Wideband THz Communication Channel Measurements for 5G Indoor Wireless Networks

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***Abstract*—The emerging technology Terahertz Band (0.3 - 10 THz) communication is envisioned to accommodate high speed wireless communication. Large bandwidth makes it a good candidate for 5G mobile networks. In this paper, fundamental experiments on channel modeling at THz Band are presented with detailed analysis of the setup. The measurement setup consisted of subharmonic mixer and vector network analyzer. Path loss and phase delay measurements from 260 GHz to 400 GHz for different distances, angles of arrival and objects acting as reflectors were examined along with their capacity limits. We have shown that LOS link can reach speeds of terabits per second. In addition, reflections from materials were also examined and results indicated that, in case of signal obstruction, a reflector can be used for establishing NLOS link.**

***Index Terms*—Channel modeling, Channel sounding, THz communication, Terabit per second (Tbps) links, THz system, THz propagation measurements.**

I. INTRODUCTION

Demands for ubiquitous access to information and entertainment at higher data rates are increasing. Consumers are expecting wireless communication to reach the throughputs of wired communications. This demand suggests that wireless data rates reaching terabits per second (Tbps) speed must be realized in 5G wireless networks [1], [2]. While current development in 60 GHz spectrum is expected to increase data rates up to 6 Gbits/s [3], the available spectrum around this frequency is limited to 9 GHz and cannot satisfy the increasing demands of higher data rates [4]. To support such high throughputs of Tbps, enormous bandwidth is required, and hence, researchers around the world are exploring the Terahertz (THz) Band.

Increased research activities in THz Band have introduced equipment with improved performance. This equipment is categorized mainly into two groups depending on its approach for generating THz Band signal. In a top-down approach, photonics technology is used by translating back the optical frequencies, while in a bottom-up approach, the operating frequency of electronics components is increased [5]. The latter approach is preferred in communication systems due to compact sized components and reduced cost.

Channel characterization is the preliminary step in design of a communication system, case studies and experiments are being carried out to understand channel characteristics and material behavior in THz Band [6]–[8]. The setups commonly used are based on subharmonic Schottky diode mixers and are thus categorized into bottom-up approach [9]–[11]. However, to develop accurate indoor channel models, there is a need to further case study the response of THz frequencies, in variant environments and to the materials that are still unexamined.

In order to get insight of channel behavior at THz frequencies, in this work a channel sounding setup was installed and detailed experiments were performed. The setup used was based on Vector network analyzer and subharmonic mixers. Currently, network analyzers available in the market support frequencies up to 70 GHz. Therefore, to characterize frequencies in THz Band, external subharmonic mixers were used.

For thorough channel modeling, experiments for both line-of-sight (LOS) and non-line-of-sight (NLOS) were conducted. LOS experiments were carried by varying distance between transmitter and receiver and recording path loss at frequencies ranging from 260 GHz to 400 Ghz. Whereas NLOS experiments included response measurement for different angles of arrival, shadowing effect and reflection from various materials. An indoor wireless channel frequently encounters obstructions, therefore, detailed experiments for NLOS link are required. To collect further data, experiments were carried, in which objects like human hand, fiber mat and glass were modeled as obstructions. In addition, effects of common objects like acoustic ceiling panel and wooden tables were also measured. These experiments help in determining absorption coefficient of the materials and their potential to be used as reflector in NLOS link.

Results suggest that huge bandwidth available in THz Band will introduce variety of applications, which require very high data rates. Some of these applications include wireless interconnection of desktop gadgets, THz femtocell mobile communication, secure Terabit wireless communication and high speed wireless back-haul connection. It can also be inferred that the higher path loss and antenna directivity can enhance frequency reuse and multiply capacity of the system 1000 times when deployed in femtocell regime. Therefore, channel characteristics are investigated for different distances, antenna orientations and materials acting as obstruction or reflector. Although huge bandwidth and directional nature of THz Band opens door for many novel applications, some apparent shortcomings suggest that it cannot replace gigahertz communication. The major drawbacks are smaller coverage area, power inefficient circuits and expensive deployment.

