3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Impact of Antenna Element Directivity and Reflection-Interference on Line-of-Sight Multiple Input Multiple Output Terahertz Systems

Duschia M. Bodet*(1) and Josep M. Jornet(1)
(1) Northeastern University, Boston, MA, 02120, https://unlab.tech/

Abstract

Terahertz (THz) communications are envisioned as the future of wireless communications. In order to combat the high path loss experienced by THz signals, beamforming using multiple-input multiple-output (MIMO) systems has been suggested. In this paper, two practical challenges for THz line-of-sight MIMO systems are investigated for the first time: the impact of antenna element directivity and self-induced inter-symbol interference on performance. Additionally, experimental results are presented to verify the findings.

1 Introduction

The Terahertz (THz) band from 0.1 to 10 THz is projected to provide the necessary spectrum for future wireless communication systems [1]. Multiple-input multiple-output (MIMO) systems are proposed specifically for THz communications to combat the high path loss through beamforming and combining techniques [2] [3]. Beamforming and combining are defined differently by various sources, but here, we use *beamforming* to refer to pre-coding at the transmitting array to maximize the received SNR. We use *combining* to refer to combining the received signals at each antenna in a way that maximizes the SNR.

We present two unique and practical challenges of beamforming and combining for LoS THz channels. First, we examine how the beamwidth of antenna elements affects the channel matrix and therefore the system performance. Secondly, we consider the effect of back-and-forth reflections between the transmitter and receiver on the system performance. Specifically, the contributions of this work are as follows: (1) Describe and fully characterize the LoS MIMO system operating with directional antennas. (2) Consider the optimal directivity of antenna elements given the geometry of the system. (3) Anticipate the back-and-forth reflections between the transmitter and receiver and how these reflections cause inter-symbol interference (ISI) and inter-frame interference (IFI) that can effect the performance. And (4) present experimental results for beamforming and combining information-bearing THz signals to verify our findings.

2 System Model

The channel between the nth transmitting antenna and the kth receiving antenna is given in [4] to be

$$h_{n,k} = \alpha(d_{n,k}, f_c)e^{\frac{-j2\pi d_{n,k}}{\lambda}}, \tag{1}$$

where $d_{n,k}$ is the physical distance between the nth transmitting antenna and the kth receiving antenna and λ is the carrier wavelength. α is the total path loss, which in the THz band is the combination of the free-space propagation loss and the molecular absorption loss.

The LoS MIMO channel matrix $\mathbf{H}$ is a $N_{rx} \times N_{tx}$ matrix where N_{rx} and N_{tx} are the number of receiving and transmitting antennas respectively. The channel vector $h_{n,k}$ is the element at the nth row and the kth column of the matrix. Thus the crucial part of this derivation is to find $d_{n,k}$. The

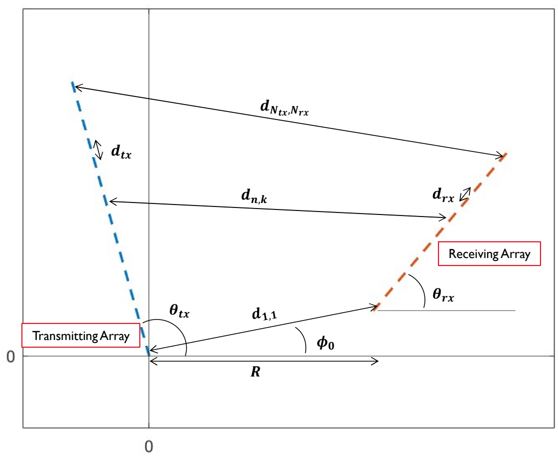


Figure 1. LoS MIMO system

THz MIMO system we investigate is shown in Figure 1. We consider uniform linear arrays (ULAs) at both the transmitter and the receiver. We have oriented the first transmitting antenna on the origin. R is the distance along the x-axis between the first transmitting and first receiving elements. ϕ_0 is the angle between the first two elements. Each array's angle with respect to the x-axis is given by θ_{tx} and θ_{rx} for the transmitter and receiver respectively. Finally, the antenna separation at each array is given by d_{tx} and d_{rx}. We assume that the receiving array is always farther along the x-axis than the transmitting array and that θ_{tx} and θ_{rx} take values between 0 and $\frac{\pi}{2}$ exclusive. In other words, we assume the transmitting array and receiving arrays are always facing each other in some capacity even if they are not parallel. After orienting the arrays in this coordinate plane, we can calculate the Euclidean distance $d_{n,k}$ between transmitting and receiving antenna elements. Thus

$$d_{n,k} = \sqrt{(x_n^{tx} - x_k^{rx})^2 + (y_n^{tx} - y_k^{rx})^2}. \quad (2)$$

Using these transmission distances in expression (1), we can find the channel matrix $\boldsymbol{H}$, which will be crucial in determining the system performance.

