Green downlink communication via replacing physical RF chains with virtual ones inspired by GreenMO uplink architecture [2]

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***Abstract*—Expanding the cellular network to accommodate the growing number of wireless users and devices presents a formidable challenge in maintaining robust over-the-air connections with high throughput. To address this challenge, multiple solutions have been proposed, including multiple user MIMO (MU-MIMO) and massive MIMO (mMIMO), which leverage an increased number of antennas to enable spatial multiplexing. However, the use of more antennas necessitates a greater number of RF chains, resulting in exorbitant power consumption. Previous research, such as the GreenMO framework, has introduced simpler uplink architectures with a focus on power and spectrum efficiency. In this study, we extend the GreenMO concept to the downlink architecture, aiming to further enhance performance through a novel approach facilitated by the HMC877LC3 broadband phase shifter board. Notably, this enhanced architecture remains applicable for uplink communication as well. Our findings demonstrate that the implementation of this new architecture yields improvements in the average signal-to-interference-plus-noise ratio (SINR) experienced by users, thus enhancing overall network performance.**

I. Introduction

With the escalating demand for greater wireless throughput in tandem with the exponential growth of wireless services in recent years, the advent of 5G technology has promised to tap into a vast spectrum of frequencies, particularly through its utilization of mmWave bands. However, despite these advancements, 5G encounters challenges such as mobility issues and blockages, which necessitate thorough examination to validate its efficacy in wireless technology deployment. In addressing the spectrum scarcity conundrum, the concept of multiple-input multiple-output (MIMO) emerges as a pivotal spatial resource. MIMO techniques leverage spatial diversity to enhance the overall throughput of a wireless system, effectively repurposing the same frequency-time resources. Going even further, massive MIMO, also known as large-scale antenna systems, asserts an impressive potential to boost spectral efficiency by up to fifty times or more.

Despite the notable performance benefits of massive MIMO (mMIMO), several challenges persist. These include issues such as the proliferation of RF chains and the resultant internal power consumption, as highlighted by Marzetta et al. [1]. Moreover, the latency associated with channel estimation escalates proportionally with the increase in the number of antennas, posing a significant hurdle to efficient deployment. This challenge is further compounded in real-world communication systems, where mMIMO must support bidirectional communication between users and base stations. Such bidirectional communication necessitates additional resources for accurate channel estimation, exacerbating the latency issue.

In recent research efforts dating back to the mid-2000s, there has been a concerted endeavor to mitigate the power consumption dilemma associated with massive MIMO systems. One approach gaining traction is the adoption of hybrid beamforming (HBF) architectures, which combine both digital and analog precoding techniques. Unlike fully-digital precoding architectures, HBF systems require fewer RF chains, as each analog precoder can serve multiple antennas. However, the efficacy of HBF systems is hampered by the inherent limitations of finite-resolution phase shifters on the analog side. These phase shifters are restricted to utilizing a finite set of phase coefficients, thereby diminishing spectral efficiency and constraining the full potential of mMIMO systems. Furthermore, the integration of analog and digital beamformers complicates the optimization process, rendering the resulting objective function non-convex. This coupling poses a significant challenge in achieving optimal system performance and exacerbates the complexity of system optimization.

In a recent publication by Gupta et al. [2], a novel uplink architecture named GreenMO was introduced. This architecture is characterized by the utilization of a single RF chain and RF switches, which deactivate certain antennas during each time slot. To offset the reduction in the number of active antennas, a higher sampling rate analog-to-digital converter (ADC) is employed. However, despite the innovation of employing just a single RF chain, the intermittent deactivation of antennas in the GreenMO architecture inevitably leads to a decrease in performance compared to a fully digital architecture. This trade-off underscores the challenges inherent in balancing system complexity with performance optimization in wireless communication architectures.

In this study, our initial focus is on enabling the implementation of the GreenMO architecture for downlink communication. However, we encounter a significant challenge in the form of out-of-band radiation, which we address by leveraging a higher sampling rate Digital-to-Analog Converter (DAC). Furthermore, instead of relying on conventional RF switches, we opt to integrate one phase shifter per each antenna into the architecture. This novel approach is aimed at enhancing the overall performance of the system. Our experimental results demonstrate that the incorporation of phase shifters leads to notable improvements in the average Signal-to-Interference-plus-Noise Ratio (SINR) experienced by users, as compared to the use of RF switches. The subsequent sections of this report delve into the background and related works pertinent to our study, followed by a detailed discussion on the design, implementation, and evaluation methodologies employed in our research endeavor.