The remainder of this paper is organized as follows. In Section II, we describe our measurement system used for experimentation along with its characterization. In Section III, we present channel measurements at THz Band for LOS and NLOS configurations. Various channel responses are shown for different distances, antenna misalignment and shadowing to account for maximum possible cases. Finally, we conclude the paper in Section IV.

II. THz Band measurement system

A. Channel Sounding Testbed Specifications

Channel modeling is a preliminary step in design of a communication system and requires careful experimentation. Special equipment is required to carry out these experiments. For millimeter wave, fully developed and integrated equipment is easily available, and hence, accurate models are already constructed by following predefined step by step approach. However, for THz Band channel modeling, the experimentation is rather difficult and much more specialized equipment is required. This is because single solution supporting up to THz Band is yet not available and separate modules must be added to the contemporary equipment. These modules must be dealt with extreme care to obtain accurate results. In this section, we discuss the equipment used for the experimentation and describe their suitability for THz Band channel modeling.

The measurement setup consists of two major parts Anritsu Vector Network Analyzer (VNA) MS4647B and VDi WR2.8MixAMC module. VNA MS4647B is a wideband equipment used to measure scattering parameters. However, the upper limit of this device is 70 GHz. To measure channel characteristics at THz frequencies, extension modules WR2.8MixAMC are attached to the VNA. These modules contain subharmonic mixers that upconverts the test signal from VNA before transmitting. This signal after passing through the channel is downconverted at the receiver module and fed back to the VNA. Difference in the transmitted and received signal is analyzed to find channel characteristics.

VDi WR2.8MixAMC is an ultra broadband module that operates from 260 GHz to 400 GHz. Typical Single-Sideband (SSB) mixing loss of this device is 15 dB. Test port waveguide has a cutoff frequency of 211 GHz. These modules are attached externally to the VNA to perform the up and down conversion function [10]. Maximum bandwidth supported is 20 GHz, however, single sweep bandwidth is limited to 19 GHz by the upconversion feature, as it operates from 1 GHz to 20 GHz. Hence, all single sweep measurements recorded are 19 GHz wide.

Due to stringent stability requirements, Yttrium iron garnet (YIG) based tunable synthesizer is used, which generates local oscillator signal f_{LO}. This signal is doubled, and then, multiplied by a factor of 12 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 sweeps the output frequency up to 20 GHz ($f_{LOTHz} + f_{IF}$). To generate frequencies higher than the single sweep limit,

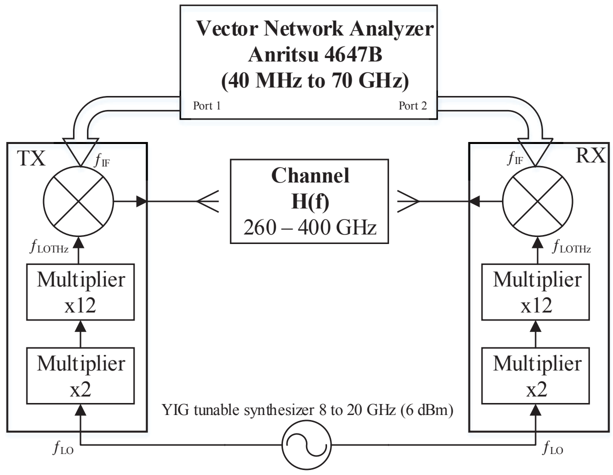


Fig. 1: *Block diagram of THz Band measurement setup.*

f_{LO} is varied from 10.79 GHz to 15.875 GHz, which allows covering the whole band of 260 GHz to 400 GHz. Phase coherence in our setup is achieved by using a common local oscillator for both the transmitter and the receiver module. The corresponding block diagram of our setup is shown in Fig. 1. The subharmonic mixer used produces Double Sideband (DSB) and thus using common f_{LO} causes two frequencies to accumulate after homodyne down conversion, this behavior can be avoided if a small offset is maintained between upconverted and downconverted signal so that the unwanted frequency may be easily filtered out [12].