It is important to note that this channel matrix assumes omni-directional antennas. No matter how the arrays are oriented, this matrix assumes that every receiving element receives a signal from every transmitting element. In practice, however, this is not always the case. Even when $\theta_{tx} = \theta rx = \frac{\pi}{2}$ corresponding to when the transmitting and receiving arrays are parallel, the directivity of the antenna elements can result in some receiving elements not observing all the transmitted signals. We will further examine this idea in the following section.

3 Geometric Effects on Performance

The maximum achievable SNR using beamforming and combining is given in [5]. Any undesirable interference will essentially be an additional noise term, which we can represent as P_{int} to find the signal-to-interference-plus-noise ratio (SINR)

$$SINR = \frac{P_{rx}}{\sigma^2 + P_{int}} \Lambda_{max}. \quad (3)$$

where P_{rx} is the average received power at each antenna element and σ is the standard deviation of the noise. Λ_{max} is the spectral norm of $\mathbf{H}\mathbf{H}^H$. From (3) it is clear that changes in the channel matrix or in the power of the interference can effect the system's achievable SINR and consequently its performance. We go on to demonstrate how the directivity of the antenna elements affects the channel matrix while the transmission distance can affect interference power. Both prove to be important considerations for short-range LoS MIMO systems.

3.1 Antenna Element Directivity

In this section, we analytically determine how the SNR changes with the antenna element directivity. We assume the ULAs are parallel (i.e. $\theta_{tx} = \theta_{rx}$) with a transmission distance R and with d_{tx} and d_{rx} given optimally by [6]. If the antenna elements' beamwidths are too narrow for each receiving element to observe the signal form each transmitting element, then the channel vector $h_{n,k}$ between some transmit and receive antennas will be zero. Although this would enhance the orthogonality of channels in the spatial multiplexing case, it could reduce Λ_{max}, degrading the system performance. If, however, some LoS signals from the various transmitting antenna elements add destructively at receiving elements, then removing LoS signals could enhance performance.

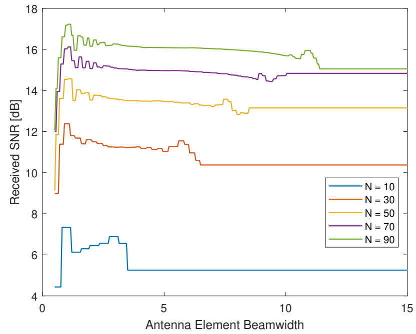


Figure 2. SNR of LoS MIMO Systems with $N_{tx} = N_{rx} = N$ Given the Beamwidth of Array Elements

Figure 2 shows how the SNR changes as a function of the beamwidth of the antenna elements for a transmission distance of $5m$. Increasing the beamwidth corresonds to increasing the number of LoS transmissions observed by each receiving element. It improves the SNR initially, but eventually it degrades the performance. For the ideal LoS MIMO THz system, the beamwidth of the transmitting and receiving elements should be given by

$$\Theta_{tx} = \Theta_{rx} = \arg \max_{\Theta_{tx}, \Theta_{rx}} \{\Lambda_{max}(H_{omni}, \Theta_{rx}, \Theta_{tx})\}, \quad (4)$$

where H_{omni} is the channel matrix assuming omnidirectional antennas and Θ_{tx} and Θ_{rx} are the beamwidths of the transmitting and receiving antenna elements respectively. (4) will yield a range of beamwidths that will depend on the system geometry (i.e. θ_{tx}, θ_{rx}, ϕ_0) as well as d_{tx} and d_{rx}.

3.2 Inter-symbol Interference from Reflections

Another important and practical consideration for the LoS MIMO THz system is ISI from reflected paths. In this analysis we have assumed a pure LoS transmission, which is possible given the directivity of the antenna elements and the short distances anticipated for some THz applications. However, there will likely be a strong reflected component caused by back-and-forth reflections between the transmitter and receiver hardware [7]. This delayed copy of the signal causes the undesirable interference that degrades the system's performance, and we proceed to calculate P_{refl}, the reflected power observed by the receiving array.