II. Background and Related Works

Multiple Input Multiple Output (MIMO) technology has become foundational in modern wireless communication systems, offering substantial enhancements in spectral efficiency and link reliability. Foschini and Gans (1998) provided seminal insights into the potential of MIMO, demonstrating its capacity to significantly increase channel capacity through the use of multiple antennas at both transmitter and receiver ends [5]. Subsequent breakthroughs, such as Alamouti's introduction of space-time block coding, further catalyzed the adoption of MIMO in practical systems [6]. Expanding upon MIMO principles, massive MIMO (mMIMO) represents a significant evolution, leveraging a large array of antennas at base stations to serve multiple users concurrently. Research by Marzetta et al. (2010) has shown that mMIMO holds promise for remarkable gains in spectral efficiency [7].

However, challenges persist, including increased hardware complexity and latency in channel estimation [8]. Moreover, the deployment of mMIMO systems introduces significant power consumption concerns, particularly due to the operation of a large number of antennas and associated RF chains. Power amplifiers, analog-to-digital converters (ADCs), and digital signal processing (DSP) units contribute substantially to overall power consumption [9]. While mMIMO systems offer considerable gains in spectral efficiency, addressing power consumption issues is imperative to ensure their practical viability and sustainability in real-world deployments.

Several related works have endeavored to address power consumption challenges in mMIMO systems and explore solutions to mitigate them. Research by Zaidi et al. (2017) investigated the power consumption characteristics of mMIMO in 5G networks, offering insights into the factors contributing to power consumption and potential strategies for optimization [10]. Additionally, Abdelrahman et al. (2017) proposed energy-efficient hybrid analog-digital precoding techniques for millimeter-wave mMIMO systems, aiming to reduce power consumption while maintaining performance [11]. Furthermore, Hoydis et al. (2013) examined the power requirements of mMIMO systems in cellular networks and provided recommendations on the optimal number of antennas for maximizing spectral efficiency while minimizing power consumption [9]. These studies contribute valuable insights into power consumption optimization strategies and inform the development of efficient mMIMO deployments.

Hybrid beamforming has emerged as a promising technique to address power consumption challenges in mMIMO systems. By combining analog and digital beamforming, hybrid beamforming architectures aim to strike a balance between performance and power efficiency. Research by Abdelrahman et al. (2017) underscored the importance of energy-efficient hybrid analog-digital precoding for mMIMO systems, demonstrating its potential to reduce power consumption while maintaining signal quality [11]. Similarly, Larsson et al. (2014) highlighted the benefits of hybrid beamforming in mMIMO for next-generation wireless systems, emphasizing its role in achieving high spectral efficiency with reduced power consumption [8]. Despite its promise, hybrid beamforming presents challenges such as the inherent trade-off between performance and complexity. Achieving optimal performance while minimizing hardware complexity and power consumption remains a significant challenge in hybrid beamforming design [12].

In [2], the authors demonstrate an adaptation strategy for mMIMO systems, wherein the number of virtual RF chains is adjusted to match the number of users, employing a many-to-many antenna to RF chain mapping scheme. This approach creates a virtual hybrid array, where multiple antennas are linked to the same RF chain, and each antenna connects to several RF chains. However, the absence of analog domain signal processing in [2] limits the optimality of their hybrid architecture. In this study, we aim to improve the performance of this architecture while extending its applicability to the downlink scenario.

III. Design

In this section, we outline the fundamental concepts of the proposed architecture. For illustrative purposes, let's consider a scenario with 8 antennas and 4 users. As depicted in Fig. 1, the architecture comprises three distinct components. The first segment entails digital domain preprocessing of the users' data streams. Within the digital precoder, instead of solely relying on channel per subcarrier information, a novel precoding matrix is employed. Here, $H \in \mathbb{C}^{4\times 8}$ and $\Phi \in \mathbb{C}^{8\times 4}$ represent the channel and phase shifting pattern matrices, respectively. Following precoding, the outputs of the precoder are interleaved to facilitate the utilization of a single RF chain. In the subsequent step, the interleaved streams undergo conversion to the analog domain using a higher sampling frequency, which in this case is 4 due to the presence of 4 users. Finally, in the third segment, the phase shifter pattern is applied before reaching the antennas, as depicted in Fig. 2.

