

Space-Time Coding, Combining, or Multiplexing: An Experimental Comparison for Sub-THz MIMO

Duschia Bodet*, Phuc Dinh*, Milica Stojanovic*, Joerg Widmer[†], Dimitrios Koutsonikolas*, Josep Miquel Jornet*

*Department of Electrical and Computer Engineering

Northeastern University, Boston, MA, USA E-mail:

{bodet.d,dinh.p,m.stojanovic,d.koutsonikolas,jmjornet}@northeastern.edu

[†]IMDEA Networks, Madrid, Spain E-mail: joerg.widmer@imdea.org

Abstract—Multiple-Input Multiple-Output (MIMO) systems have been presented for Terahertz (THz) communications to combat high path loss and enable Terabit-per-second (Tbps) links. The lack of experimental MIMO channel measurements and data transmission, however, has restricted the majority of THz MIMO work to the theoretical realm. Additionally, of the experimental MIMO sub-THz platforms presented, there has yet to be a side-by-side comparison of various physical-layer implementations. In this paper, we have presented sub-THz MIMO channel measurement results and results of data transmission comparing different MIMO implementations: maximum ratio combining, space-time coding, and spatial multiplexing. We demonstrate achievable data rates up to 89.8 Gbps, and from the measured data, we offer discussion for future directions of sub-THz MIMO technology.

Index Terms—Terahertz (THz), sub-THz, MIMO, channel sounding, experimental results, experimental platform, terahertz communications, data transmission, Alamouti, space-time coding, spatial multiplexing.

I. INTRODUCTION

The Terahertz (THz) and sub-THz bands have attracted much interest recently due to the broad bandwidths available for communications and sensing applications. Particularly for communications, there is potential to reach Terabit-per-second (Tbps) wireless speeds, but to reach these bit rates with practical hardware and bandwidth constraints, multiple-input multiple-output (MIMO) systems must be used [1]. Although MIMO has been deployed in everyday applications such as Wi-Fi at lower frequencies, there are still many open research challenges when it comes to implementing MIMO in the (sub-)THz band.

First, due to the high propagation losses in the (sub-)THz band, directional antennas are generally used to close the transmission link. Although this approach is effective in increasing the signal-to-noise ratio (SNR), it makes MIMO more challenging; traditional MIMO approaches rely on multipath propagation from omnidirectional antennas, so they do not work as well for sub-THz and THz MIMO systems that use directional antennas. Additionally, the broad bandwidths expected for (sub-)THz communications beget their own set

of challenges, ranging from designing devices that can operate over such a wide spectrum to the signal processing overhead for measuring and estimating broadband channels. In particular, MIMO implementations requiring channel state information at the transmitter require additional overhead since the transmitter must receive feedback from the receiver.

A first step in addressing these challenges is developing a measurement-based understanding of the (sub-)THz MIMO channel. Channel sounding and measurement have been a central focus area for bringing (sub-)THz MIMO closer to fruition [2]–[4]. These works have provided measurements of the THz MIMO channel to enable proper understanding and modeling. There have also been no shortage of theoretical papers presenting and building on channel models to engineer THz MIMO systems that would ideally be deployed when the technology is available [5]. In this work, we perform channel measurements of the sub-THz MIMO channel in a conference room setting and then send data over the channel, comparing three different MIMO implementations: maximum ratio combining (MRC), space-time coding (STC), and spatial multiplexing (MUX). Aside from demonstrating a 89.9 Gbps achievable data rate, we also analyze the measured data and discuss potential future directions given our findings.

The remainder of the paper is organized as follows. We provide a summary of related works in Sec. II. Then, in Sec. III we present the channel measurement methodology and results. The data transmission is presented in Sec. IV followed by discussion and future directions in Sec. V. Finally, the work is concluded in Sec. VI.

