Multi-Beam Methods for Increased Throughput and Reliability

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***Abstract*—This project addresses the problem of maintaining high reliability millimeter-wave links despite potential blockages. To address this problem, we develop methods for simulating and evaluating constructive multi-beamforming and tracking that is robust to blockages while offering a SNR gain compared to single-beam methods. We simulate SNR gain for varying numbers of beams in an indoor and outdoor environment. For the indoor scenario, we observe a 0.93 dB constructive SNR gain for two beams, reaching a maximum gain of 2.6 dB at 4 beams, reaching a point of diminishing return for more than 4 beams. For the outdoor scenario, we see little to no SNR gain for any number of beams. These results highlight the importance of the multi-path profile of the environment, especially for milimeter-wave applications, where the type of environment may dictate whether low-attenuation constructive channels exist. This shows that performance of these methods may vary greatly depending on the environment.**

I. Introduction

Millimeter-wave communication is desirable due to the large range of available bandwidth at higher frequencies. However, millimeter-wave communication comes with its own set of challenges that need to be addressed with engineering solutions in order to provide reliable, high-throughput communication at these frequencies.

At higher frequencies, electromagnetic waves have smaller wavelength, which makes them more susceptible to absorption from the environment. This means that path loss increases with frequency, causing there to be less available high-strength paths to the receiver in addition to the line-of-sight (LOS) path. This poses a challenge of reliability, as it is much more likely that communication will be interrupted if there is an occlusion in the LOS path.

Figure 1 shows a MATLAB simulation for the multi-path profile of a 3D environment with labeled path loss. In the top image, the simulation was run at 300 MHz, whereas the bottom image, the simulation was run at 30 MHz. It is clear through this simulation that the relative path loss between the LOS path and other reflected paths is much greater at millimeter-wave frequencies, leaving much fewer useful paths at higher frequencies.

Traditional MIMO benefits from rich scattering and independent spatial channels

Traditional multi-input multi-output (MIMO) communication systems benefit from environments with rich scattering and independent spatial channels, utilizing methods such as space-time precoding at the transmitter, maximum ratio combining at the receiver, or other methods. These methods exploit diverse multi-path profiles, utilizing many reflected channels in addition to the LOS path to give a higher gain at the receiver.

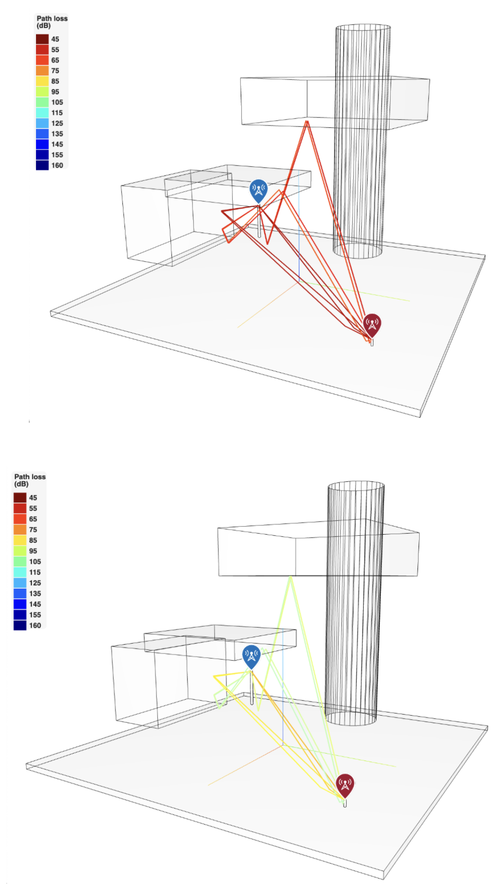

Fig. 1. MATLAB simulation for multi-path profile of environment at 300 MHz (top) and 30 GHz (bottom)

The main problem at millimeter-wave frequencies is that increased path loss diminishes the potential gain and reliability that comes from utilizing reflected paths to the receiver.