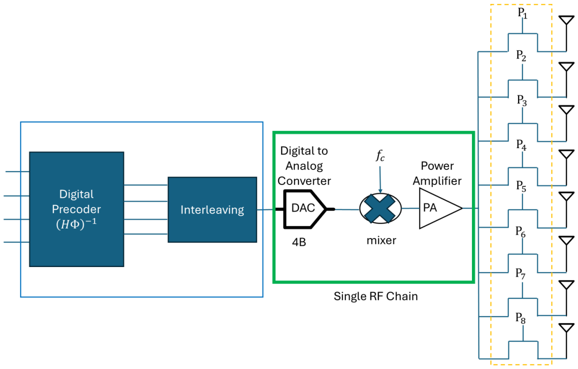

Fig. 1. Block diagram of the architecture which contains three separate parts including digital precoding, single RF chain, and phase shifters on the antennas

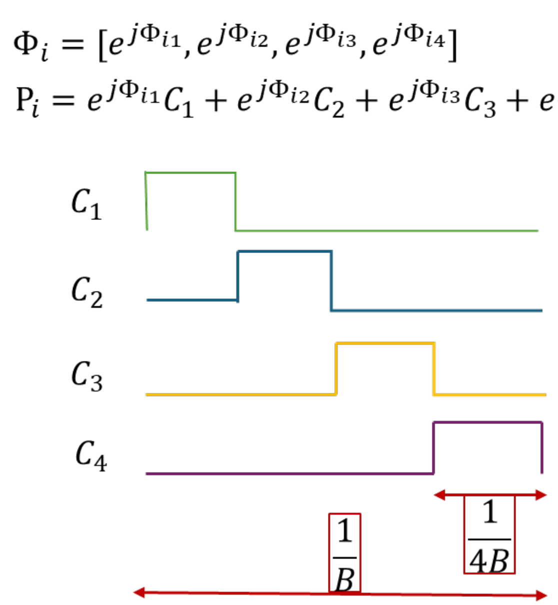

Fig. 2. Phase shifter pattern used in each antenna as a combination of the Φ matrix which shows the phase shifter matrix

Now, we mathematically describe the problem at hand. Since there are 4 users, then synthesizing only 4 virtual RF chains and resorting to hybrid beamforming is the energy-saving approach. The problem of finding the optimal hybrid precoding is still under ongoing research. In our system we assume that the channel is known and apply its Hermitian transpose at the analog domain, then we use ZF as the digital precoder of the composite channel $H\Phi$ and try to find how it will operate with the virtual RF chains. Since using phase shifters imposes a constant modulus constraint on the entries of Φ, we set $\Phi = \angle H^{\mathrm{H}}$, where $(.)^{\mathrm{H}}$ is the Hermitian transpose operator and $\angle(.)$ is the phase of a complex number. We can search for the optimal precoder in future work.

Let $\mathbf{x} \in \mathbb{C}^2$ be the data to be transmitted. The digitally-precoded data, $\mathbf{y}$, can be written as,

$$\mathbf{y} = (H\Phi)^{-1}\mathbf{x} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix}.$$

In the case of physical RF chains, each of these streams passes through the analog precoder to produce the transmitted signal. We assume the most general hybrid architecture, namely the fully connected hybrid architecture in which all RF chains are connected to all the antennas via phase shifters (or any other system). The transmitted signal, $\mathbf{z}$, is

$$\mathbf{z} = \Phi\mathbf{y} = \sum_{i=1}^{4} \phi_i y_i,$$

where ϕ_i represents the i-th column of Φ, i.e., the phase shifts from the i-th RF chain to all the antennas. Restricting the analog precoder to phase shifters makes the system limited to narrowband scenarios only, otherwise, we will need a system that assigns different phases or amplitudes to each subcarrier, however, this is a limitation of any phase-shifters based analog precoding and is not a side effect of GreenMo.