II. RELATED WORKS

Several experimental sub-THz MIMO platforms have been proposed across recent studies. Sawaby et al. [6] demonstrate spatial multiplexing using a vector network analyzer to provide the transmitter with channel state information, though practical systems ideally acquire this information independently. Other studies, such as Castro et al. [7] and Zhou et al. [8], address orthogonal channel creation by leveraging different polarizations and orbital angular momentum (OAM) topological orders, respectively. While these are effective methods, incorporating spatial diversity could further enhance capacity in sub-THz MIMO systems. Farid et al. [9] introduce subarrays of eight patch antenna elements at 135 GHz, and a similar array is

proposed in Abu et al. [10], where each subarray is powered by an individual RF chain for digital beamforming rather than spatial multiplexing. These two studies are, to our knowledge, the only experimental works achieving an array-of-subarrays (AoSAs) structure in (sub-)THz systems, yet they simplify the full AoSAs approach. Although phased arrays have also been presented, they are limited to beamforming and are not discussed further in this section. In a subsequent work, Saab et al. [11] build on Abu et al.'s platform to implement a 2x2 MIMO system achieving 24 Gbps over 4 GHz bandwidth. Bodet et al. [12] demonstrate a 2x2 MIMO system with space-time coding. With 10 GHz of bandwidth, this is the most broadband solution presented to date, but they do not compare it to combining or spatial multiplexing. Ju et. al [13] use a channel measurement platform to predict the performance of sub-THz MIMO systems and provide guidance for when spatial multiplexing might be preferable to beamforming, but no data is transmitted over the measured channels to compare the capacity to achievable data rates.

III. MEASURED CHANNEL CAPACITY

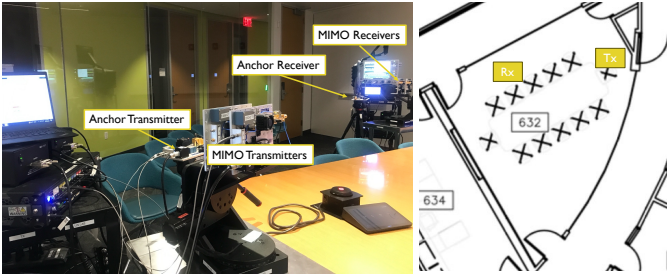


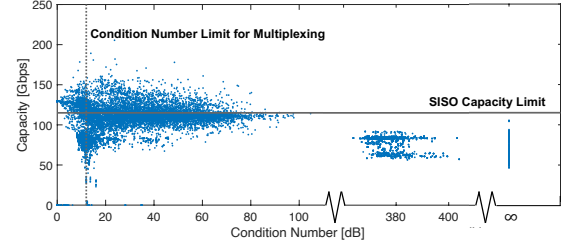
Fig. 1: Channel Sounder set-up for measuring the channel capacity.

To measure the channel capacity we use the correlation-based channel sounder with absolute timing reference from [14]. The position and setting of the measurement is shown in Fig. 1. The transmission distance is 3.7 m, the spacing between the MIMO transceivers is 6 cm. The transmission power is 13 dBm before the antenna, and the antennas each have a 21 dBi gain. The “Anchor” transmitter and receiver are used to establish an absolute timing reference at 115 GHz while the MIMO transmitter and receivers are operated at 150 GHz to avoid interference. The channel is measured sweeping each MIMO transceiver from -60° to $+60^\circ$, assuming 0° is perfect alignment. (More details on the channel sounding platform and procedure can be found in [14].)

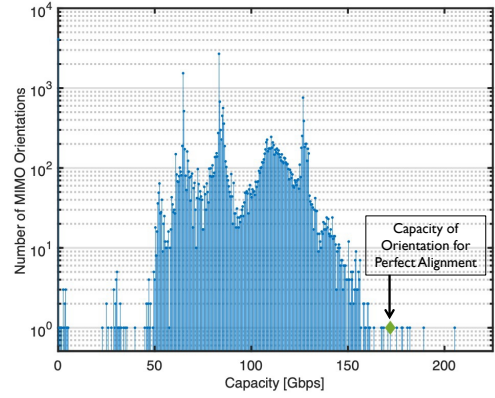
The channel sounding measurement is used to calculate the time delay profile of the broadband (20 GHz) channel in MATLAB, and from this we are able to determine the broadband channel matrix $H_{MIMO}(f)$. The measured capacity of the measured sub-THz MIMO channel is then given according to the Shannon limit taking into account water-filling. We use the expression [15]:

$$C_{MIMO} = \Delta f \sum_{f=0}^B \log_2 \left(\det(I_{M_r} + P_{MIMO,opt}(f) * \frac{(H_{MIMO}(f) * H_{MIMO}(f)^H)}{N_0 \Delta f M_t}) \right), \quad (1)$$

where Δf is the system's resolution in frequency. M_t and M_r are the numbers of transmit and receive antennas respectively. $P_{MIMO,opt}(f)$ is a matrix with the optimal power for each MIMO channel at the frequency f according to water-filling. $H_{MIMO}(f)$ is the channel matrix at frequency f . N_0 is the noise power spectral density. Here, $.$ represents element-wise multiplication while $*$ represents matrix multiplication.



