Analysis of Beamforming in a Complex Indoor Environment

Dalyana Mercado-Perez and Feng Ye

Department of Electrical and Computer Engineering
University of Wisconsin-Madison, Madison, WI, USA
dmercadopere@wisc.edu, feng.ye@wisc.edu

Abstract. In a wireless system, transmitted signals suffer from multipath propagation and can deteriorate the received signal strength. Beamforming is a viable solution in a multiple-input-multiple-output system to improve the overall transmission by focusing the transmitted gain in a specific direction. This paper presents an evaluation of beamforming in a complex multipath indoor environment where the line-of-sight path is blocked. In specific, evaluations are conducted by steering the main beam in the direction of the different paths of the transmitted signal in three cases. From the results, it is shown that the traditional beamforming that focuses on the directional path may not be the best approach in complex indoor environments.

Keywords: beamforming, multipath propagation, indoor environment

1 Introduction

Due to the exponential growth of mobile traffic and new disruptive services, the fifth-generation (5G), sixth-generation (6G) systems and beyond are expected to provide high throughput, ultra-low latency, high reliability, and high capacity [1]. One of the technologies that can achieve this is multiple-input-multiple-output (MIMO) systems. Beamforming is one of the techniques that utilizes a MIMO system to enhance the overall transmission quality. In particular, beamforming applies different amplitudes and phases to an antenna array to maximize the received signal power and minimize the interference signal power [2]. Existing work focuses on applying beamforming to millimeter-wave (mm-wave) bands. This is due to their small wavelength, which causes them to have distinctive propagation characteristics [3]. Based on these works, they are testing the performance of beamforming in different scenarios. Most of the existing work assumes a directional beamforming between the transmitter (Tx) and the receiver (Rx). Misaligned beamforming usually degrades the achievable gain. For example, work [4] focuses on the implementation of beamforming in a vehicular system by mentioning the effect of beam misalignment. Work [5] was working with the energy loss that occurs due to beam misalignment in a crowded indoor scenario. Work [6] uses the information from ray tracing to implement multi-user directional beamforming in a mm-wave indoors scenario.

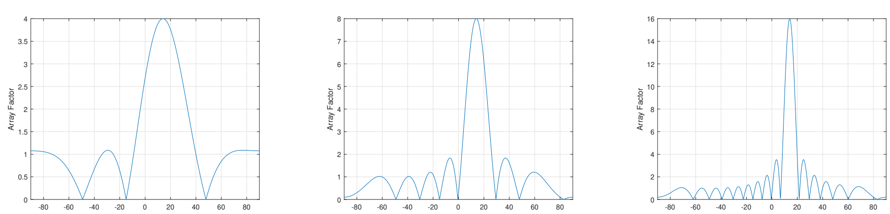
However, in a complex indoor environment, wireless transmissions can be highly affected by multi-path effect, where a Tx signal can arrive through multiple paths to the Rx. The multi-path effect occurs due to the environment by scattering, diffraction, shadowing, and reflection. These multiple paths cause interference at the receiver, which could be constructive or destructive. This work explores the scattering paths that occur in an indoor environment. For better illustration, it is assumed that the line-of-sight (LoS) path is blocked, which causes an added loss to the signal on the receiver side if using directional beamforming. Beamforming is applied by varying the beampattern based on the angle-of-departure (AoD) of the considered paths. Three cases are considered and it is modeled in Sionna [7] by using the Ray Tracing module to extract the channel state information (CSI) of the scattered paths. This paper is divided as follows: Section 2 provides a background to beamforming and calculations based on multipath propagation, in Section 3 the evaluation results are presented, and Section 4 is the conclusion.

2 Background and preliminary

2.1 Beamforming

Beamforming is a technique that uses phased array antennas to be able to focus the radiated power to a desired direction [8]. This is achieved using an N number of antennas and having all the antennas focus their signal on a set angle. Depending on the number of antennas used and the directivity of the signal, the signal strength will vary. As a graphical representation, the radiation pattern of the antenna array is modeled by calculating the array factor,

$$AF[\theta] = \sum_{n=0}^{N-1} e^{j(nkd\sin\theta - nkd\sin\theta_s)}, \tag{1}$$



(a) N = 4. (b) N = 8. (c) N = 16.

Fig. 1: Array Factor with different amount of antennas.

where N is the number of antennas in the antenna array, k is the wave number $(2\pi/\lambda)$, d is the spacing between the antennas, $\theta \in [-180°, 180°]$, and θ_s is the angle where the beam is directed to.

