Development of a MIMO System for Education in Digital Communications: A CDIO Approach

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***Abstract*— This work discusses the implementation of the Multiple Input, Multiple Output (MIMO) Digital Communication System using the C programming language. The goal is to provide educational material that helps students understand both fundamental and intermediate aspects of communication systems and signal processing. This is in response to the growing demand for high-capacity wireless communications and services, driven by the advancement of fifth-generation (5G) mobile networks. The project aligns with the Conceive, Design, Implement, and Operate (CDIO) initiative and aims to contribute to the telecommunications community by offering comprehensive documentation and free availability.**

***Keywords*— MIMO, CDIO, Digital communications, Education.**

I. Introduction

The evolution of mobile networks, particularly the fifth-generation (5G) brought about significant advancements in various sectors and increased the demand for high-capacity wireless communications. This has led to continuous technological innovation, with Multiple Input Multiple Output (MIMO) systems emerging as a key technology. MIMO enhances data speed and network capacity, impacting the physical layer of wireless communication systems [1]. However, these advancements pose challenges in academia, where there is a need to expand course content to accommodate these advancements, while undergraduate programs are trending towards shorter durations [2].

In this scenario, offering students a theoretical background and primarily hands-on experience with telecommunications systems is a vital component in boosting the quality of education and improving the curriculum [3]. The CDIO (Conceive, Design, Implement, Operate) educational framework [4] is particularly relevant in this context, as it emphasizes the importance of practical engineering skills alongside theoretical knowledge. By integrating the CDIO approach, students can gain a comprehensive understanding of the entire lifecycle of engineering products, from conception to operation.

There are several high-level open source projects that implement MIMO, in Matlab or Python. However, they often hide implementation details, which makes difficult their adoption in CDIO scenarios. In this paper, we present the development of a MIMO digital communication system using the C programming language called C MIMO available at GitHub[1] and with detailed documentation. The innovative aspect of this work is to provide a complete yet pedagogical MIMO implementation that can be used in projects involving embedded systems due to the wide support of various microprocessors and microcontrollers for the C language. This work aims to provide a comprehensive understanding of the basic aspects of digital communications and MIMO, following the CDIO approach.

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[1] https://github.com/lasseufpa/c_mimo

II. System Overview

The system depicted in Fig. 1 represents the implemented MIMO system based on Singular Value Decomposition (SVD), where each block represents an assignment of the implemented functions. By using SVD, the MIMO channel is transformed into a set of parallel, non-interfering sub-channels: $\mathbf{H} = \mathbf{U}.\mathbf{S}.\mathbf{V}^T$, where $\mathbf{U}$ and $\mathbf{V}$ are unitary matrices, and $\mathbf{S} = \text{diag}(\lambda_1, \ldots, \lambda_{\min(N_r,N_t)})$ is a diagonal matrix containing the singular values of channel $\mathbf{H}$, with $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_{min(N_r,N_t)}$. The singular values represent the gain of each sub-channel, directly impacting the data rate and reliability of the communication system. Higher singular values correspond to better channel conditions and thus higher potential data rates [5].

A user-inputted text is first read by the function `tx_data_read` (a) and converted it into a sequence of bits. Then, the `tx_data_padding` (b) function performs padding of this data with zeros, if necessary. The `tx_qam_mapper` (c) function maps binary data into a sequence of QAM (Quadrature Amplitude Modulation) symbols, which are complex numbers. The `tx_layer_mapper` (d) function maps data from a vector to a matrix. The `tx_precoder` (e) function multiplies the symbols of the streams by the $\mathbf{V}$ matrix resulting from the SVD. The `channel_gen` (f) function generates the complex channel matrix $\mathbf{H}$ with additive white Gaussian noise (AWGN).

The `rx_combiner` (g) function multiplies the signals received by the receive antennas (N_r) by the $\mathbf{U}$ matrix.

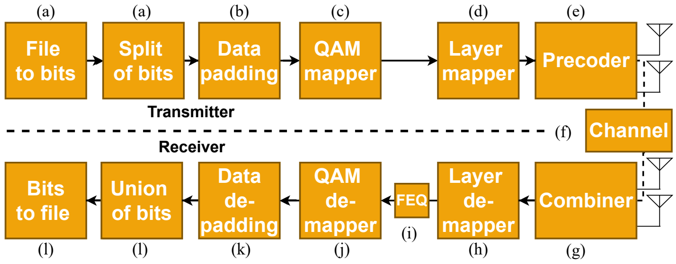

Fig. 1: Block diagram of the digital MIMO system.