Jain et al. address these concerns in [1], where they propose beamforming with phased arrays to scan the environment for two or more low-attenuation channels with constructive gain to improve SNR at the receiver, while remaining robust to blockages. This addresses the issue of reliability by utilizing multiple beams, which are unlikely to all be occluded at the same time. This also addresses the concerns with multi-path gain at the receiver by utilizing phased arrays and scanning to find and leverage the strongest of the reflected paths that sum constructively at the receiver.

We aim to replicate some results of this work, while extending some of the analysis to identify limitations. To do this, we create 3D environments for high-multi-path and low-multi-path environments. We will call these indoor and outdoor environments respectively. Our goal is to show the point at which adding more beams reaches a point of diminishing return, where either beam-forming that number of beams becomes impractical with standard hardware, or the multi-path profile of the environment is incapable of providing more constructive gain.

Our results show that the performance is highly dependent on the environment and its multi-path profile. Implementing these methods in a commercial manner may be difficult, as the optimal number of beams may vary greatly from environment to environment and may require extensive setup and calibration to maximally exploit the multi-path profile of the environment.

II. Background and Related Work

This section will detail the related work that serves as a background for this project and the paper of interest [1]. This paper builds off the theoretical and practical foundation that has been laid in the literature for millimeter-wave communication and its challenges, beamforming with phased arrays, and multi-beamforming for millimeter-wave applications.

A. Millimeter-wave Communications

[2], [3], and [4] introduce millimeter-wave communication and fundamental challenges such as path loss. These works serve as a foundation for many other works relating to millimeter-wave communications.

[5], [6], and [7] introduce the fundamental challenge of human blockages in millimeter-wave communication. These works analyze these issues and present methods to model these obstructions. [8] introduces challenges to MIMO communication at milliliter-wave frequencies, and proposes signal processing techniques to improve performance.

B. Beamforming for Millimeter-wave applications

Many works present analysis on beamforming to address the challenges that come with millimeter-wave communication.

[9], [10], and [11] introduce beamforming and scanning for finding low-attenuation paths and avoiding blockages in millimeter-wave systems, while [12] proposes methods for using multiple beams for high-throughput and blockage-reliable millimeter-wave communication. [1] extends these methods, focusing on beam scanning for constructive gain, beam tracking, and provides real-world experiments to justify the theoretical gain for multi-beam methods in millimeter-wave communications.

III. Design

A. Constructive Multi-Beam

This section will outline the theory and architecture for the constructive multi-beamforming simulations used to reproduce and extend the results in [1].

From MIMO theory, we can give a theoretical upper bound on the SNR gain for n beams summing at the receiver. We first assume normalized transmit power, giving a per-beam gain of $\frac{1}{\sqrt{n}}$. For n channels, assuming zero path loss and perfect constructive summation at the receiver, we see a gain of

$$\frac{1}{\sqrt{n}} \cdot n = \frac{n}{\sqrt{n}} = \sqrt{n} \tag{1}$$

at the receiver. This gives a maximum constructive SNR gain of n.

Given the path loss inherent to millimeter-wave systems, the SNR gain will likely be much less in practice. To exploit this SNR gain, we must scan the multi-path profile of the environment, modeling the various channels for attenuation and phase shift. An optimal group of n channels would be those whose complex channels sum is maximum.

With full (or uniformly sampled) channel knowledge of the environment, we can choose the group of channels $\mathbf{h}$ whose sum is maximized as

$$\mathbf{h}^* = \arg_{\mathbf{h}} \max \sum^{\mathbf{A},\phi\in\mathbf{h}} \mathbf{A}\mathbf{e}^{\mathbf{j}\phi} \tag{2}$$

In MATLAB, we can simulate the multi-path profile for a 3D environment and search the channels for this set of optimal constructive paths. Figure 6 shows plots of the simulated multi-path profile and two optimal constructive channels in the top and bottom images respectively.