(a) Condition Number v. MIMO Capacity Scatter Plot



(b) Histogram of all MIMO orientations

Fig. 2: Measured capacity given by channel sounding results

Using Eq. (1), we determine the measured capacity of the MIMO channel in Fig. 1, and the results are shown in Fig. 2. In Fig. 2a, we show a scatter plot of the measured capacity given by Eq. (1) on the y-axis, with the maximum condition number of the broadband channel matrix on the x-axis. Each point in the plot corresponds to a given orientation of the MIMO transceivers (i.e., a possible combination of steering angles for the two transmit and two receive antennas). The condition number is a measure of how well a channel is able to support spatial multiplexing; in general, condition numbers below 12 dB indicate channels capable of supporting spatial multiplexing, while larger condition numbers mean that spatial multiplexing is impractical.

There are two key observations we can take from these results; first, that spatial multiplexing is only practical for a small fraction of orientations in this setting, and second, that even without spatial multiplexing being feasible, the MIMO system can offer substantial increase in performance compared to that of the single-input single-output (SISO) system with a maximum capacity of 115 Gbps¹. This second finding is a large part of our motivation to explore and compare the

¹This limit is found calculating the Shannon capacity of each measured MIMO sub-channel and taking the maximum value.

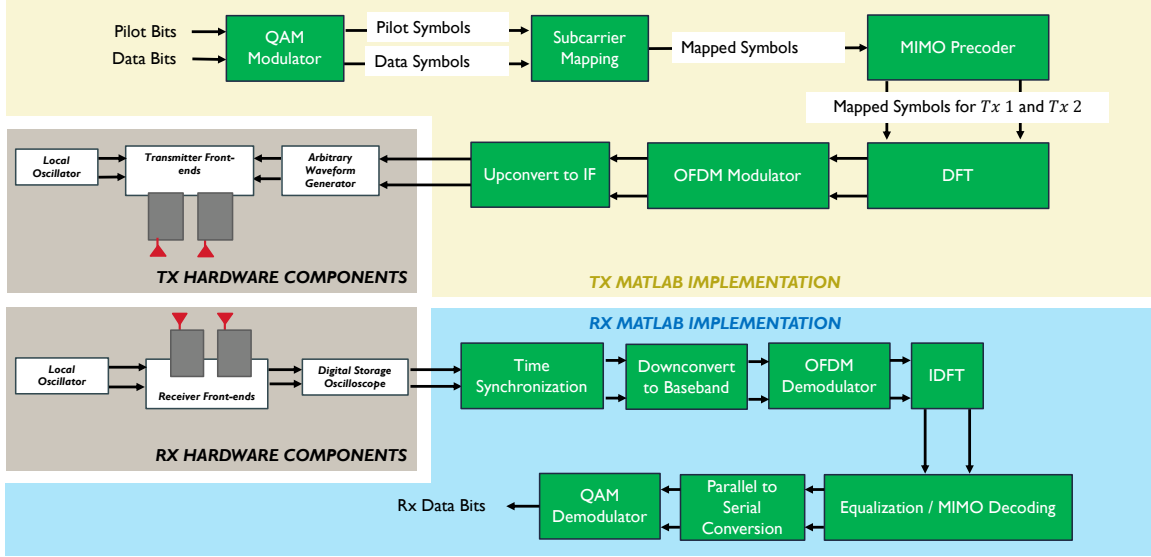


Fig. 3: Block diagram for data transmission

performance of various MIMO implementation strategies (i.e., STC, MUX, and MRC) in this work.

