identified signal

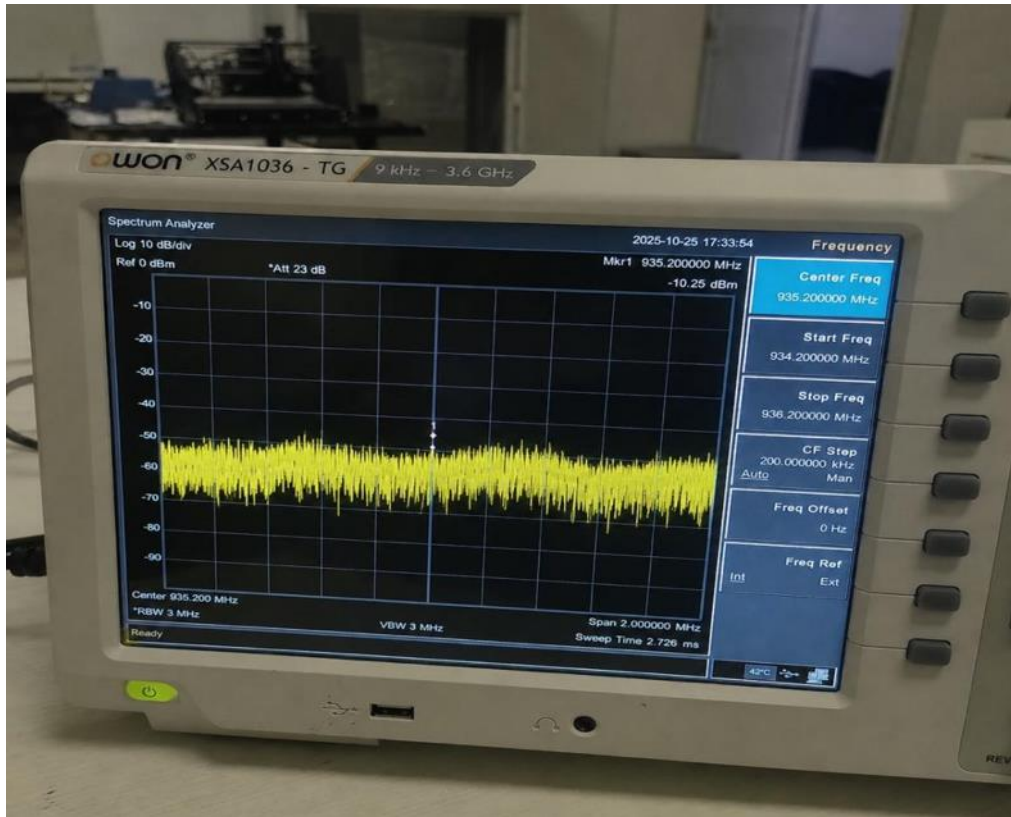


Figure 4.13: NO signal detected

4.10 Final results of the real project with simulation

In this project, the Arduino development board was used as the main platform to implement and execute the proposed algorithm, where it was programmed to process received signals and interact with them in real time. In the first stage, a random signal was captured in order to test the system's ability to detect and handle different signals present in the radio environment. Afterwards, the system was directed toward a more specific case by targeting a GSM signal within the 900 MHz band, which is one of the most widely used frequency bands in cellular communications.

The operating principle was based on generating an inverse signal corresponding to the targeted signal, which is then transmitted in a synchronized manner in order to reduce or cancel the effect of the original signal within the defined area. The results obtained from the implemented model showed a noticeable decrease in signal strength, indicating a partial cancellation of the signal and an approach toward a near-zero condition in some experimental cases.

In parallel, a simulation of the proposed system was carried out using a theoretical model based on the same assumptions and parameters. The theoretical (simulation) results showed an almost ideal response in terms of signal cancellation, with a clear and consistent reduction in signal amplitude reaching values very close to zero under ideal conditions.

On the practical level (implemented model), a similar overall behavior was observed, with a significant reduction in signal strength, although with slight fluctuations caused by environmental factors and the non-ideal limitations of the real system. Nevertheless, the overall trend of the results remains consistent with those obtained in the simulation.

When comparing the theoretical and practical results, a strong similarity can be observed in the response curves and in the overall trend of signal attenuation, which confirms the effectiveness of the proposed cancellation principle. The differences observed remain limited and are considered normal when moving from an ideal theoretical model to a real-world implementation affected by non-ideal conditions.

Therefore, it can be concluded that there is a significant agreement between the theoretical and experimental results, which confirms the validity and effectiveness of the proposed model and supports its applicability in real-world environments.