The reflected paths' variations in distance will depend on the shape of the front end and the orientation of the arrays. For our analysis we assume the worst case scenario where each receiving antenna observes a reflected signal from all the transmitting antennas and we assume each of these reflected signals travel $3d_{min}$, where d_{min} is the minimum of

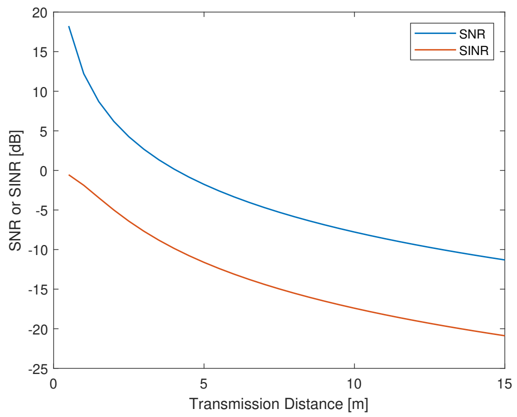


Figure 3. SNR and SINR of LoS MIMO system as a function of transmission distance with $N_{tx} = N_{rx} = 2$

all $d_{n,k}$. We also assume that none of the reflected signals add destructively at the receiver. Thus

$$P_{refl} = \alpha(3d_{min}, f_c)P_{tx}N_{rx}N_{tx}. \qquad (5)$$

The SINR considering the back-and-forth reflections is compared with the SNR in Figure 3. In this scenario, we assume each receiving element receives LoS components from all transmitting elements. The SINR shown by the red curve is significantly lower than the the SNR in blue. It is also clear that the effects of ISI are worse for smaller transmission distances.

It is important to note that if the system uses directional antennas such that each receiving element does not observe LoS components from all the transmitting elements, then it is still possible that all the receive antennas observe a reflected signal from all the transmit antennas. Because the reflected signals are reflected at the angle of incidence and continue to spread radially as they propagate, the reflected beam is wider than the originally transmitted beam. Thus the interference is created by all the transmit antennas and is likely received by all the receiving antennas. For this reason we expect IFI and ISI mitigation techniques to enhance the system performance.

4 Experimental Results

Now that we have analytically investigated the effects of antenna beamwidth and ISI on the system, we proceed to experimentally verify our findings.

4.1 Experiment Set-up

We use the TeraNova test bed, described in [8], to implement a MIMO system consisting of 2 transmitting front-ends and 2 receiving front-ends operating at 125 GHz with 10 GHz of bandwidth. The transmission distance is 1.5m, and both the receiver and transmitter antenna separations are 20cm. Figure 4a shows the system with the same antenna beamwidth used at the receiving and transmitting elements. Figure 4b shows the set-up with a more directive antenna element at the transmitting array. In Figure 4c we put absorptive material in front of the metal on the receiver front-ends to help mitigate back-and-forth reflections.

Although the two transmitter front-ends are similar, they are not identical; they implement different amplifier gains and suffer varied conversion losses. Additionally, the more directive antennas introduce a significant antenna gain. Thus, the transmission power is adjusted at the AWG to ensure both receivers in all test scenarios observe comparable SNR before combining.

4.2 Results for Antenna Element Directivity

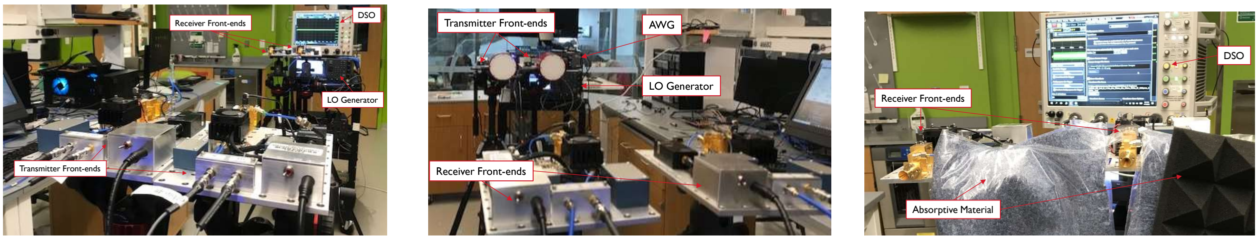
To validate the findings shown in Section 3.1 we implement the 2x2 MIMO system described above using antenna elements of with different beamwidths at the transmitting array. When using antennas with a beamwidth of 8°, both receivers are able to observe a LoS signal from both transmitters, but when we instead use antennas with a beamwidth of 1.6°, each receiver will only observe a LoS signal from the transmitter directly in front of it. Recalling Figure 2a, for our 2x2 MIMO system, we expect to observe better performance with the 8° antenna elements. The results are shown in Table 1. As anticipated, the system achieves a lower EVM when both receiving antennas observe LoS signals from both transmitting antennas.