Orientation	Average SNR [dB]	Capacity [Gbps]
Tx1: 0° Tx2: 0° Rx1: 0° Rx2: -10°	9.61	205.5
Tx1: 0° Tx2: +10° Rx1: 0° Rx2: 0°	9.16	189.2
Tx1: 0° Tx2: 0° Rx1: -10° Rx2: -10°	8.00	182.0
Tx1: 0° Tx2: 0° Rx1: 0° Rx2: +10°	8.38	180.8
Tx1: 0° Tx2: 0° Rx1: -20° Rx2: -10°	8.42	178.4
Tx1: 0° Tx2: 0° Rx1: -10° Rx2: -10°	8.49	177.9
Tx1: 0° Tx2: +10° Rx1: -10° Rx2: 0°	8.41	175.3
Tx1: 0° Tx2: 0° Rx1: 0° Rx2: 0°	11.20	172.0

TABLE I: Highest measured channel capacities.

The histogram in Fig. 2b further emphasizes that there are many possible orientations that enable data rates above the capacity limit for the SISO case. Furthermore, we identify the capacity of the perfectly aligned scenario with a green diamond. (This is the orientation that most closely resembles the channel we use to send data in the next section.) One interesting observation is that although this perfectly aligned scenario corresponds to a very high measured capacity of 172.0498 Gbps, it does not correspond to the orientation with the maximum measured capacity. There are seven other orientations that can provide higher data rates, up to 205.289 Gbps, despite having lower signal-to-noise ratio (SNR). The orientations providing the eight highest capacities are listed in Table I along with the average SNR over the 20 GHz of bandwidth. We discuss these findings further in Sec. V

IV. DATA TRANSMISSION

A. Experimental Set-up

To explore the performance of spatial multiplexing, space-time coding, and maximum ratio combining, we transmit data using each of these three schemes over the channel measured in Sec. III. The block diagram is shown in Fig. 3.

We start by sending the pilot and data bits through a QAM modulator. The resulting symbols are mapped to the appropriate subcarriers and sent through the MIMO encoder

block. For these experiments, we compare three different MIMO implementations: space-time coding (STC), maximal ratio combining (MRC), and spatial multiplexing (MUX). For STC, the MIMO encoder is equivalent to an 2x2 Alamouti encoding scheme [16]. The transmitter has no prior channel knowledge, so for MRC and MUX the only MIMO precoding involves sending the same stream on each antenna and sending completely different streams on each antenna, respectively.

After precoding, we take the discrete Fourier transform and send the resulting streams through an OFDM modulator to create DFT-s-OFDM modulated signals. (The signals are designed in MATLAB. We use a DFT-s-OFDM with each subcarrier using the same M-QAM modulation. This modulation scheme allows for lower peak-to-average power ratio than traditional OFDM, while also simplifying frequency-domain equalization for our broadband system.) These signals are brought to an intermediate frequency before being passed to an arbitrary waveform generator that converts them from digital to analog signals that are then given to the transmitter front-ends.

On the receiver side, the signals are digitized by the digital storage oscilloscope, then in MATLAB we perform time synchronization, downconvert to baseband, and demodulate the DFT-s-OFDM signals by sending them through an OFDM demodulator and inverse discrete Fourier transform block. At this point, we perform channel estimation and MIMO decoding. This process is slightly different for each MIMO implementation. For STC this block includes a MIMO channel estimation process as done in [12] and that Alamouti decoding process as described in [16]. In the case of MRC, the same channel estimation strategy is used, but instead of Alamouti decoding, the signals are combined to maximize the SNR. In the case of MUX, after channel estimation, the received symbols are multiplied by the conjugate transpose of the channel estimate.

The hardware set-up for the data transmission is the same as shown in Fig. 1 except we replace the 21 dBi antennas with