In the case of GreenMo we have only one DAC. To synthesize the RF chains, we serialize the data in $\mathbf{y}$ with quadruple the rate and pass them through the DAC. At the first time instant, we have y_1 output from the DAC, in this case, we tune the phase shifters to be $\mathbf{\Phi}_1$, then y_2 is output from the DAC, so we tune the phase shifters to be ϕ_2, and so on. It is obvious that in such a case we need phase shifters that can change their phase 4 times faster than the data rate.

let the channel from the Tx to the first user be $\mathbf{h}_1 \in \mathbb{C}^8$. In the physical RF chains case, the signal received at user 1 at a single time instant is

$$s_1 = \mathbf{h}_1^{\mathrm{H}}\mathbf{z} = \sum_{i=1}^{4} \mathbf{h}_1^{\mathrm{H}} \phi_i y_i. \quad (1)$$

We can see that the received signal at a single time instant is a linear combination of all y, while in the virtual RF case, we have only one of them at each time instant. We can consider the channel stationary over four consecutive time instants as the data changes at a rate four times the system's BW. To imitate the physical RF chains case, the receiver should add the values of each four consecutive time instants to mimic the equation in (1). This difference between uplink and downlink GreenMo is because in the uplink the upsampling is done after the channel, i.e., it combines the effect of both the signal and the channel, while in downlink the channel is not upsampled, thus the receiver also has a role in the despreading.

IV. Implementation

To bring the proposed architecture to fruition, we are pursuing both simulation and hardware implementation approaches. Currently, simulation efforts are ongoing, while the hardware implementation remains at a conceptual stage requiring further development. In our simulation endeavors, we initiated with

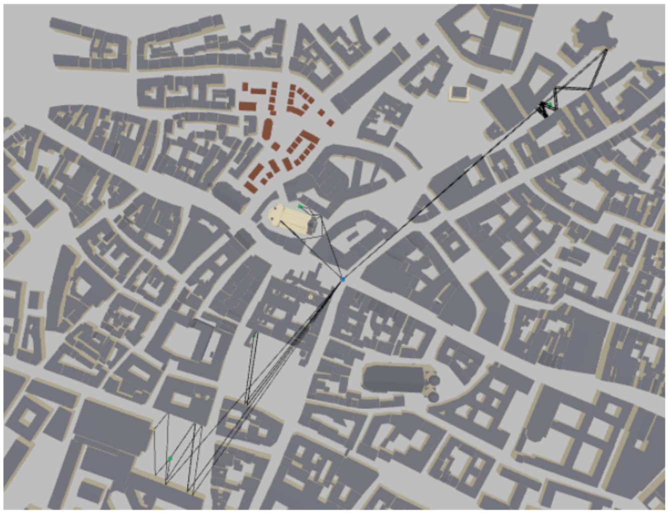

Fig. 3. Channel impulse response visualization using Sionna ray tracing model for four number of users and a four-antenna base station(Green dots show the users locations and blue dot shows the base-station location)

fundamental mathematical simulations to contrast the utilization of RF switches versus phase shifters. Subsequently, we employed OFDM-MIMO code to corroborate the outcomes of our initial simulations. Transitioning to hardware implementation, we have already established the architecture and delineated the primary component, namely the phase shifter. However, additional refinement is necessary to fully realize the implementation of the architecture.

A. Mathematical Simulation

To ensure the effectiveness of the architecture, mathematical simulations are conducted prior to any signal processing simulations. This comparison is carried out for 4 users across varying numbers of antennas in the base station. To generate the results, the Sionna simulation tool is utilized to generate the channel frequency response. For each number of antennas, 100 different scenarios involving the locations of 4 users are considered. Figure 3 illustrates one configuration of users.

In the GreenMO architecture, the digital precoding block integrates both the estimated channel matrix $\hat{H}$ and a binary switching matrix S with dimensions $N \times 4$, where N represents the number of base station antennas. The mathematical representation of this operation is as follows: each row of the R matrix, which has dimensions 4×4, serves as the received signal for the corresponding user. These rows encapsulate both noise and user interferences. Ideally, this matrix should resemble an identity matrix. During simulation, the S matrix is defined as a full-rank matrix.

$$R = (\hat{H}S)^{-1}(HS)$$

In contrast to GreenMO, our architecture utilizes phase shifters instead of binary switches. The mathematical description of this architecture is as follows, where Φ represents the phase shifter matrix. By employing this approach, we aim