While this shows the ability for this algorithm to select two optimal constructive beams, the practical implementation will require steering a phased array in the direction of these channels and considering the non-idealities and side-lobes of the phased array. This will be the topic of the implementation section.

B. Beam Tracking & Optimal Beamforming

This section will shift focus to the theory and implementation of the beam tracking and optimal beamforming algorithms. Instead of a more rigorous Channel Impulse Response (CIR) method to determine optimal beam weights, we iterate through all four beam paths to determine signal power and thus adjust the beam weights.

To maintain a high quality link under user mobility, we use a proactive tracking mechanism similar to the paper's proposed "Super-Resolution" algorithm. The core principle is to leverage instantaneous variations in received signal power to infer the new location of the intended target. This form of tracking eliminates the high overhead of continuous beam scanning.

The tracking uses the following relationship:

$$G_T(\theta) = \frac{\sin(N\pi\sin(\theta))}{\sin(\pi\sin(\theta))}, \tag{3}$$

where N is the number of antenna elements, θ represents the spatial angle relative to the antenna array, and $G_T(\theta)$ is the transmit beam pattern of the phased array antenna. The tracking algorithm executes in the following manner:

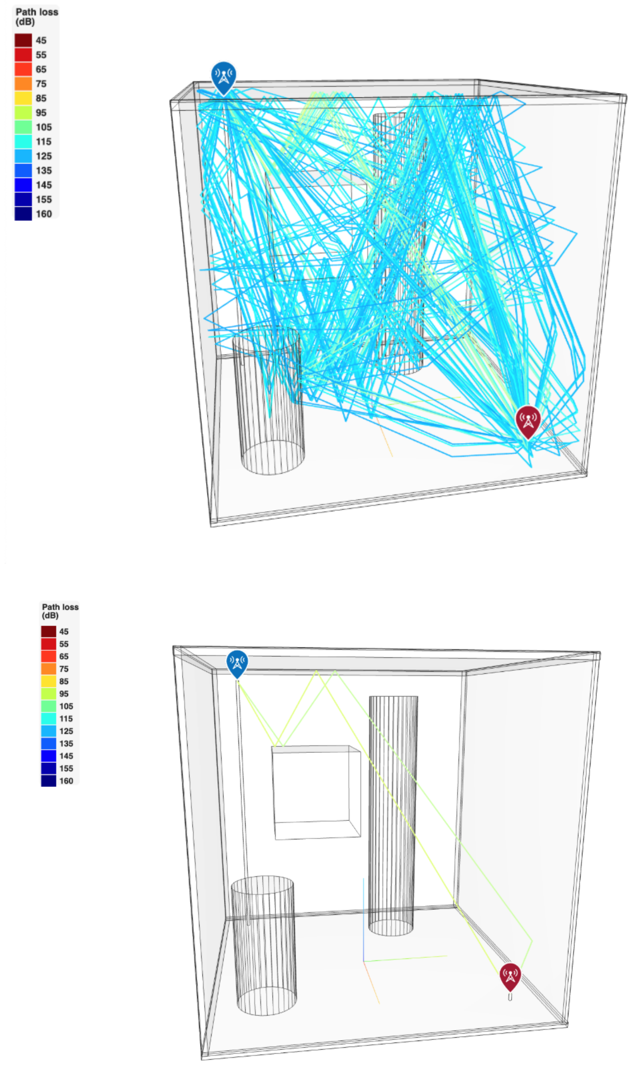

Fig. 2. MATLAB simulation for multi-path profile of environment (top) and two optimal constructive channels (bottom)

1) Power Measurement: The system periodically measures the received power P_{curr} using the previously estimated beam direction.

2) Misalignment Estimation: A measured drop in power relative to the reference power P_{ref} suggests a misalignment in the current beam formation. The magnitude of angular error $|\Delta\theta|$ is then calculated by inverting the beam pattern function given the ratio P_{curr}/P_{ref}.