Fig. 1 show the distribution of radiated energy by changing the number of antennas. In the figures, it is noted that there are lobes of different sizes. The biggest is called the main lobe, while the smaller ones are the side lobes. As a consequence, using a small number of antennas will cause to have a wide main lobe, while a greater number of antennas will cause a narrow main lobe. The main lobe is where the radiated energy is the highest. On the other hand, the sidelobes will have an energy lower than the main lobe. When the main beam is directed to the LoS path, it is called aligned beamforming. On the other hand, when the main beam is not directed to the LoS path, it is referred to as misaligned beamforming. Another type of beamforming depending on the directionality of the main beam is multidirectional beamforming. This type of beamforming has more than one beam focusing most of the energy in different directions simultaneously.

2.2 Multipath Propagation and Channel State Information

The Shannon Capacity Theorem is used to calculate the maximum transmission rate in a communication system, s.t., $C = B\log_2(1 + \text{SNR})$, where B is the bandwidth of the channel, and SNR stands for signal-to-noise ratio. To estimate the received power (P_r), the Friis transmission equation is used, s.t., $P_r = P_t + G_t + G_r + 20\log\left(\frac{c}{4\pi R f}\right)$ [dBm], where P_t is the transmitted power, G_t and G_r are the transmitted and received gain, c is the speed of light, R is the distance between the transmitter and the receiver, and f is the carrier frequency.

In a wireless system, AoD is required to apply beamforming. From this angle, the transmission gain is calculated as $G[\theta] = |AF[\theta]|^2$. However, in reality, wireless communications suffer from multi-path effect. This is due to reflections, diffractions, scatterings, and shadowing that are occurring in the environment. Hence, on the receiver, multiple signals will arrive with the same information. These signals will have different amplitudes, phases, and transmitted gain. Due to the propagation factor, the received power becomes $P_r = \sum_{s=1}^{S} g_s(\theta_s)A_s\phi_s$, where g_s is the calculated beamforming gain of the scattered signal at AoD θ_s, A_s is the magnitude of an individual scattered path, and ϕ_s is the phase of an individual scattered path. In the next section, we provide evaluation results on various beamforming settings in a complex indoor environment.

3 Evaluation Results

We assumed an indoor environment inspired by our research lab at the University of Wisconsin-Madison. In this environment, an access point (AP) and two stations are allocated. By using the ray tracing module from Sionna, multiple paths are scattered to each station as presented in Fig. 2a, Fig. 2c, and

Fig. 2e. Due to the limitations of the program, if there is one object between the direct path of two antennas, a reflection will always occur. Taking this into consideration, the LoS path information is modeled apart and then added to the calculations. Table 1 lists the system settings of the environment.

Table 1: System settings.

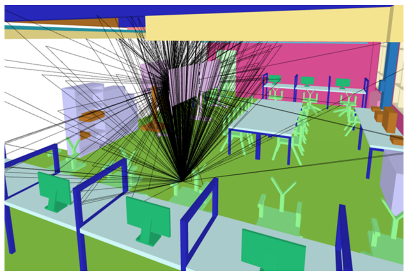
Parameters	**Value**
Number of access point antenna	8
Number of station antenna	1
Carrier frequency	5.8 GHz
Bandwidth	20 MHz
Transmit power	20 dBm
Receive gain	0 dBi
Obstacle loss	10 dB

After modeling the paths, the top-most significant paths are selected and the magnitude, phase, and delay of each individual path are extracted from the ray tracing module. Based on the delay of each path, the AoD is approximated as the current simulation setup does not provide exact path information. This was done by multiplying the delay by the speed of light, adding the value to the total distance of the LoS, and adding 5 more meters. The approximated AoDs for each path to each receiver are presented in Table 2. From here onward, the path names will be used to present the results. We will investigate the exact path information in our future work.

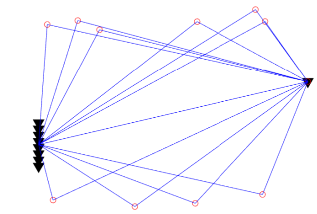
Table 2: Angle of departure of each path for each station.