B. Channel Sounding Testbed Configuration

Channel transfer function is acquired by recording scattering parameters (s-parameters) using the THz Band measurement setup. One of the most important part in making good s-parameters measurement is VNA calibration. While VNA is designed with quite precaution to attain high-linearity and spectral purity in its sources, some imperfections like frequency mismatch, imperfect directivity of the internal coupler and added test cables and modules makes it necessary to perform calibration. Calibrating the VNA corrects these imperfections along with other defects in measurements. Several types of calibrations can be performed depending on the application of interest [6], [13], [14]. For channel modeling, through/reciprocal calibration is performed with direct interconnection of the module's waveguide. All the later measurements are taken with diagonal horn antenna attached at both the transmitter and the receiver. Gain of the antennas at center frequency is 25 dBi each. Whereas at the lowest frequency (260 GHz) it is 2 dB lesser and at the highest frequency (400 GHz) it is 1.5 dB higher.

Full 19 GHz band measurements are recorded with 10 points averaging and 1 KHz IFBW. These parameters significantly reduces noise floor and improves dynamic range [13], [15]. Test signal with power of 0 dBm is used that provides dynamic range of 60 dB. Details of the measurement parameters are

TABLE I: Setup parameters

Parameter	Symbol	value
Measurement points	N	1000
Test signal power	P_{in}	0 dBm
Start frequency	f_{start}	1 GHz
Stop frequency	f_{stop}	20 GHz
Bandwidth	B.W.	19 GHz
IFBW	Δf_{IF}	1 KHz

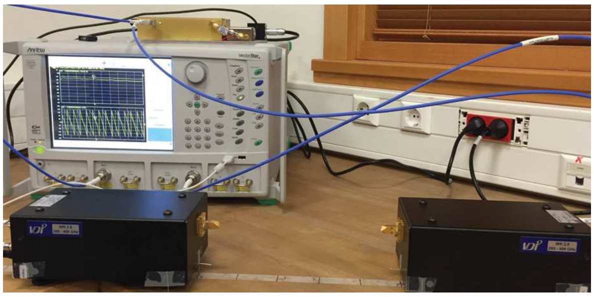


Fig. 2: *THz Band channel measurement setup.*

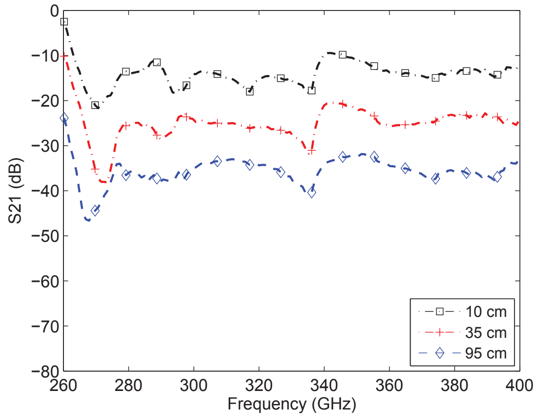


Fig. 3: *Full band channel response.*

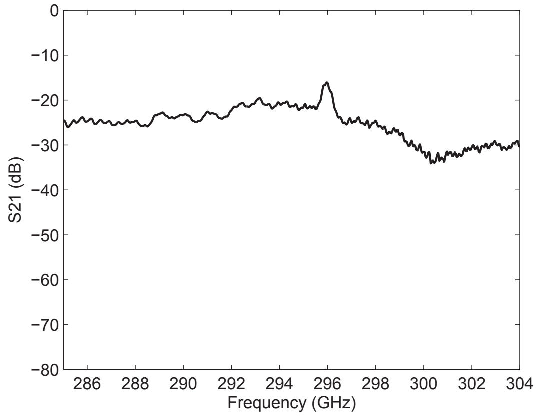


Fig. 4: *Single sweep magnitude respone of THz channel.*

given in the Table I. Trace smoothing of 5% is used for more robust interpretation of the results.

III. THz Band channel measurements

A. Line-of-sight Channel Measurements

Simplest channel model is the LOS channel, in which the transmitted signal is directly received without any obstruction. The measurement setup is shown in Fig. 2. In LOS channel measurements, we measured transmission coefficient at different distances from 10 cm to 95 cm, that are often expected in a typical office desktop table. All the measurements were performed on a wooden base and antenna height in the system was kept as 3 cm. Path loss measurements were recorded in segments of 19 GHz and compiled to produce the frequency response from 260 GHz to 400 GHz in Fig. 3. Graph depicts how the path loss increases as the distance is increased and gives a first insight into the basic capabilities and practical success of THz Band communication system. These measurements include antennas with gain of 25 dBi, and hence, considered as a part of system. Therefore, while considering channel transfer function the gain of antennas may be subtracted.