3) Direction Resolution: The power drop provides only the magnitude of error. Therefore, the system performs a tentative angular shift. If the SNR improves, the direction is confirmed; otherwise, the shift is reversed. This calculated angular shift is then applied to all beams in the multi-beam configuration.

Building off of the earlier constructive multi-beam discussion, this section will explore another method of constructive beamforming. Using a similar relationship to equation (2), the optimal weight vector $\mathbf{w}_{opt}$ for a multi-path channel $\mathbf{h}$ is the conjugate of the channel response, normalized to unit power:

In this implementation, equation (3) is decomposed into a constructive multi-beam vector. For a channel with $\mathbf{k}$ paths, each having a steering vector $\mathbf{v}(\theta_k)$ and a complex channel gain h_k, the optimal beamforming vector is:

$$\mathbf{w}_{mm} = \sum_{k=1}^{K} \alpha_k \mathbf{v}(\theta_k)$$

where α_k represents the complex weight for path k.

Thus, we implement optimal beam scaling, where the magnitude of the weight α_k is dynamically scaled proportional to the path's estimated strength $|h_k|$. That is to say the phase of α_k is set to cancel the channel phase. Additionally, if path k is blocked, its channel gain $|h_k|$ will approach zero.

IV. Implementation

A. Constructive Multi-Beam

This section focuses on the practical implementation of phased array steering, tuning, and channel application and receiver summation. This will take the channels identified in the previous section $\mathbf{h}^*$ and steer a phased array in their direction. Then the phased array response will be applied to every multi-path element from the simulation and summed at the receiver.

First, we model the COSMOS phased array in MATLAB. We use MATLAB's phased array toolbox and define a uniform rectangular array of 8x8 elements at 28 GHz with $\lambda/2$ spacing. From the channel model, we can extract the altitude and elevation angles for the optimal beams. From these angles, we compute the length 64 steering weight vector $\mathbf{w_k}$ for one of the n channels using MATLAB's inbuilt functions. We can construct the multi-beam weights W_{norm} as the sum of the weights for each beam with normalized transmit power as

$$W_{\text{norm}} = \frac{W}{||W||_2}, \tag{4}$$

where

$$W = \sum_{k=1}^{n} w_k. \tag{5}$$

Figure 3 plots the phased array gain for each possible angle. It is important to note that there is a nonzero gan applied in every direction. To simulate transmission from this configuration, we can apply the phased array gain to each channel from the multi-path simulation. Given the multi-path simulation gives all possible paths between the transmitter and the receiver with up to 8 reflections, this can approximate a real world response well.

In the bottom plot in Figure 3, we scatter the multi-path samples in blue. For each multi-path channel, we can apply the phased array gain G_k to the channel estimation and sum at the reviver. For M channels, this can be represented as