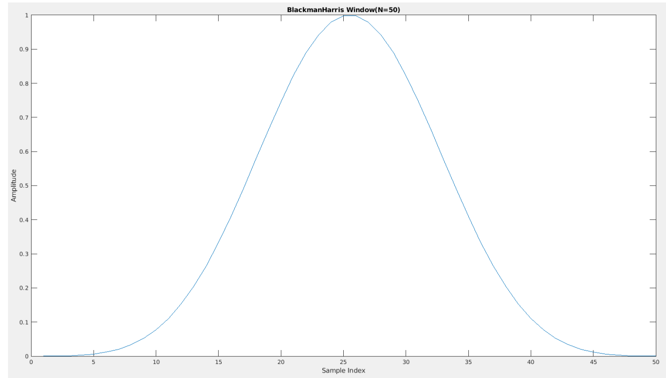

Fig. 4. Blackman-Harris window used to simulate the analog signal in Matlab

to achieve performance levels closer to digital beamforming, thereby surpassing the capabilities of GreenMO. It should be noted that in both cases, the same SNR is used in receiver antennas.

$$R = (\hat{H}\Phi)^{-1}(H\Phi)$$

B. Signal Processing Simulation

In addition to the mathematical simulation conducted earlier, a comprehensive signal processing simulation of the proposed architecture has been implemented to validate the previous results. In this simulation, the channel is assumed to be known, thereby omitting the channel estimation phase, which will be examined separately at a later stage.

In this simulation, assessing the impact of switching on the spectrum of the signal is a primary focus, representing a critical challenge in implementing the GreenMO downlink architecture. Through an analysis of the spectral characteristics of the signal, our objective is to comprehend how switching operations influence overall spectrum efficiency and interference levels within the system. This evaluation is vital for refining the design and enhancing the performance of the GreenMO architecture in downlink scenarios. To conduct this simulation, we utilize the Blackman-Harris window, as illustrated in Fig. 4, to simulate the spectrum of the analog signal in a digital computer environment.

C. Hardware Implementation

As previously mentioned, implementing the architecture using hardware necessitates one phase shifter per antenna, with the main component being the phase shifter depicted in Figure 4 [3]. The HMC877LC3 broadband phase shifter is distinguished by its exceptionally low rise time, facilitating rapid phase shifting essential for the proposed architecture. In contrast to analog phase shifters employed in hybrid beamforming architectures, this broadband board offers high resolution, enhancing its precision and effectiveness in signal manipulation.

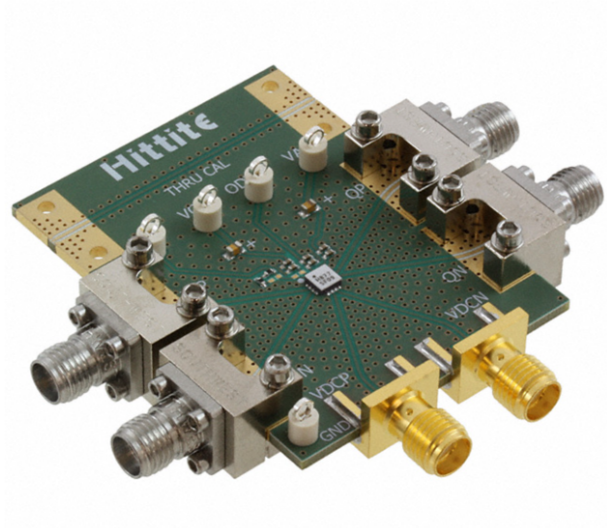

Fig. 5. Photograph depicting the broadband phase shifter board utilized in the hardware implementation of the architecture. The gold bases correspond to the differential control voltage, while the two silver pairs denote the input and output signals of the board

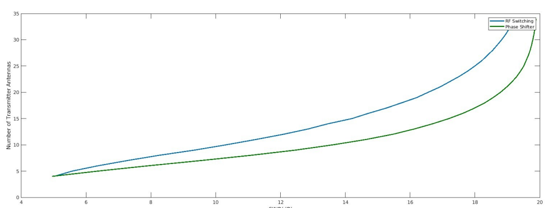

Fig. 6. Channel impulse response visualization using Sionna ray tracing model for four number of users and a four-antenna base station(Green dots show the users locations and blue dot shows the base-station location)

V. Evaluation

The mathematical results are anticipated to illustrate superior performance for the phase shifter architecture. As evidenced in Fig. 6, it becomes apparent that achieving the same Signal-to-Interference-plus-Noise Ratio (SINR) requires fewer antennas when employing the phase shifting architecture. This observation suggests that utilizing phase shifters can effectively reduce interference between users. Unlike RF switches, which solely select antennas for transmitting data corresponding to specific users, phase shifters refine the channel in a manner conducive to improved data transmission for individual users. Hence, the results underscore the efficacy of phase shifting in enhancing the overall performance and efficiency of the architecture.