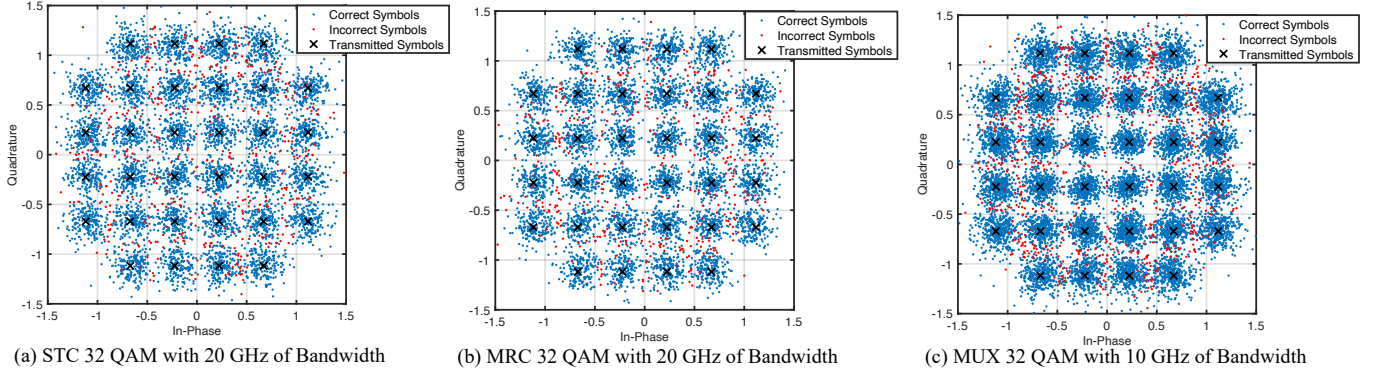


Fig. 4: Received constellation diagram for data rates of 65.56 Gbps

40 dBi antennas which require a larger antenna separation of 24 cm.

B. MIMO Precoding & Receiver-side Channel Estimation

In all three MIMO implementations, there is no channel knowledge at the transmitter. In the MRC case, the “MIMO Precoding” block in Fig. 3 consists of simply duplicating the symbols to send them simultaneously from both antennas. For STC, the precoding is the Alamouti space-time code for a 2x2 MIMO system given in [16], and for MUX, the precoding block simply involves separating the data into two independent streams.

At the receiver, the first ten DFT-s-OFDM symbols are used to as pilot symbols to estimate the channel for each subcarrier. We use a scaled least squares channel estimate, where the least squares estimate is given by [17]

$$H_{LS} = RT^\dagger. \quad (2)$$

R represents the received pilot symbols, T represents the expected or transmitted pilot symbols, and $\dagger$ indicates the pseudoinverse. The channel estimate is found by:

$$H_{est} = \frac{H_{LS}}{H_{LS}^H H_{LS} r \sigma_n^2}, \quad (3)$$

where r is the number of receiving antennas and σ_n is the variance of the noise.

This channel estimate is used according to [18] in the case of MRC, and according to [16] in the case of STC. For spatial multiplexing, we multiply by the conjugate transpose of the channel estimate, H_{est} . Because the channel matrix is nearly diagonal, zero forcing (ZF) and minimum mean square error (MMSE) channel estimation are not required.

C. Experimental Results

As mentioned previously, for this data transmission we use DFT-s-OFDM with the same M-QAM constellation on each subcarrier. We varied the modulation scheme between 32- and 64-QAM for bandwidths of 5 GHz, 10 GHz, and 20 GHz. The respective bit rates and data rates (accounting for bits used for time synchronization and channel estimation) are shown in Table II. In total the data rates span from 16.4 Gbps to

BW	Mod.	Impl.	Bit Rate (Gbps)	Data Rate (Gbps)
5 GHz	32 QAM	STC	22.7	16.4
		MRC	22.7	16.4
		MUX	45.4	32.8
	64 QAM	STC	27.2	19.7
		MRC	27.2	19.7
		MUX	54.5	39.3
10 GHz	32 QAM	STC	45.4	32.8
		MRC	45.4	32.8
		MUX	90.7	65.6
	64 QAM	STC	54.5	39.3
		MRC	54.5	39.3
		MUX	108.9	78.7
20 GHz	32 QAM	STC	90.8	65.6
		MRC	90.8	65.6
		MUX	181.6	131.1
	64 QAM	STC	108.9	78.6
		MRC	108.9	78.6
		MUX	217.9	157.4

TABLE II: Bit and data rates for data transmission experiments.

157.4 Gbps. The received constellation diagrams for the case with a 65.56 Gbps data rate are shown in Fig. 4 and full error vector magnitude (EVM) and bit error rate results are shown in Fig. 5.

