Experimental Throughput Analysis of Low-THz MIMO Communication Channel in 5G Wireless Networks

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Abstract—This letter presents first results of a Terahertz (THz) Band line-of-sight (LOS) 2×2 multiple-input multiple-output (MIMO) channel. The system architecture is based on a subharmonic mixer that translates the measuring frequency of vector network analyzer (VNA) in the range of 298 - 313 GHz. The system uses virtual antenna array technique to characterize a MIMO channel. The antenna element spacing is derived from the principles of diffraction limited optics to establish parallel channels for higher system throughput and reliability. The MIMO channel measurements are then used in simulations to evaluate performance of the communication system operating in THz Band MIMO communication channel. Finally, we have shown the MIMO link in THz Band operating at 7 Gbps, with higher reliability, in comparison with the single channel operating at 5.55 Gbps.

Index Terms—Antenna arrays, channel sounding, indoor propagation measurements, MIMO systems, spatial diversity, THz channel propagation measurements, THz communication, THz system.

I. INTRODUCTION

Terahertz Band (0.3 - 10 THz) communication is attracting more interest due to its large available bandwidth, small antenna size and high directivity. The large bandwidth is fundamental in enabling very high speed communication that is envisioned in future generation of wireless communication. Since the demand for higher data rates is ever increasing, MIMO techniques should be incorporated in the THz Band communication. This technique has the potential to not only increase the data throughput but also improve reliability of the systems. MIMO communication links provide higher data throughput without increasing the system bandwidth. Multiple closely spaced transmitters (TX) and receivers (RX) are used to establish parallel communication channels that can simultaneously enhance the throughput and reliability of the system.

MIMO in conventional low frequency communication systems (2 - 5 GHz) exploits multipath signals in a non-line-of-sight (NLOS) channel to achieve spatial diversity. However, in THz Band communication, LOS MIMO is more suitable due to small antenna size and high directivity. Although high directivity is more prone to link breakage caused by path obstructions, a large array of MIMO links can easily mitigate this shortcoming.

To characterize THz Band radio channel, several channel sounders and measurements have been reported. A 300 GHz

measurement system is described using single transmitter receiver with 9 GHz bandwidth in [1]. In [2] and [3], channel response of single-input single-output (SISO) at 300 GHz is shown using subharmonic schottky diode mixer and a VNA. LOS and NLOS measurements at 300 GHz are performed with a system bandwidth of 20 GHz in [4]. However, to date, no MIMO link operating in THz Band has been investigated.

To evaluate a MIMO channel operating in THz Band, we have emulated a 2×2 MIMO system by linearly displacing a single transmit and receive antenna to form a virtual antenna array as in [5]. Separation between the transmitter and receiver are calculated using the principles of diffraction limited optics, [6]. The measured MIMO channel matrix is then used in a communication system simulation to evaluate the channel performance. Results confirm that THz Band LOS MIMO link can be used to transmit 7 Gbps of data. The higher path loss and antenna directivity can enhance frequency reuse and multiply capacity of the THz Band system when deployed in a femtocell regime.

The remainder of this letter is organized as follows. In Section II, we describe our THz Band MIMO measurement system and channel response. In Section III, we show the performance of our emulated MIMO link. Finally, we conclude the letter in Section IV.

II. THZ BAND MIMO MEASUREMENT SYSTEM

A. Channel Measurements Testbed Specifications

The setup used for MIMO channel measurements consists of two major parts, Anritsu Vector Network Analyzer (VNA) MS4647B and VDi WR2.8MixAMC modules. VNA MS4647B is a wideband equipment with the upper frequency limit of 70 GHz. To extend the frequency of the system to 300 GHz, WR2.8MixAMC are attached with the VNA. These extension modules are based on subharmonic mixers that upconvert and downconvert the RF signal of the VNA. Detailed description of the setup is given in [4]. The block diagram of our setup is shown in Fig. 1.

Yttrium iron garnet (YIG) based synthesizer was used to generate a common local oscillator signal f_{LO} of 12.357 GHz for both the upconverter and downconverter modules to achieve phase coherence. WR2.8MixAMC module multiplies this f_{LO} signal 24 times to generate THz Band signal, which is fed to f_{LOTHz} port of subharmonic mixer. Intermediate frequency f_{IF} port of this mixer is attached to the VNA that generates a sweep signal from 1 - 15 GHz. After mixing,

Fig. 1: Block diagram of THz Band measurement setup.