For the known frequency, distance and antenna gain, one can easily find the path loss between transmitter and receiver using friss transmission equation [16]. For distances, $d = 10cm$, $d = 35cm$ and $d = 95cm$ the theoretical calculated free space loss at 290 GHz is 15.7 dB, 26.57 dB and 35.24 dB, respectively. Whereas the experimental results recorded are 17.2 dB, 27.4 dB and 36.1 dB, respectively. This variation can be reduced by thorough calibration, using anechoic environment and perfect module alignment.

To examine results more carefully, single sweep channel response from 285 GHz to 304 GHz is shown in Fig. 4 and Fig. 5 for 35 cm distance. It can be seen from the results that phase shift is mostly linear throughout the band but shows non-linear characteristics at some frequencies with unexpected magnitude response. This is due to unwanted resonances that can be avoided in an anechoic environment.

To further elaborate our results, Shannon's capacity theorem [17] was applied and capacity (C) of our measured channel was calculated using

$$C = W \cdot log_2(1 + P/N) \tag{1}$$

where W is the bandwidth, P is signal power and N is noise power. For the distances, $d = 10cm$, $d = 35cm$ and $d = 95cm$ average path loss from 260 GHz to 400 GHz was measured as 14.23 dB, 24.14 dB and 35.75 dB, respectively and the corresponding channel capacity was calculated as 9.26 b/s/Hz, 7.62 b/s/Hz and 5.713 b/s/Hz. The noise floor for the proposed setup was approximately -70 dB. It can be seen that, if distance is increased 3.5 times, the capacity of the channel falls by 18%. However, for short distances, Tbps throughput is achievable by the large bandwidth. Consider for the case of 10 cm, using bandwidth of 140 GHz, one can reach speeds of 1.29 Tbps, which is more than 200 times faster than the speeds of currently available technologies.

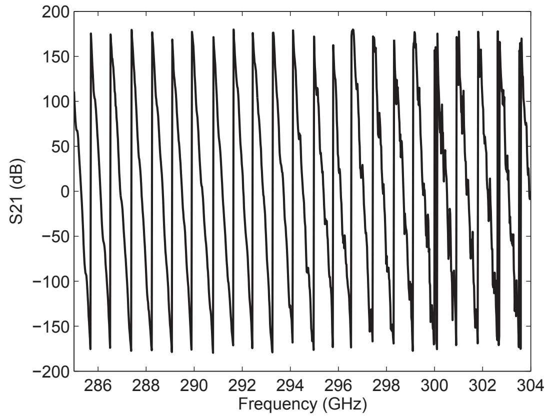


Fig. 5: *Single sweep phase respone of THz channel.*

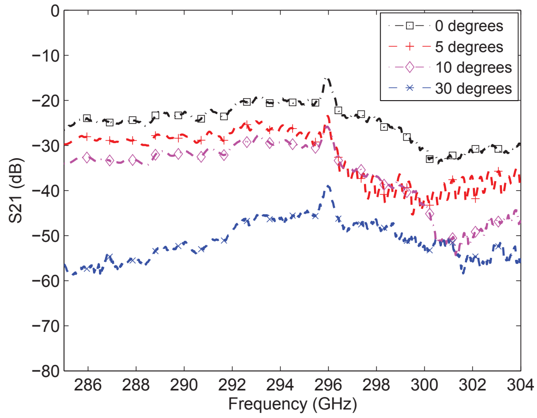


Fig. 6: *Transfer function for antenna misalignment.*

B. Non-line-of-sight Channel Measurements

Future wireless communication is expected to support high speed data communication reaching throughput of Tbps. Applications will include mobile communications, wireless local area networks or interconnection of gadgets on desktop like HDMI and flash memory. These applications require channel measurements with regard not only LOS communication but also NLOS communication as users cannot be expected to place their devices perfectly aligned. Hence, for more comprehensive results, antenna misalignment effects were measured by varying the angle of arrival from 0 to 30 degrees in azimuth direction. All measurements were recorded with 35 cm distance and shown in Fig. 6. Due to highly directive antennas used, signal power drops rapidly. This behavior suggests that robust beamforming algorithms will be required to make Tbps communication viable. These algorithms must easily adapt alterations and mitigate the affect of misalignment.