Path name	**AoD to station 1**	**AoD to station 2**
Path 1	$-43.42°$	$-95.37°$
Path 2	$53.95°$	$-127.28°$
Path 3	$-84.11°$	$107.73°$
Path 4	$78.17°$	$-92.50°$
Path 5	$-58.40°$	$100.82°$
Path 6	$-29.33°$	$94.61°$
Path 7	$88.37°$	$-99.60°$
Path 8	$63.02°$	$-106.26°$
Path 9	$82.90°$	$102.77°$
Path 10	$57.55°$	$-118.26°$
LoS path	$30.55°$	$119.60°$

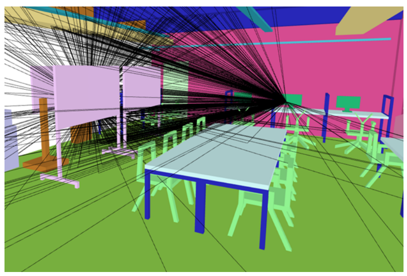
With the calculated AoDs, the selected paths are modeled in Fig. 2b and Fig. 2d, depending on the location of the stations. Fig. 2f models the system as a whole, making the red lines (left) the paths to station 2 and the blue lines



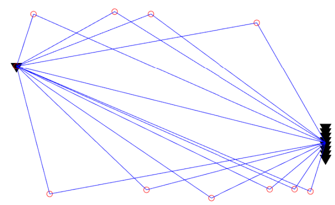
(a) Station 1 Rx: Ray tracing simulation.



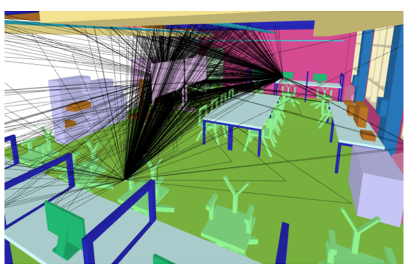
(b) Station 1 Rx: Selected paths.



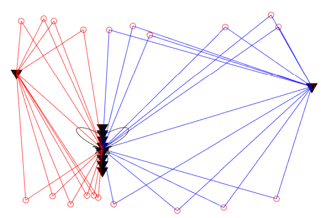
(c) Station 2 Rx: Ray tracing simulation.



(d) Station 2 Rx: Selected paths.



(e) Two stations: Ray tracing simulation.



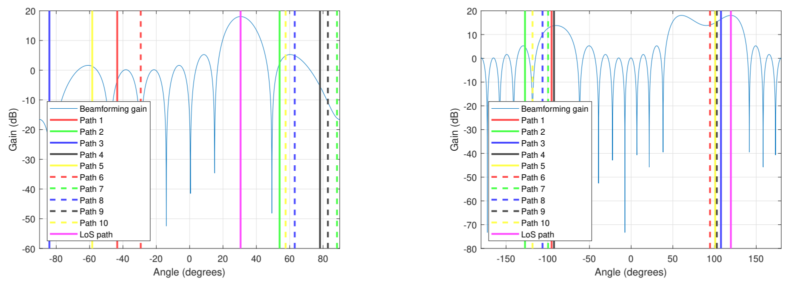
(f) Two stations: Selected paths.

Fig. 2: Path modeling in the studied scenarios.

(right) the paths to station 1. For the results, the main beam will be focused based on the angle of each selected path.

3.1 Case I. One access point to one station

This case assumes that the environment only has one access point and one station. To calculate the transmitted gain of each path, the beampattern is calculated based on the angle at which the main beam is steered. For example, Fig. 3 shows the beampattern of the 8 antennas focused on the LoS of station 1 and station 2, respectively. The vertical lines represent the angle of the path and how much energy is passing through. In this case, two subcases are considered: individual transmission to station 1 and individual transmission to station 2.



(a) Station 1. (b) Station 2.

Fig. 3: Beamforming gain pattern when the main beam is directed to LoS path.

Transmitting to station 1, Fig. 4 presents the calculated channel capacity with respect to the background noise by focusing the main beam on the different angles of the scattered paths. In this subcase, the top 4 paths that perform with high capacity are paths 1, 2, 5, and 10. Similarly, Fig. 5 shows the channel capacity when the transmitting signal is sent to station 2. For this subcase, the top 4 paths are paths 4, 5, 6, and 9. In these two subcases, focusing the main beam on the scattered paths outperforms the main beam focused on the LoS path.