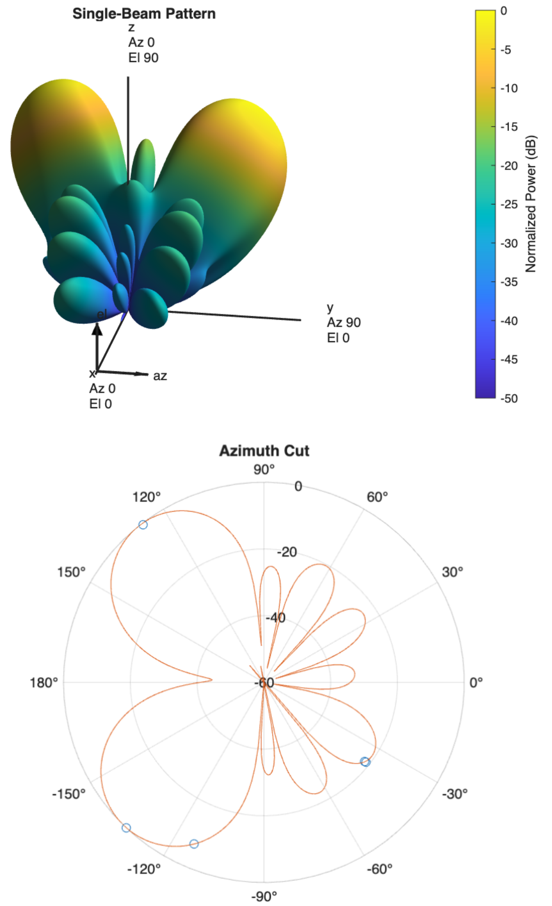

Fig. 3. Phased array response for two beams: 3D plot (top) and 2D slice (bottom)

$$\sum_{k=1}^{M} G_k A_K e^{j\phi_k}. \tag{6}$$

Ideally, the phased array gain should attenuate all directions other than the main constructive paths to give a constructive sum of the main channels at the receive with nonzero but negligible influence from all other directions.

We can apply this simulation to varying numbers of beams and different environments, which will be the topic of the evaluation section.

B. Beam Tracking & Optimal Beamforming

This section will explore the implementation of the beam tracking and optimal beamforming method's discussed in the previous section.

The beam tracking logic was embedded directly within the simulation loop, operating at a resolution of one discrete time step. To evaluate tracking performance, we simulated user motion as a constant linear drift of 0.15 degrees per time step. At each interval, the **measure_power** function retrieved the received signal strength and compared it against the beam's original power level. This power ratio was fed as the primary input for the **invert_beam_pattern** function. The observed power drop was then converted to an estimated angle shift proportional to the power drop. Using this angle, a tentative positive shift was applied followed by a new power measurement. If this shift resulted in an improved SNR, then the direction was accepted as successfully; otherwise, it was reversed.

In order to validate the optimal beamforming approach, the simulation utilized a complex weight vector, **w_mm**, which would be updated during each loop iteration. While mm-Reliable utilized a super-resolution approach [1] to estimate channel parameters, this step was simplified by using true current channel gains **curr_gains** in the weights. calculations. The multi-beam weight vector was subsequently constructed by scanning all four paths and applying the Maximum Ratio Combining (MRC) by scaling each steering vector by its conjugate. This ensured that if one path was blocked, the system shifted the link reliance to the remaining paths.

V. Evaluation

A. Constructive Multi-Beam

This section will focus on evaluating the SNR gain for an increasing number of beams for varying environments. These results will be compared to the original paper as a benchmark.

Using the methods discussed in the implementation, we can sweep simulations across $n = [1, 5]$ beams for a high-multi-path indoor 3D scene and a low-multi-path outdoor 3D scene. Figure 4 plots the SNR gain relative to the single beam for varying number of beams in the indoor environment. The theoretical upper-bound of SNR gain of n is also plotted in orange. Here we can see that we get a SNR gain for increasing the number of beams to 4. Increasing the number of beams after 4 does not improve the gain.

Figure 5 plots the SNR gain relative to the single beam for varying number of beams in the outdoor environment. Here we can see that there is no SNR gain for increasing the number of beams whatsoever.

In comparison to the results in the original work [1], our performance is quite similar. We observed a relative SNR gain of 0.93 and 2.26 dB for 2 and 3 beams respectively, while the original observed a relative gain of 1.04 and 2.27 dB respectively. Additionally, we extended their analysis to consider increasing the number of beams to a point of diminishing return.

The broader implications of these results will be discussed in the Conclusion.

B. Beam Tracking & Optimal Beamforming

This section, will analyze the simulation results for the beam tracking and optimal beamforming methods. Additionally, the results will be compared to [1] as well as the more general simulation discussed in section III. A. Constructive Multi-Beam.

