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Experimental Demonstration of Multiple Input Multiple Output Communications above 100 GHz

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***Abstract*—The terahertz (THz) band (0.1 - 10 THz) will be instrumental in the next generation of wireless communication systems, largely due to its ability to provide 10s of gigahertz (GHz) of contiguous bandwidth. One of the main challenges facing THz communication systems is the high propagation losses experienced by THz signals. Multiple-input multiple-output (MIMO) systems have been suggested as a method to overcome the challenging propagation of THz signals. In this paper, an information-bearing ultra-broadband 2x2 MIMO system above 100 GHz is built for the first time and utilized to explore the performance of transmit beamforming and maximal ratio combining in real-world setups.**

I. INTRODUCTION

Future generations of wireless communications are expected to surpass 100 gigabits per second (Gbps) data rates [1]. The terahertz (THz) band (0.1 - 10 THz) can facilitate these rates with access to ultra-wide bandwidths of 10s of gigahertz (GHz) over long transmission distances and multiple THz at over short distances [2].

However, THz frequencies face the unique challenge of overcoming molecular absorption from water vapor in addition to the greater spreading loss due to their higher frequency [2]. Molecular absorption manifests as very strong loss at resonance frequencies of water vapor and limits the available bandwidth by forcing communications into absorption-free windows. Highly directional antennas are used to compensate for the spreading loss, but multiple-input multiple-output (MIMO) systems have also been suggested to aid in overcoming these losses [3].

Spatial multiplexing has been demonstrated using various MIMO set-ups [4] [5], and phased-arrays have been used to demonstrate beamforming in the THz range [6] [7]. In this paper, we experimentally demonstrate digital transmit and receive beamforming using physically separate front-ends in a 2x2 MIMO system. We show improved Error Vector Magnitude (EVM) for THz data signals and therefore demonstrate MIMO's potential for improving THz system performance.

II. MIMO BACKGROUND

Digital transmit beamforming (also called pre-coding or maximal ratio transmitting (MRT)) is the process of using channel knowledge to pre-code IQ symbols at the transmitter such that the radiated signals are directed towards the receiver. In MIMO systems, digital transmit beamforming is often supplemented by digital receive beamforming (also called decoding, combining, or maximal ratio combining (MRC)). A beamforming receiver uses channel knowledge to combine received IQ symbols in a way that maximizes the signal-to-noise ratio (SNR). Thus when implementing both beamforming and combining, the received signal after processing is given by [3]

$$y = \mathbf{W}^H \mathbf{H} \mathbf{F} \mathbf{x} + \mathbf{W}^H \mathbf{n}, \tag{1}$$

where $\mathbf{W}$ is the de-coder used at the receiver, $\mathbf{F}$ is the pre-coder used at the transmitter, and $\mathbf{H}$ is the channel matrix. The noise is denoted by $\mathbf{n}$, and the vector $\mathbf{x}$ is comprised of the information-bearing IQ symbols. $\mathbf{W}$ and $\mathbf{F}$ are chosen using the channel matrix, such that the SNR given by [8]

$$SNR = \frac{P_s}{\sigma^2} \Lambda_{max}, \tag{2}$$

where Λ_{max} is the largest eigen-value of HH^H, P_s is the average power observed by each receiver. In this way, the SNR can be maximized as long as the transmitter and receiver have knowledge of the channel.

III. EXPERIMENTAL SET-UP

A. Testbed and Transmission Characteristics

We leverage the TeraNova testbed for sending modulated data in the THz band, previously presented in [9]. The testbed is shown in Figure 1. We use a Keysight arbitrary waveform generator (AWG) and digital storage oscilloscope (DSO) for generating and capturing our signal, respectively. The AWG produces the transmitted signal at 90 giga-samples-per-second (GSas) and the DSO digitizes the received signal at 160 GSas. These are attached to Virginia Diode Inc. (VDI) Mixer Amplifier Multiplier Chain (MixAMC) RF front-ends that mix the signal with a THz carrier and send it over-the-air.

For our scenario, we use 21 dBi antennas on all MixAMCs. They have a horizontal beamwidth of 8°, which drives a link distance of 1.5 m with 18 cm of separation between the pairs of antennas at each end. This is the scenario seen in Figure 1.