Simulation results from signal processing and the OFDM-MIMO code reveal significant insights into the performance of the proposed architectures. The signal processing simulation demonstrates a decrease in the average Bit Error Rate (BER) of users with an increasing number of antennas, with the BER of the phase shifter architecture found to be lower than that of RF switching. Additionally, utilizing the OFDM-MIMO code to compare the average BER of users across different numbers

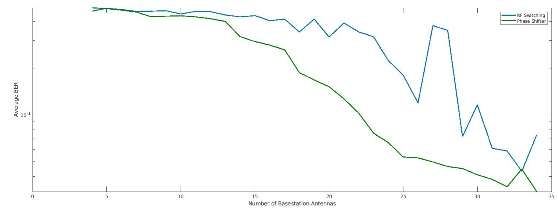

Fig. 7. Simulation results from signal processing demonstrate a decrease in the average Bit Error Rate (BER) of users with an increasing number of antennas. Additionally, the BER of the phase shifter architecture is found to be lower than that of RF switching. These findings underscore the superior performance of the phase shifter architecture in minimizing errors compared to traditional RF switching methods.

of antennas for both GreenMO and phase shifter architectures reaffirms the superiority of the phase shifter architecture, as depicted in Figure 7. These findings not only validate the previous mathematical results but also underscore the enhanced performance and reliability offered by the phase shifter architecture in minimizing errors compared to traditional RF switching methods.It is important to note that the irregularities observed in the figures are attributed to the utilization of a limited number of user location configurations, owing to time constraints.

In my work, certain limitations are acknowledged that warrant consideration for future research and development. Firstly, while the architecture demonstrates promising capabilities, an aspect yet to be explored thoroughly is channel estimation. Investigating channel estimation techniques tailored to the architecture's specifications could provide valuable insights into optimizing communication channels further. Additionally, the absence of hardware imperfections in the architecture, while advantageous for theoretical analysis, may not fully capture real-world conditions. Future research could incorporate models or simulations that account for hardware imperfections to enhance the architecture's practical applicability and robustness. Furthermore, while prioritizing low power consumption and improved performance, it is essential to address the power consumption associated with phase shifters. Balancing power efficiency with performance enhancements presents a significant challenge that necessitates careful consideration and innovative solutions. Identifying and mitigating these limitations will be crucial for advancing the architecture's effectiveness and applicability in real-world scenarios.

VI. Conclusion

In conclusion, while our study has provided valuable insights into implementing the GreenMO architecture in the downlink scenario and enhancing its performance through signal processing techniques, further exploration through hardware measurements is warranted. While simulations offer a valuable means of analysis, real-world hardware measurements are essential to validate the feasibility and effectiveness of the proposed architecture in practical scenarios. By conducting hardware measurements, we can assess factors such as power consumption, latency, and overall system robustness, providing a more comprehensive understanding of the architecture's performance in real-world conditions. Therefore, future research efforts should prioritize conducting hardware measurements to validate and refine the proposed architecture, ultimately ensuring its practical viability and effectiveness in real-world deployments.

VII. Team contribution

Adel's contributions to the project have been multifaceted and pivotal in advancing the research endeavors. Firstly, Adel conducted an extensive literature survey to identify and comprehend the related works in the field, providing valuable insights into existing research and methodologies. This survey laid the foundation for the project by informing subsequent decisions and approaches. Additionally, Adel played a crucial role in generating channels using Sionna for mathematical simulations, contributing to the empirical understanding of channel behaviors and characteristics within the proposed architecture. Furthermore, Adel's expertise was instrumental in writing the OFDM MIMO code from scratch, demonstrating proficiency in algorithm development and implementation. Adel also conducted basic simulations to evaluate the broadband board, showcasing a comprehensive understanding of hardware components and their functionalities. Finally, Adel took charge of writing the midterm and final reports, demonstrating exceptional communication skills and a thorough understanding of the project's objectives and outcomes. Adel's contributions have been indispensable in advancing the project's progress and ensuring its success.

VIII. Acknowledgement

We would like to express our heartfelt gratitude to Ish Jain and Agrim Gupta for their invaluable contributions to this paper. Their insights, feedback, and support have greatly enriched the quality of our work. Additionally, we extend our thanks to ChatGPT for its assistance in refining the writing and enhancing the clarity of our ideas. The AI's prompt responses and suggestions have been instrumental in shaping the final version of this manuscript.

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