Fig. 2: THz Band $N \times N$ LOS MIMO system.

the signal generated at the output of the subharmonic mixer contains frequencies from 298 - 313 GHz ($f_{LOTHz} + f_{IF}$). This signal undergoes attenuation and phase alteration as it passes through the wireless channel. The signal is received at the receiver and fed back to the VNA after down conversion. The VNA determines changes in the received signal based on the information of transmitted signal and calibration data to show scattering parameters (s-parameters) of the channel. For measuring channel response, through/reciprocal calibration is performed with direct interconnection of the module's waveguide [3], [4]. All the later measurements are recorded with horn antenna attached at the output and input port of the transmitter and receiver, respectively. Antenna gain is 25 dBi each, with 3 dB beamwidth of 12° .

B. MIMO Measurements Based on Diffraction Limited Optics

Unlike conventional low frequency MIMO that depends on NLOS multipath signals, THz Band MIMO is more appropriate with LOS spatial diversity scheme. This is because in THz Band, the high pathloss causes the multipath signals to get very attenuated. On the other hand, the peculiar behavior of small antenna size makes LOS MIMO more promising technique as large number of antenna elements can be placed alongside a small area to make multiple parallel channels. The high directivity will make sure that the inter channel interference, generated due to closely placed transmitters, is minimal. The concept of THz Band $N \times N$ LOS MIMO is shown in Fig. 2.

In THz Band LOS MIMO, antenna separation D is a very important parameter ensuring multiple transmitters can be

TABLE I: Measurement parameters of VNA

Parameter	Symbol	value
Measurement points	N	7368
Test signal power	P_{in}	-10 dBm
Start frequency	f_{start}	1 GHz
Stop frequency	f_{stop}	15 GHz
Bandwidth	B.W.	14 GHz
IFBW	Δf_{IF}	1 KHz

Fig. 3: THz Band MIMO channel measurement setup.

distinguished at the receiver. This problem is addressed by using diffraction limited optics theory [6], [7], which states that for LOS MIMO, the antenna element spacing should be kept as

$$D = \sqrt{\frac{R \cdot \lambda}{N}}, \quad (1)$$

where R is the distance between transmitter and receiver, λ is the free space wavelength of the carrier frequency and N is the number of elements at the receiver. This condition is very similar to Rayleigh criterion. It is evident that there will be cross channel interference among different channels, this interference can degrade the performance and must be reduced using a channel separation network, as shown in Fig. 2.

Measurements were conducted in NWCL lab, which is a typical single floor office environment. The setup for 2×2 LOS MIMO channel experimentation was placed on a solid aluminum optical breadboard with matte anodized finish that reduces unwanted reflection. Distance between the transmitter and the receiver was kept as $R = 25$ cm. For such small distance and narrow antenna beamwidth along with high pathloss, reflected NLOS signals can be neglected. At a center frequency of 305.5 GHz, the corresponding inter element spacing calculated using (1) is $D = 1.2$ cm. On the other hand, VNA was configured to record full 14 GHz band measurements with 1 KHz intermediate frequency bandwidth (IFBW). Details of the measurement parameters are given in Table I and our measurement setup is shown in Fig. 3.

To acquire a full 2×2 LOS MIMO channel matrix, we first recorded the response of MIMO TX 1 in both the channels. This was carried out by placing transmitter module at antenna location 1 of the TX and the receiver module at antenna location 1 (RA1) of RX. The receiver module was then displaced to antenna location 2 (RA2) of RX. In our setup, the desired phase response was obtained at 1.257 cm away from the previous position, which agrees with our theoretical estimate based on (1). The first configuration measures the response of signal transmission in channel 1 (CH1) and the

Fig. 4: Signal magnitude of TX 1 at RA 1 and cross channel interference magnitude at RA 2.

Fig. 5: Signal phase of TX 1 at RA 1 and cross channel interference phase at RA 2.

second configuration measures cross channel interference in channel 2 (CH2) due to MIMO TX 1. The downconverted magnitude response is shown in Fig. 4 and phase response in Fig. 5. It can be seen in Fig. 5 that the phase difference of the received signal at adjacent antennas is 180° . Similarly, frequency response of MIMO TX 2 was recorded at both RX antenna locations to create a virtual array. The recorded measurements were combined to generate a full 2×2 channel matrix. This matrix was used to perform post processing on a computer to evaluate the performance of THz Band 2×2 MIMO channel.

The cross channel signal at any receiver is out of phase and can be suppressed using a channel separation network. This network mainly consists of delay elements, amplifiers, and splitter/combiner. The architecture of channel separation network is shown in Fig. 6. The optimal values of the amplifier and phase delay element were iteratively determined while minimizing cross channel interference. In CH1, the corresponding optimal value for amplifier gain was found as 7.24 dB and the phase delay was 85.19° whereas, in CH2, the amplifier gain was 7.69 and the phase delay was 84.58° . The slight difference in these component parameters is due to

Fig. 6: Schematic of 2×2 THz Band MIMO system.