Using the simulation discussed in the relevant **Beam Tracking & Optimal Beamforming** section, we simulate a multi-path environment in the best case scenario with four con-

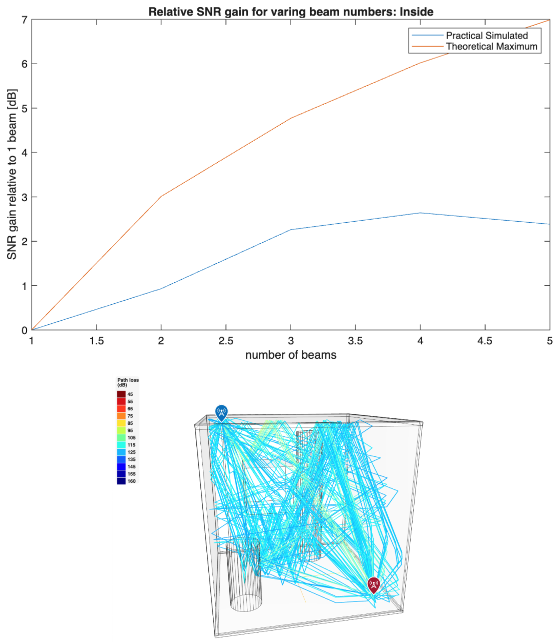

Fig. 4. Plot of SNR gain vs. number of beams for indoor environment with environment visualization

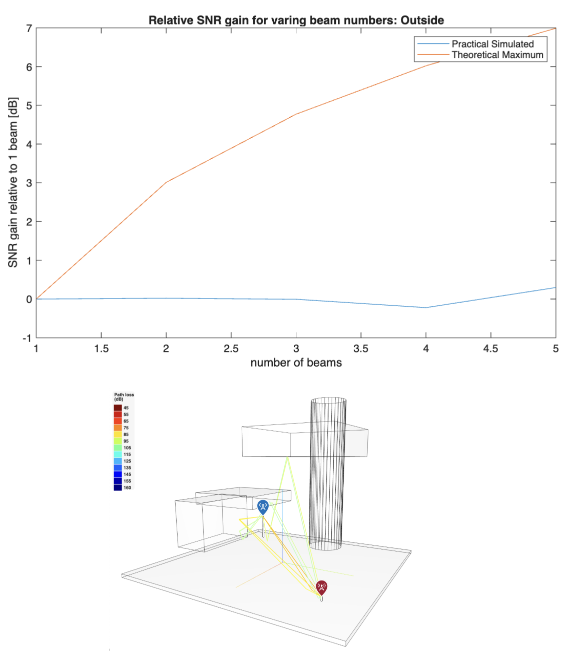

Fig. 5. Plot of SNR gain vs. number of beams for outdoor environment with environment visualization

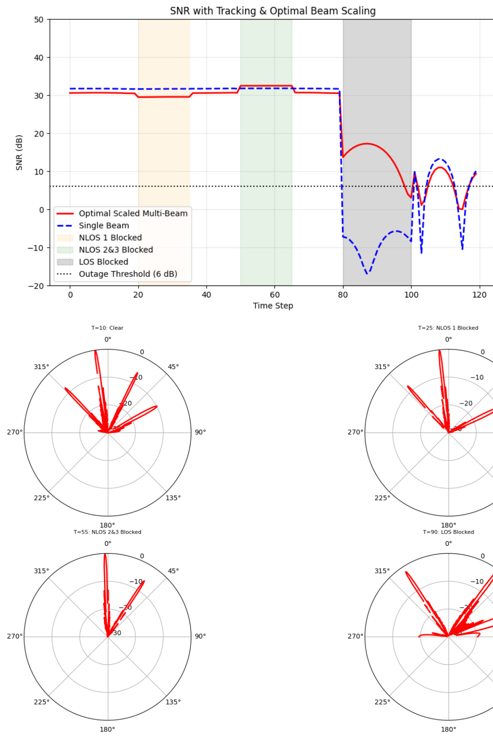

Fig. 6. Simulation output plots showing the effectiveness of the tracking algorithm with respect to SNR (top) the corresponding optimal beam output (Uniform Linear Array) (bottom)