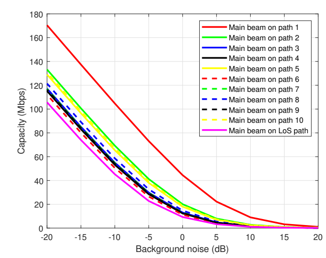
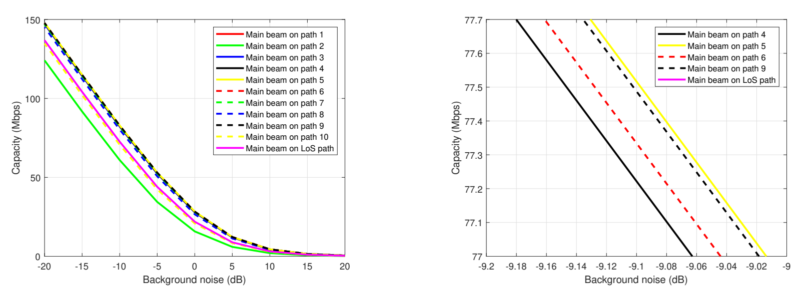


Fig. 4: Focusing the main beam at different paths to station 1.

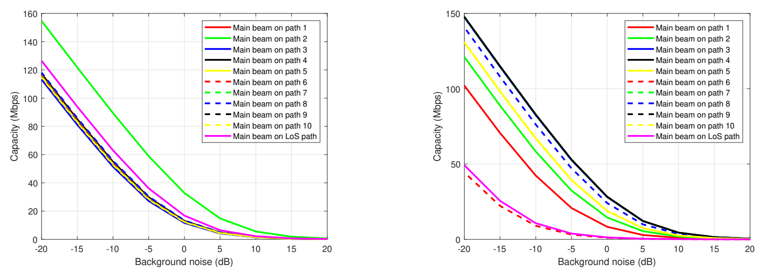


(a) All paths. (b) Top 4 paths.

Fig. 5: Focusing the main beam at different paths to station 2.

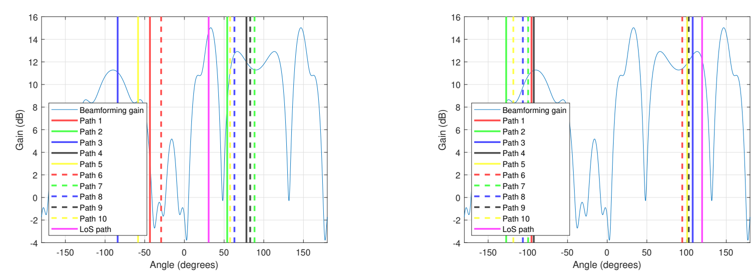
3.2 Case II. One access point to two stations - Downlinks

This case focuses on one router transmitting to two stations and 2 subcases are considered. The first subcase is the channel capacity calculation of the stations taking the beampattern shape of the paths of the opposite station. Fig. 6a shows the channel capacity of station 1 while focusing the main beam on the paths of station 2. Based on the calculated results, focusing the main beam to path 2 of station 2 (AoD $= -127.28°$) is the only direction that outperforms the LoS direction of station 2.



(a) Channel capacity on station 1. (b) Channel capacity on station 2.

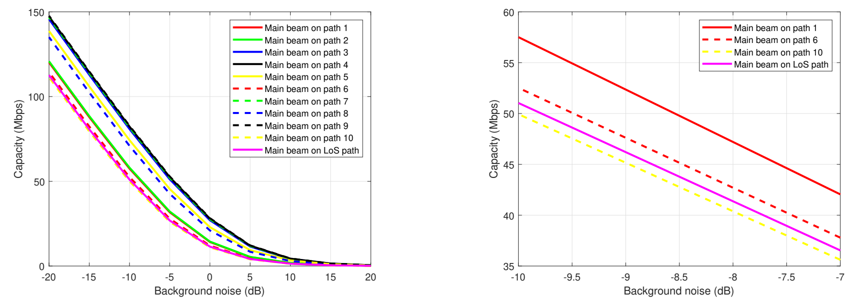
Fig. 6: Channel capacity: (a) Focusing the main beam at different paths of station 2; (b) Focusing the main beam at different paths of station 1.



(a) Paths of station 1. (b) Paths of station 2.

Fig. 7: Beamforming gain pattern when the main beam is aligned along LoS.

Meanwhile, Fig. 6b is the calculation of the channel capacity of station 2 using the beampatterns of the directions of the paths of station 1. From these calculations, only the direction of path 6 of station 1 (AoD $= -29.33°$) performs worse than the direction of the LoS path. The second subcase applies multi-directional beamforming. In other words, half of the array antennas focus the beampattern to each station specifically. Fig. 7 is an example of how the energy is distributed in this scenario. At the same time, these figures show where their respective paths are passing through the pattern. For these figures, the main beam is focused on the LoS paths of each station. As a result, Fig. 8 and Fig. 9 present the performance of applying beamforming that adjusts to the two devices. The main beam for both sides is focused on the same variable name from Table 2. From the results, focusing the main beam on the other paths outperforms the LoS path for station 1. Meanwhile, for station 2, all but path 10 (AoD $= -118.26°$) outperforms the LoS path.