Indoor wireless radio channel is rather more challenging as it is frequently susceptible to shadowing. Mainly shadowing is caused by any obstacle appearing between transmitter and receiver. This obstacle attenuates the signal power depending

TABLE II: Absorption coefficient of different objects

Object	α_{290GHz}	α_{350GHz}
Fiber mat	$0.168\ mm^{-1}$	$0.171\ mm^{-1}$
Glass	$0.049\ mm^{-1}$	$0.048\ mm^{-1}$
Empty water glass	0.958	0.962
Hand	0.995	0.982

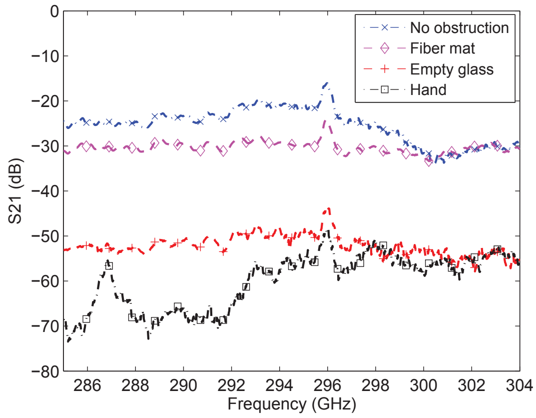


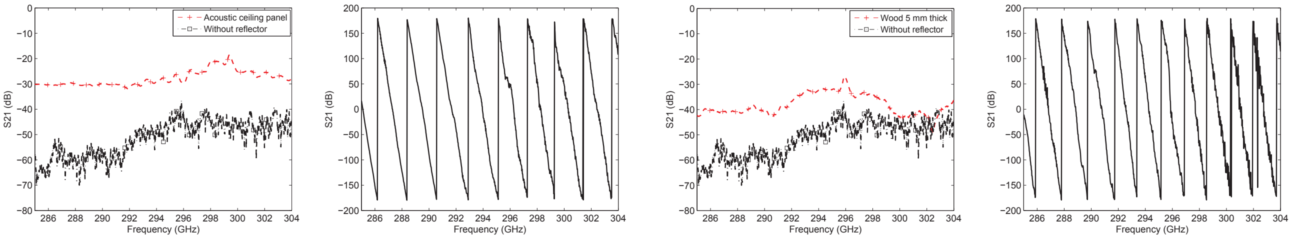
Fig. 7: *Transfer function for shadowing effect.*

on the material type. A strong attenuation can even block the signal and stop communication [18]. To model channel characteristics in the presence of obstruction, experiments were performed for fixed distance of 35 cm between transmitter and receiver. The attenuation due to shadowing by human hand, empty glass of water and a 80 grams fiber mat with 3 mm thickness is shown in Fig. 7. No obstruction shows transmission loss without any obstruction in transmission path.

Absorption coefficient of different materials was determined using the transmission loss. The attenuated signal power was subtracted from the reference signal to get added transmission loss due to the object. Finally, this extra loss was used to calculate the absorption coefficient of the material. For instance, a clear glass with thickness of $t_{glass} = 2\ mm$ or a 80 gram fiber mat with thickness of $t_{fiber} = 3\ mm$, attenuation of approximately 6.14 dB and 27.55 dB, respectively, were measured at 290 GHz. In the case of a human hand placed as obstruction, 45.6 dB of attenuation was observed. The attenuation coefficient of different materials is summarized in the Table II.

The results show that, if a thin glass or a fiber sheet appears as obstruction in the communication link, the SNR of channel decreases, and hence, the data rate also decreases. However, if obstruction is a human hand, the intense signal attenuation might lead to disconnection of communication link. To reestablish communication, the system should turn to a NLOS path that utilizes reflection properties of the materials in the surroundings.

To measure reflections from different materials available in a typical indoor channel, system configuration was kept so that the transmitted signal was incident at 45 degree on the object under observation. Distance between antenna and the reflecting



(a) (b) (c) (d)

Fig. 9: NLOS measurements with reflectors (a) and (b) magnitude and phase response, respectively, with acoustic ceiling panel as reflector while (c) and (d) magnitude and phase response, respectively with wood as reflector.