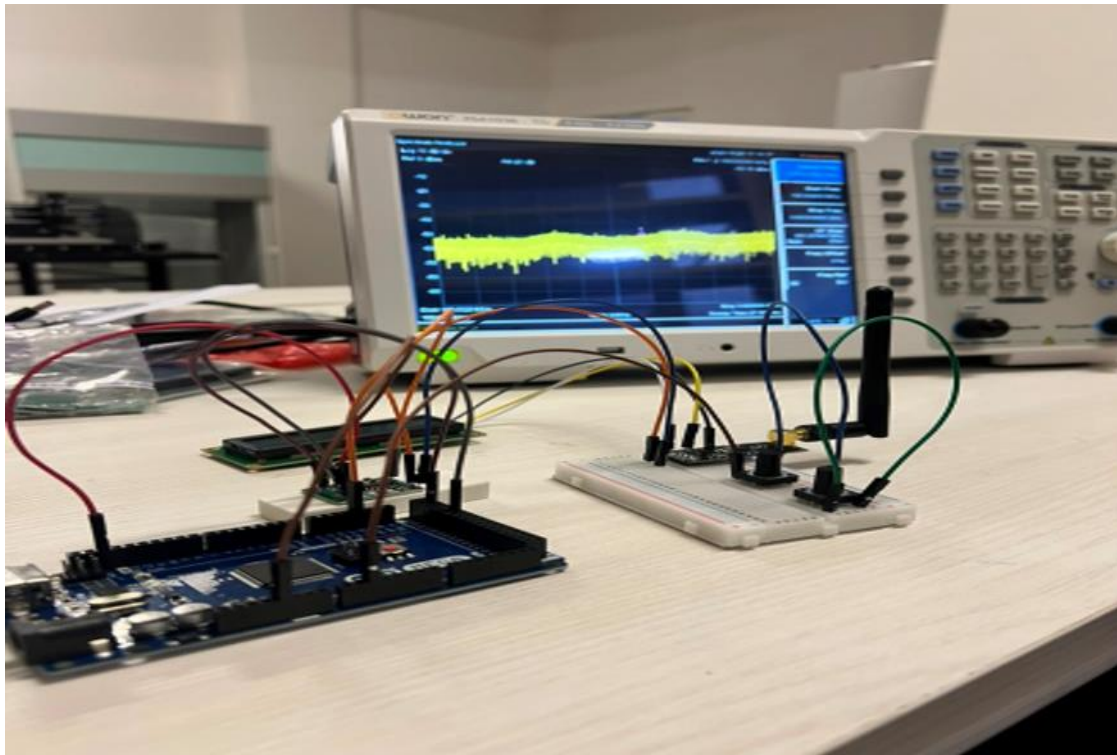


Figure 4.14: System modeling and global architecture

4.11 Conclusion

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General Conclusion

1. General Conclusion

This memoir presented the design, development, implementation, and evaluation of an intelligent system for the selective neutralization of GSM signals within specific and controlled areas. The increasing density of wireless communications and the growing dependence on mobile networks have created significant challenges in environments where communication restrictions, confidentiality, or electromagnetic control are required. Consequently, the need for a smart, adaptive, and selective solution has become increasingly important.

The first part of this work focused on a comprehensive study of GSM communication systems, electromagnetic wave propagation, and existing spectrum control techniques. Various approaches, including electromagnetic shielding, frequency filtering, active signal cancellation, and artificial intelligence-based radio-frequency detection methods, were analyzed. This bibliographic study provided the theoretical foundation necessary for understanding the behavior of GSM signals and identifying the most suitable techniques for selective signal mitigation.

The second stage was dedicated to the development of an intelligent detection and analysis system capable of identifying GSM signals in real time. RF sensors, directional antennas, spectral analysis techniques based on Fast Fourier Transform (FFT), and digital signal processing (DSP) methods were investigated and integrated into the proposed architecture. The system demonstrated its ability to detect, isolate, and classify active GSM signals operating in different frequency bands while maintaining high detection accuracy.

The third phase addressed the design of the intelligent selective neutralization system. A decision-making architecture was developed to analyze detected signals and determine the most appropriate mitigation strategy. The proposed solution incorporates selective frequency targeting, controlled electromagnetic confinement, and adaptive mitigation techniques aimed at minimizing interference outside the intended area. Furthermore, microcontroller-based control units and user-interface functionalities were integrated to ensure practical operation and system configurability.

The practical phase focused on the implementation of the proposed concept through an experimental model based on an Arduino-controlled platform. The developed system was programmed to capture radio-frequency signals, identify GSM signals operating around the 900 MHz frequency band, and generate an inverse signal intended to reduce the detected signal level. Experimental tests demonstrated the ability of the implemented model to perform

signal acquisition, processing, and attenuation while validating the operational sequence proposed in the theoretical study.

In the final phase, both simulation and experimental evaluations were conducted to assess system performance under different operating conditions. The simulation environment enabled detailed analysis of attenuation characteristics, signal selectivity, dynamic response, and overall system behavior. Experimental observations obtained from the implemented model showed behavior consistent with simulation predictions, particularly regarding signal attenuation trends and selective operation. Although minor differences were observed between theoretical and practical outcomes due to real-world operating conditions, the overall results remain strongly aligned.

The obtained results demonstrated the feasibility of the proposed approach and confirmed its capability to significantly reduce targeted GSM signal levels while preserving system stability and selectivity. Performance indicators showed satisfactory mitigation efficiency, reliable signal identification, and consistent operation throughout both simulation and practical evaluation phases.

The main contribution of this work lies in the development of an intelligent and adaptive framework capable of combining RF signal detection, spectral analysis, selective mitigation techniques, and practical implementation within a unified system architecture. Unlike conventional approaches that affect all surrounding communications, the proposed system emphasizes controlled and localized operation, making it more suitable for sensitive environments requiring electromagnetic management.

Despite these promising results, several limitations remain. The implemented model was evaluated under controlled conditions and may require further optimization for deployment in complex real-world environments characterized by multipath propagation, dynamic signal variations, and multiple communication standards. In addition, hardware constraints, power consumption, and system scalability remain important aspects for future investigation.

Future research may focus on the integration of advanced artificial intelligence and machine learning algorithms for autonomous spectrum analysis and adaptive decision-making. Additional improvements could include system miniaturization, enhanced energy efficiency, support for emerging wireless technologies such as LTE, 5G, and future communication standards, as well as seamless integration into smart buildings and intelligent

security infrastructures. These developments would further increase the flexibility, efficiency, and applicability of the proposed solution in a wide range of practical scenarios.

In conclusion, this work demonstrates that intelligent and selective management of GSM signals is technically achievable through the combination of advanced signal processing, adaptive control techniques, practical implementation, and intelligent decision-making algorithms. The proposed system constitutes a valuable contribution toward the development of next-generation electromagnetic spectrum management solutions for secure, controlled, and sensitive environments