As anticipated, the STC and MRC results, displayed in blue and green, respectively, have similar performances. Looking at the error vector magnitudes (EVM) shown as a percentage in Fig. 5, they remain within 2% of each other, with slightly more deviation for higher bandwidths. This separation is likely due to the fact that because we use highly directional antennas, there is little crosstalk between transmitter 1 and receiver 2 and between transmitter 2 and receiver 1; most of the power from transmitter 1 goes to receiver 1 while most of the power from transmitter 2 goes to receiver 2. STC actually takes advantage of power in the those cross-channels, and in the 20 GHz bandwidth case when there is a lower SNR across all channels, the information in those cross-channels is likely less

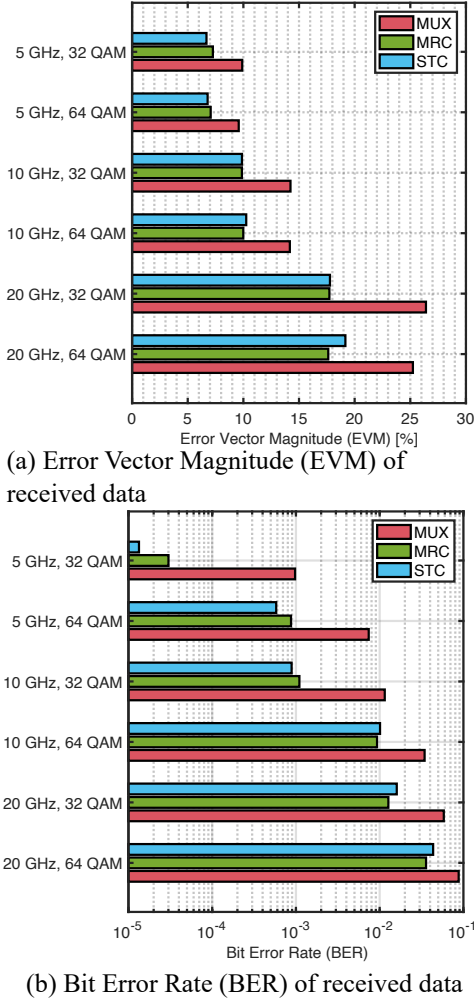


Fig. 5: Performance metrics of transmitted data with various MIMO implementation methods

useful leading to some reduced performance when compared to MRC. However, this difference is quite minimal.

The BER performance generally follows the trend of the EVM. The only exception occurs in the 5 GHz, 32-QAM case where the MRC exhibits slightly better BER performance despite a slightly worse EVM. This can happen when the exterior symbols are those received with more noise since they have fewer neighbors and are less likely to be detected incorrectly. The BER and EVM of the multiplexed waveforms are much worse than STC and MRC, as expected since the multiplexed waveforms send twice as much data.

In order to more clearly illustrate the achievable information rate of the channel if forward error correction were implemented, we show the effective data rate given by

$$R_{\text{eff}} = R_{\text{data}}(1 - H_p(\text{BER})), \quad (4)$$

where R_{data} is the data rate from Table II and the BER is taken from Fig. 5b. $H_p(x)$ is the binary entropy function given by [19]:

$$H_p(x) = x \log_2 \left(\frac{1}{x} \right) + (1 - x) \log_2 \left(\frac{1}{1 - x} \right). \quad (5)$$

Eq. (5) gives the entropy of the binary symmetric channel with probability of error x . Thus R_{eff} is a measure of the information-theoretic capacity given our experimental results.

We plot the calculated values of R_{eff} in Fig. 6. Especially at the lower data rates, the throughput of the multiplexing system nearly doubles that of the combining and space-time coding counterparts. However, as the data rate increases, the achievable information of the combining and space-time coding system approach the performance of the multiplexing system, reaching about 2/3 for the 20 GHz case.