structive paths. This is in contrast to a typical three available paths for constructive beamforming as demonstrated in [1]. After accounting for path loss, in Figure 6 (top) we see that during the time period where the Line-of-Sight (LOS) is totally blocked, the multi-beam implementation performs better than the single beam implementation. The scaled multi-beam sees an immediate SNR drop of around 15 dB which aligns with the results in [1]. On the other hand, during the same time period, we see the single beam implementation have it's SNR drop just shy of -10 dB. The single beam performance falls in the SNR range measured in [1]. While both implementations experience a drop in signal quality, the multi-beam approach only has it's SNR fall below the outage threshold at time step 97 while the single beam approach see's the complete link drop for the entire duration of the LOS blockage.

Additionally, in Figure 6 (bottom), we see the optimal beamforming implementation successfully adjust beam power for a given outage event. This supports the earlier constructive beamforming findings in Figure 3.

VI. Conclusion

The multi-beamforming results previously discussed highlight a main challenge for implementing millimeter-wave communication in practice. It was observed that the SNR gain for multi-beamforming varied highly between the two simulated environments. The indoor environment naturally supported many different multi-path channels, while the outdoor environment had few. With high attenuation, there is a high chance that no constructive channels exist that are strong enough to give a significant gain at the receiver in sparse environments.

This poses a challenge for commercial implementation, where the environment may vary greatly based on application. The optimal number of beams may also vary based on environment. Future work will be required to create robust algorithms for understanding the environment and deciding when to leverage multi-beamforming and how many beams to use.

It is also worth noting that the work described in this project relies on a narrowband assumption, which may not hold in practical millimeter-wave systems. In wideband systems, such as OFDM, where information is transmitted over a range of subcarriers, fixed beamforming weights can become frequency-dependent, leading to reduced beamforming gain across the bandwidth. Therefore, future work is needed to develop hardware and processing methods capable of applying subcarrier-dependent beamforming weights.

The most significant insight yielded by the beam tracking and beam forming simulation was the important role of multi-beam tracking and power scaling. As demonstrated, single-beam systems perform poorly in an environment containing blockages and target mobility when compared its multi-beam counter part. Even in a simulation with a total of four paths, as opposed to a more complex multi-path environment, it was still observed that the single-beam implementation dropped well below the 6 dB outage threshold while the multi-beam version maintained connectivity for 97% of the LOS blockage event. One way this work can be improved is be removing the current rigid-body motion simulation parameters. In a practical multi-path environment, one must also consider techniques required to maintain a valid signal link with a target moving in a more unpredictable way. Beamforming overhead can additionally be reduced by avoiding the power recalculation during each iteration of the system loop. While this implementation yielded similar results to [1], the Channel Impulse Response (CIR) is more practical for a real world environment where hardware limitations must be taken into account.

VII. Acknowledgment

The use of AI was limited to the occasional general conceptual question and debugging. Both ChatGPT and Gemini were used sparingly to increase the efficiency of the software debugging process (e.g. explain this error message, etc.).

VIII. Team contribution

Jamie's responsibility was to model and simulate the multi-path profile of the 3D scenes, write the algorithm for scanning the multi-path profile for constructive beams, model the COSMOS phased array and simulate practical implementation of the phased array steered at constructive angles, and sweeping the simulations across varying number of beams and various environments.

Edgar's responsibility was to implement and simulate beam tracking and optimal beamforming algorithms. In contrast to Jamie's implementation, the simulation utilized a Uniform Linear Phase Array (ULA). The simulation implemented rigid user motion and various blockage scenarios to imitate a real-world situation.

Any activities not listed (such as the report) received equal contribution from group members.

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