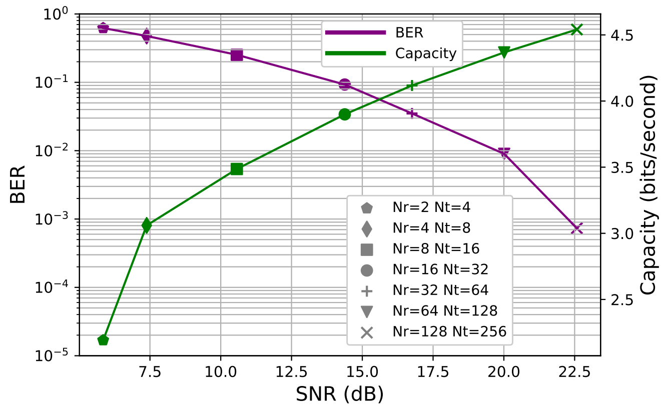

Fig. 2: BER and channel capacity against SNR for different numbers of antennas.

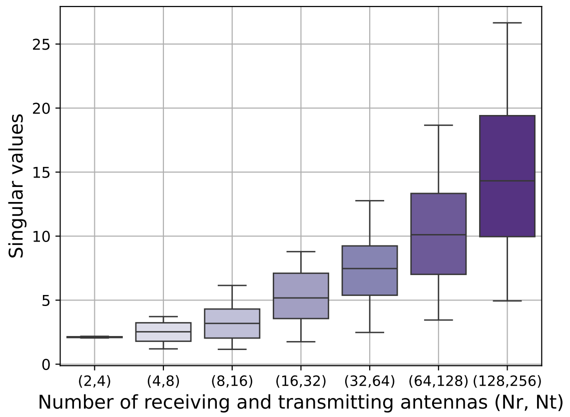

Fig. 3: Boxplot of the singular values (λ) of the channel for different numbers of antennas.

The `rx_layer_demapper` (h) function maps data from a matrix to a vector. The `rx_feq` (i) function performs channel equalization using the singular value matrix $\mathbf{S}$ obtained from SVD. The `rx_qam_demapper` (j) function demaps the QAM symbols to binary data. The `rx_data_depadding` (k) function removes the "null" symbols that were padded in the transmitter. Finally, the `rx_data_write` (l) function recovers the original bytes. Each of these functions plays a crucial role in the operation of the MIMO system, contributing to the overall process of data transmission and reception. To see implementations details, check the source documentation[2].

III. Simulation Results

To evaluate our model, we conducted a series of simulations transmitting a poem[3] through the MIMO system using Quadrature Phase Shift Keying (QPSK) modulation. The poem contains 521 characters. Each character is encoded into a QPSK symbol, resulting in a total of 2084 QPSK symbols, as each QPSK symbol can represent 2 bits of information.

We performed the tests under a fixed noise power and a variable number of antennas to assess the system's performance. The Signal-to-Noise Ratio (SNR), channel capacity, Bit Error Rate (BER) and singular values were calculated for each configuration, providing different indicators of the system's performance. Fig. 2 illustrate the performance of our simulation model, considering a varying number of receive antennas ($N_r \in \{2^1, 2^2, \cdots, 2^7\}$) and transmit antennas ($N_t \in \{2^2, 2^3 \cdots, 2^8\}$), such that $N_t = 2N_r$.

The graph illustrates that both the BER and the channel capacity are substantially influenced by the number of antennas on N_r and N_t. This is due to the increase in SNR with more antennas, which in turn reduces the BER, thereby enhancing system performance. Concurrently, the average channel capacity, obtained by averaging $\log_2(1+\text{SNR})$ across all layers, increases, allowing for more error-free information transmission.

In Fig. 3, the boxplot of the channel's singular values reveals that, as the number of antennas increases in the test configuration (N_r, N_t), the minimum singular values also increase compared to previous configurations. This slight increase in channel gain suggests that increasing the number of antennas already improves the system. Configurations with very high number of antennas are called "Massive MIMO" [6] and bring up new challenges, including higher power consumption, hardware costs, computational requirements and increased overhead for channel estimation.

[2] `https://lasseufpa.github.io/cMIMO/`

[3] The poem *"Soneto da Fidelidade"*, from Vinicius de Moraes.

IV. Conclusion and Future Work

This work introduces a practical methodology, based on the CDIO approach, to aid education in digital communications. Our experiments assessed the system under different configurations, showcasing its versatility and educational potential. Classroom-based tasks, such as text transmission, allow students to explore the impact of varying parameters like antenna count and character volume on key metrics such as BER, SNR, capacity and other implemented statistics. Future work will aim to improve the simulator's flexibility with a better parser for easy modification of parameters, such as antenna count, modulation and SNR. We also intend to incorporate Software-Defined Radio (SDR) experiments into our methodology.

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