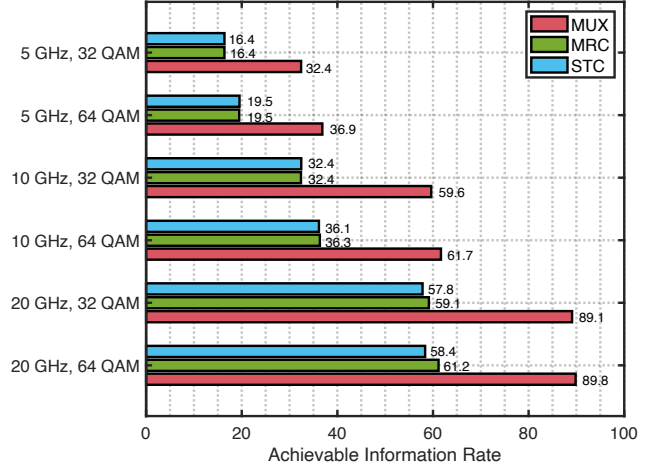


Fig. 6: Achievable data rate of transmitted data with various MIMO implementation methods

V. DISCUSSION & FUTURE DIRECTIONS

There are a few findings we would like to emphasize and discuss further in this section because we believe they motivate interesting future work.

A. Raw power is not everything... Should we mis-align on purpose?

Considering, capacities measured in Sec. III, it is perhaps counter-intuitive that the channel with the highest average SNR does not correspond to the channel with the highest capacity. However, in MIMO channels, the capacity is given by Eq. (1), which means the phases play a significant role in determining the channel's potential.

Especially in the sub-THz MIMO channel, which is primarily LOS, introducing more phase differences between MIMO subchannels is often necessary to improve the channel capacity. We observe these changes with the radios at different steering angles because the axis of rotation for the radios is not at the antenna, so changing the steering angle leads to slight changes in the transmission distance. With the $\approx 2\text{mm}$ wavelength at 150 GHz, these fluctuations in the transmission distance lead to substantial changes in the propagation phase.

One potential area of future research would be to explore how to introduce these slight changes in the propagation phase intentionally; perhaps through tailored mis-alignment such that the transmitting and receiving arrays are not in parallel planes or by slightly changing the elevation of antenna elements on a given array proportionally to the wavelength.

B. There is a substantial gap between capacities and achieved throughput... What can we do to help close it?

We demonstrate high throughput of up to 89.8 Gbps in Fig. 6. These results are high, but there are several strategies that could enable an even closer approach to the channel capacity.

1) *Using channel knowledge at the transmitter to tailor the broadband signal:* The data transmission system we design only assumes that the transmitter and receiver are pointed at each other (i.e., the transmitter and receiver know each other's angular direction). This makes the system less complicated and reduces the amount of overhead that is required. However, it is at the cost of performance. The system performance could be improved if the transmitter acquired a complex channel estimation for each subcarrier of the broadband signal and used that estimate to pre-code its signal. This estimation would require a feedback loop between the transmitter and receiver and would increase the overhead processing, but it is a viable option for improving sub-THz MIMO systems. The overhead could also be mitigated by integrating deep learning solutions to help with channel estimation.

2) *Using untraditional modulation and coding schemes:* The channel capacity is calculated irrespective of the modulation and coding scheme used; it assumes the most optimal method of organizing bits onto a signal, but it does not give us any information on what that method might be. There have been some works to design optimized constellations for the channel [20], and these works could be extended to MIMO systems to help approach the channel capacity.

C. When multiplexing gains start to dwindle can we take a hybrid approach?

As mentioned in Sec. IV, the multiplexing waveform allows for effective data rates almost exactly double that of the space-time coding and combining waveforms for the lower data rates, but in the 20 GHz, 64QAM case, where the effective data rate for multiplexing drops to $R_{\text{eff}}^{\text{MUX}} \approx \frac{3}{2} \times R_{\text{eff}}^{\text{MRC}}$. As we continue to push the data rate, the ratio would continue to approach 1. In these situations, there could be a hybrid approach, where instead of choosing combining or space-time coding or multiplexing, some combination of the three options can be implemented to maximize throughput. This approach would be similar to the concept of using an array of subarrays (AoSA), which allows MIMO systems to perform both beamforming and spatial multiplexing from a hardware perspective; however, exploring from a system perspective ways to merge different MIMO implementations could lead to interesting results as well.

VI. CONCLUSION

In this paper, we have presented sub-THz MIMO channel measurement results and corresponding results of data transmission comparing different MIMO implementations: maximum ratio combining, space-time coding, and spatial multiplexing. We demonstrate effective data rates up to 89.8 Gbps, and from the measured data offer discussion for future directions of sub-THz MIMO technology.

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