Fig. 7: Path loss of CH1 (TX1_to_RX1) and CH2 (TX2_to_RX2) along with cross channel interference magnitude at receiver 1 (TX2_to_RX1) and receiver 2 (TX1_to_RX2), after channel separation network.

the fact that the response for both channels was not exactly identical in an office environment. Signal magnitude after channel separation network is shown in Fig. 7. It can be seen that the cross channel interference is 13.9 dB below the main signal magnitude and is much higher than the noise level, which is -40 dB. Hence the throughput will be determined by the signal to interference ratio. However, for distances greater than 50 cm, the noise will dominate and hence the throughput will be chiefly determined by the signal to noise ratio (SNR).

III. RESULTS OF 2×2 LOS THz BAND MIMO

The THz Band MIMO channel was evaluated offline for communications by transmitting and receiving bits over it, in the baseband. The setup consists of a transmitter that generates pseudorandom binary sequences, the measured MIMO channel response, a channel separation network and an equalizer. The system was analyzed for different configurations such as single transmit mode, MIMO CH1 and MIMO CH2. While operating in single transmit mode, other channel was kept silent, whereas, in MIMO channel configuration, other channel was excited by uncorrelated bits to imitate cross talk scenario. Output of the equalizer was used to generate eye diagram, bit error rate (BER) contours and Bathtub using statistical eye methodology, [8]. All configurations are compared based on same eye height.

In single transmit mode, the channel was excited with data rate of 5.55 Gbps. The corresponding eye diagram with BER contour, for the value of 10^{-12} , is shown in Fig. 8(a). Height of the eye is 0.052 volts and height of BER contour is 0.038

Fig. 8: Eye patterns at (a) 5.55 Gbps without cross talk (b) 3.5 Gbps on CH1 with cross talk (c) 3.5 Gbps on CH2 with cross talk and (d) Voltage Bathtub for both channels operating at 3.5 Gbps.

TABLE II: Performance of THz Band 2x2 LOS MIMO system

Parameters	BER	Single Channel	MIMO Channel	
			CH1	CH2
Height (V)	10^{-12}	0.038	0.033	0.033
	10^{-6}	0.050	0.051	0.051
	-	0.052	0.052	0.052
Width (ps)	10^{-12}	64.81	82.8	82.86
	10^{-6}	83.71	132.9	132.9
	-	100.8	155.7	155.7

volts. One can calculate the capacity for a flat channel using Shannons capacity formula as 148.8 Gbps, with an SNR of 32 dB and bandwidth of 14 GHz. However, in our case, neither the channel is flat nor the phase response is perfectly linear thus causing the significant decrease in the throughput.

In the MIMO channel mode, eye height of 0.052 volts for individual channel was achieved at 3.5 Gbps with 10^{-12} BER contour height of 0.033 volts. Ideally, the data rate must remains the same and overall system throughput should have doubled, however, due to addition of cross channel interference, the data rate was decreased. However, the combined system throughput of 7 Gbps is still higher than the single transmit mode. The corresponding eye diagram and BER contour is shown in Fig. 8(b) and Fig. 8(c), for CH1 and CH2, respectively. The BER performance of the MIMO link from 10^0 to 10^{-16} , for both channels, is depicted using voltage bathtub, in Fig. 8(d). The curve tells maximum tolerable noise for a give BER and shows how an increase in noise can decrease the BER performance of our system, for instance, if signal is sampled exactly at 320 ps, the maximum tolerable noise, depicted by the tub width at BER 10^{-16} , would be 0.028 Volts. Whereas, a noise of 0.033 volts will reduce the system performance to a BER of 10^{-12} . The Performance parameters are summarized in Table II.

IV. CONCLUSION

We have presented THz Band 2×2 LOS MIMO system operating at 7 Gbps. Spatial diversity scheme is utilized with antenna element spacing derived from the principles of diffraction limited optics. The channel transmission and inter channel interference is measured and recorded using virtual antenna array technique and channel sounder based on VNA and frequency extenders. We have shown that cross

channel link vectors are out of phase and can be suppressed using channel separation network. Optimal channel separation parameters were determined for minimal cross channel interference. Finally, THz Band 2×2 MIMO link was evaluated for digital communication system and confirmed to achieve 7 Gbps. However, a significant difference was seen between the theoretical and experimental throughputs that opens up the need for further research. Moreover, our results suggest that single carrier might not provide the ultimate benefit of such a wireless communication channel, instead multi-carrier modulation will perform better in terms of spectral efficiency, given its relative immunity to fading and interference. Future works in this domain are to analyze systems with larger one-dimensional and two-dimensional arrays transmitting real time data in different indoor environments. Performance of multi-carrier modulation system may also be analyzed.

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