4.3 Results for Back-and-forth Reflection ISI

In order to verify that back-and-forth reflections between the transmitter and the receiver can adversely affect LoS MIMO THz MIMO systems, we mitigate the effects of ISI and IFI from back-and-forth reflections between the transmitter and receiver front-ends. We calculate the time delay between a receiver observing the original transmitted signal and observing the reflected version of the signal. In our case, the time delay is $4.5 * 10^8$s. We break the signal frame into segments no longer than $4.5 * 10^8$s and ensure a pause of at least $4.5 * 10^8$s between each of these segments to eliminate the effect of back-and-forth reflections on the demodulated signal. We also add the absorptive material shown in Figure 4c as an additional measure to ensure no back-and-forth reflections. The results are shown in the right two columns of Table 1. We see that the EVM of the the MIMO system that mitigates back-and-forth reflections is lower than that of the system without the mitigation techniques. Thus, as discussed in Section 3.2, the back-and-forth reflections can impact the performance of LoS THz MIMO systems.

5 Conclusion

In this paper we have introduced and investigated two specific and practical challenges facing LoS THz MIMO sys-



(a) 2x2 MIMO set-up with 8° beamwidth antennas at the transmitter and receiver

(b) 2x2 MIMO set-up with 1.6° beamwidth antennas at the transmitter and 8° beamwidth antennas at the receiver

(c) Receive array with absorptive material

Figure 4. 2x2 MIMO system using TeraNova platform

	EVM		
Modulation	1.6° Antennas	8° Antennas	8° Antennas w/ ISI Mitigation
4 PSK	18.91%	15.92%	13.27%
8 PSK	16.27%	13.46%	11.47%

Table 1. Error Vector Magnitude of Received Constellations

tems. We show that the beamwidth of the antenna elements in a LoS THz array can effect the system performance and that back-and-forth reflections between the transmitter and receiver can introduce interference. Experimental results validate our findings, and these results should be considered in future design of LoS THz MIMO systems. Future work in this area will likely consider ISI and IFI mitigation techniques that allow for more efficient performance. Additionally, methods to leverage the impact of antenna element directivity on the performance of short-range LoS MIMO systems should be explored.

6 Acknowledgements

We would like to thank Jacob Hall for assisting in data collection and proofreading the paper. We would also like to acknowledge the funding received by the US Air Force Research Laboratory Grant FA8750-20-1-0200 and the US National Science Foundation Grant CNS-2011411 which made this work possible.

References

[1] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Madanayake, S. Mandal, A. Alkhateeb, and G. C. Trichopoulos, "Wireless communications and applications above 100 ghz: Opportunities and challenges for 6g and beyond," *IEEE access*, vol. 7, pp. 78 729–78 757, 2019.

[2] B. Ning, Z. Tian, Z. Chen, C. Han, J. Yuan, and S. Li, "Prospective beamforming technologies for ultra-massive mimo in terahertz communications: A tutorial," *arXiv preprint arXiv:2107.03032*, 2021.

[3] T. Merkle, A. Tessmann, M. Kuri, S. Wagner, A. Leuther, S. Rey, M. Zink, H.-P. Stulz, M. Riessle, I. Kallfass *et al.*, "Testbed for phased array communications from 275 to 325 ghz," in *2017 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS)*. IEEE, 2017, pp. 1–4.

[4] D. Tse and P. Viswanath, *Fundamentals of wireless communication*. Cambridge university press, 2005.

[5] P. A. Dighe, R. K. Mallik, and S. S. Jamuar, "Analysis of transmit-receive diversity in rayleigh fading," *IEEE transactions on communications*, vol. 51, no. 4, pp. 694–703, 2003.

[6] F. Bohagen, P. Orten, and G. E. Oien, "Design of optimal high-rank line-of-sight mimo channels," *IEEE Transactions on Wireless Communications*, vol. 6, no. 4, pp. 1420–1425, 2007.

[7] H. Do, S. Cho, J. Park, H.-J. Song, N. Lee, and A. Lozano, "Terahertz line-of-sight mimo communication: Theory and practical challenges," *IEEE Communications Magazine*, vol. 59, no. 3, pp. 104–109, 2021.

[8] P. Sen, D. A. Pados, S. N. Batalama, E. Einarsson, J. P. Bird, and J. M. Jornet, "The teranova platform: An integrated testbed for ultra-broadband wireless communications at true terahertz frequencies," *Computer Networks*, vol. 179, p. 107370, 2020.