(a) All paths. (b) Lower 4 paths.

Fig. 8: Channel capacity vs. background noise on station 2: Focusing the main beam at different paths of both stations.

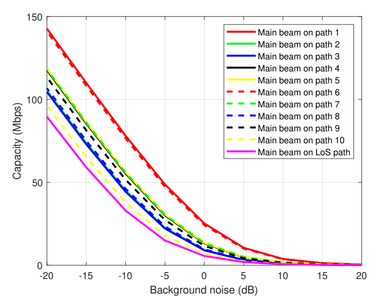


Fig. 9: Channel capacity vs. background noise on station 1: Focusing the main beam at different paths of both stations.

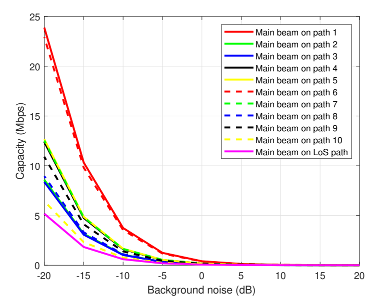


Fig. 10: Full duplex channel capacity vs. background noise on station 1: Focusing the main beam at different paths of both stations.

3.3 Case III. One access point to two stations - Full Duplex

Lastly, in this case, the interference of the signals is considered. It is assumed that station 1 is the downlink (DL) while station 2 is the uplink (UL). Self-interference is neglected on the access point side, and the SINR is calculated for station 1. Fig. 10 shows the channel capacity. The paths behave as Fig. 9, but have a lower channel capacity due to the interference.

4 Conclusion

This work presented the effect of applying beamforming in a complex indoor environment. The simulated environment was set up by localizing an access point in which the LoS path to the two receivers was weakened by an obstacle. Three scenarios were considered: transmission to one station, transmission to two stations as downlinks, and transmission in Full Duplex mode. The tested scenarios were achieved by applying ray tracing and using the extracted CSI to calculate the channel capacity by using different beampatterns by steering the main beam to the different directions the multiple paths took. From the simulated results, it is shown that there is at least one path that outperforms the channel capacity compared to the direction of LoS.

5 Acknowledgment

This project was supported partially by the U.S. National Science Foundation under the grant ECCS-2336234.

References

1. Jiang, W., Han, B., Habibi, M.A., Schotten, H.D.: The road towards 6g: A comprehensive survey. IEEE Open Journal of the Communications Society 2, 334–366 (2021)
2. Ali, E., Ismail, M., Nordin, R., Abdulah, N.F.: Beamforming techniques for massive mimo systems in 5g: overview, classification, and trends for future research. Frontiers of Information Technology & Electronic Engineering 18(6), 753–772 (Jun 2017), https://doi.org/10.1631/FITEE.1601817
3. Kutty, S., Sen, D.: Beamforming for millimeter wave communications: An inclusive survey. IEEE Communications Surveys & Tutorials 18(2), 949–973 (2016)
4. Kanthasamy, N., Du, R., Gill, K.S., Wyglinski, A.M., Cowlagi, R.: Assessment of positioning errors on v2v networks employing dual beamforming. In: 2018 IEEE 88th Vehicular Technology Conference (VTC-Fall). pp. 1–5 (2018)
5. Lee, J., Kim, M.D., Kim, K.W., Park, J.J.: Measurement-based beam mis-alignment analysis of millimeter-wave directional beamforming in large indoor environments. In: 12th European Conference on Antennas and Propagation (EuCAP 2018). pp. 1–5 (2018)
6. Fuschini, F., Zoli, M., Vitucci, E.M., Barbiroli, M., Degli-Esposti, V.: A study on millimeter-wave multiuser directional beamforming based on measurements and ray tracing simulations. IEEE Transactions on Antennas and Propagation 67(4), 2633–2644 (2019)
7. Hoydis, J., Cammerer, S., Ait Aoudia, F., Vem, A., Binder, N., Marcus, G., Keller, A.: Sionna: An open-source library for next-generation physical layer research. arXiv preprint (Mar 2022)
8. Introduction to MIMO and Beamforming Technology, chap. 8, pp. 207–222. John Wiley & Sons, Ltd (2023), https://onlinelibrary.wiley.com/doi/abs/10.1002/9781394210640.ch8