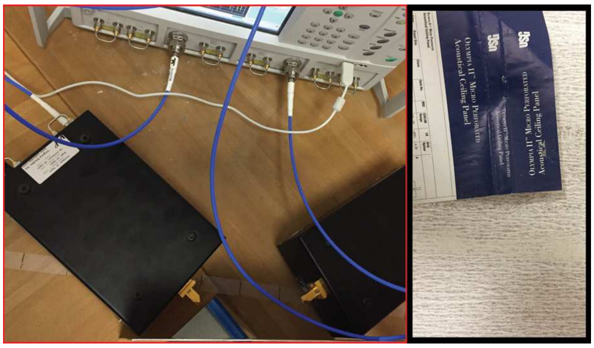


Fig. 8: *Reflections measurement setup.*

object was kept 5 cm, and thus, the total distance our signal travels is 10 cm. Setup for measuring material reflection is shown in Fig. 8. Path loss for signal reflected from an acoustic ceiling panel of 4 mm thickness and wooden ply of 3 mm thickness are shown in Fig. 9(a) and 9(c), respectively. Ceiling panels are often used in indoors and its transfer function depicts that the panel can be used to establish NLOS link in case when LOS link is blocked. However, signal reflected from wood was very weak and thus wood can't be considered a good candidate for NLOS links. Phase measurement for both configurations is shown in Fig. 9(b) and 9(d) to confirm that it delays linearly in case of reflected signal as well.

Channel capacity for LOS and NLOS channels are compared in Table III. Huge decrease in capacity can be seen in NLOS links. For instance, if angle of arrival is 10 degrees, the capacity of the system falls by 30%. However, in case of reflection analysis, acoustic ceiling panel shows very promising results. It can be used in establishing NLOS link with decent throughput. These panels are widely installed in offices and hence, if used, can be a very cost effective solution.

Further case study on this topic can include multiple-input multiple-output (MIMO) antenna technique. MIMO is a very popular technique that can enhance the capacity of a wireless link by introducing multiplexing gain. The basic idea is to use multiple transmit and receive antennas to exploit the multipath behavior of the channel. Although the results show that the THz band channel has very weak multipath components, but

TABLE III: Capacity comparison for measured scenarios

Link	Distance	Obstruction	Angle of arrival (degrees)	Capacity (b/s/Hz)
LOS	10 cm	-	-	9.26
	35 cm	-	-	7.26
	95 cm	-	-	5.713
NLOS	35 cm	-	5	7.03
	35 cm	-	10	6.44
	35 cm	-	30	3.23
	35 cm	Fiber mat	-	6.732
	10 cm	Ceiling panel	90	6.719

as long as reflectors like metal or even ceiling panel exits in the path, MIMO systems in THz band can be implemented. Our setup can be easily modified to implement virtual antenna arrays to observe MIMO characteristics of the channel as shown in [19].

IV. Conclusion

We have presented Terahertz Band channel characteristics using Vector Network Analyzer and subharmonic mixers based measurement system. Channel impulse response from 260 GHz to 400 GHz are recorded and presented. System capabilities and parameters are investigated in detail. We have measured simple transmission coefficient for LOS link to analyze basic capabilities and practical success of THz Band communication system. Measured results show that Tbps throughput is achievable in THz Band. It has become evident that THz Band will enable a plethora of applications such as high speed mobile communications, wireless local area networks or interconnection of gadgets on desktop like HDMI and flash memory. Results for LOS measurements confirm that high gain antennas are necessary to mitigate the path losses at THz frequencies. In addition, the experimental setup demonstrated in this work is a significant example that can boost studies on 5G indoor wireless communication.

We have also presented NLOS channel measurements with antenna misalignment, shadowing and reflections. Moreover, we have shown the reduction in capacity due to antenna misalignment that suggests that robust beam forming algorithms are required in THz Band communication. Absorption coefficient for different materials were also demonstrated. Finally, we have shown that acoustic ceiling panel acts as a good reflector at THz Band and can be used as low cost component to develop NLOS links.

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