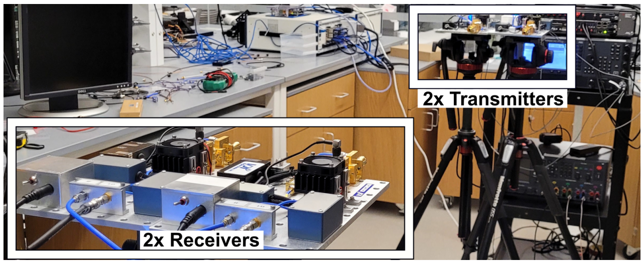

Fig. 1: TeraNova Testbed

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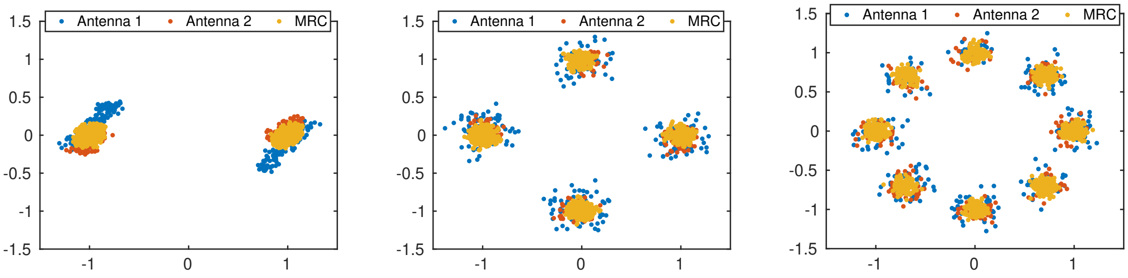

(a) BPSK

(b) QPSK

(c) 8PSK

Fig. 2: Received Constellations

We transmit messages modulated with single-carrier BPSK, QPSK, and 8PSK at a symbol rate of 2.5 giga-symbols-per-second (GSyms) with 5 GHz of bandwidth, and they are mixed with a carrier frequency of 125 GHz. The messages contain real information bits, and have a packet structure consisting of an 18-symbol header for time synchronization, a 240-symbol pilot sequence, and a 1200-symbol data payload. Our frames are custom designed and generated using MATLAB.

Our packet size is constrained by the coherence time of our system, which [9] determines to be approximately 1 μs due to single side-band (SSB) phase noise.

B. Beamforming and Signal Processing

For demonstration purposes, we assume the transmitter knows the geometric position of the receiver with respect to itself. From this knowledge, it calculates the required precoding vector in MATLAB and applies the vector to the IQ symbols being transmitted. On the receiver side, after the digitized signals are stored by the DSO, MRC is performed in MATLAB. The receiver performs channel estimation using the pilot sequence and the minimum mean squared error (MMSE) technique. The estimated channel is then used to perform MRC.

In addition to demonstrating the 2x2 MIMO case with both transmitters and both receivers in use simultaneously, we also demonstrate the 1x2, 2x1, and 1x1 scenarios for comparison. When only one receiver is used, MMSE equalization is performed at the receiver.

IV. RESULTS

At the receiver, the EVM is calculated, and the results are shown in Table I. As anticipated, the highest EVM corresponds to the 1x1 single-input single-output (SISO) scenario, where only one transmit and receiving antenna are used and therefore no pre-coding or combining takes place. Implementing MRT or MRC (i.e. adding an additional antenna at the transmitter or receiver, respectively) improves the performance from the SISO case, while implementing both MRT and MRC together for a full 2x2 MIMO system yields the best performance.

The received constellations for a BPSK, QPSK, and 8PSK signal are shown in Fig. 2. For all three constellations, MRC provides the tighter constellation that we would expect. The BPSK and QPSK experience no bit errors with or without MRC & MRT but for 8PSK the BER was able to be improved.

EVM

Mod.	SISO	MRC	MRT	MRC & MRT
BPSK	26.4%	20.7%	17.3%	14.8%
QPSK	20.2%	18.6%	19.7%	16.4%
8PSK	21.4%	17.3%	14.9%	12.1%

TABLE I: Average EVM

V. CONCLUSION

With an experimental 2x2 MIMO link, we have been the first to validate MRT's and MRC's ability to improve the SNR of a THz link and correct bit errors present in a SISO link. We transmit BPSK, QPSK, and 8PSK with 5 GHz of bandwidth and show that EVM can be improved by over 10%.

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