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T-RIS and R-RIS Experimental Characterization in the Sub-THz Band

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Abstract—sub-terahertz (sub-THz) communications is expected to be a key element for future wireless communications enabling extremely high data transmission rate. Its performance can be further emphasized by the use of reconfigurable intelligent surface (RIS), which provides the beamforming possibility of electromagnetic (EM) waves in a desired direction. The channel measurement is a fundamental element in understanding the characteristics of the propagation channel. To emulate a system composed of transmissive RIS (T-RIS) and reflective RIS (R-RIS), an electrically large transmit-array and reflect-array were designed. The paper presents the results of the single directional channel measurement of the sub-THz channel composing a concatenation of non-reconfigurable T-RIS and R-RIS. The results presented in this paper demonstrate the feasibility and scalability of establishing a sub-THz link by concatenating multiple RIS units for future applications.

Index Terms—RIS, measurements, VNA, channel sounding, THz communication.

I. INTRODUCTION

In recent years, the importance of sub-THz communication has been notably emphasized as a key element for enabling seamless future wireless communications, targeting the availability of extremely high data transmission rates for prospective future wireless communications, commonly referred to as 6G [1]. Consequently, the fundamental research on the sub-THz propagation channel has been continuously conducted ranging from mathematical discussions [2] to direct measurements of the actual propagation channels [3]–[5].

Indeed, the recent focus of the sub-THz communications paradigm has gradually shifted from just exploiting its inherent propagation characteristics to more actively intervening in the wave propagation to control them in a desired manner through the use of reconfigurable intelligent surface (RIS) [6].

Basically, a RIS refers to an umbrella term describing surfaces that consist of many discrete elements with programmable properties [7]. By tuning each discrete element individually, the propagation characteristics of incoming EM waves can be actively modified in a desired manner. Particularly, the most remarkable feature is the ability to control the direction of the EM wave toward the desired direction enabling the coverage extension of wireless communications network by a strategic employment of RIS. In line with this, the preliminary study on experimental characterization of sub-THz

channel using a single RIS has been conducted through channel measurement at the sub-THz frequency spectrum of 300 GHz [8].

Going beyond the use of a single RIS to overcome line-of-sight (LoS) blockage, it will not be a far-fetched idea to construct communication links supported by multiple concatenations of RIS units to leverage a more seamless and more robust mobile access experience.

To comprehensively understand the characteristics of the propagation channel established by multiple RISs, the propagation channel at 300 GHz has been measured through the Vector Network Analyzer (VNA) in an anechoic chamber and the channel sounder in an indoor environment. Thereby, non-reconfigurable T-RIS and R-RIS were employed to emulate a specific beamforming state. This approach provides two advantages: 1) it allows implementation of large metasurface, which is not yet feasible due to the current reconfigurable technologies and 2) it serves to establish an upper bound for RIS performance, given the fact of additional inevitable loss due to the introduction of reconfigurable elements.

The main focus of the paper lies in the initial assessment of the experimental characterization of channel measurement with the concatenation of both T-RIS and R-RIS. The remaining part of the paper is organized as follows: the T-RIS and R-RIS used for channel measurement are specified in Section II. Section III describes the RIS measurement in an anechoic chamber. Section IV describes the channel measurement setup in an indoor environment. The corresponding results are discussed in Section V. Finally, a brief conclusion and future work are followed in Section VI.

II. RIS SPECIFICATION

The RISs used for measurements were designed and manufactured as passive surfaces to demonstrate a single solid beamforming state without the reconfigurability of individual unit cells. The information regarding each T-RIS and R-RIS will be provided in the following sections in detail.

A. T-RIS

The linearly-polarized T-RIS based on a 3-bit anisotropic unit cell in Fig. 1 was designed by CEA Leti [9] to generate a fixed high-gain beam at broadside, i.e. peak realized gain

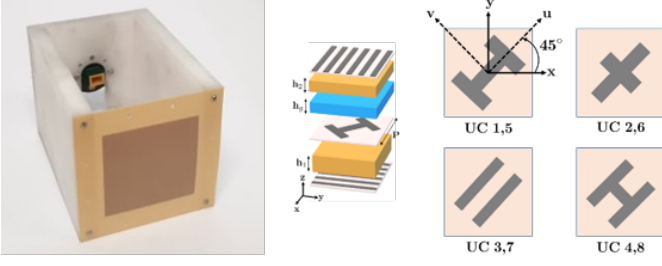


Fig. 1: Photo of T-RIS prototype and the schematic view of the 3-bit anisotropic unit cell [9].

of 37 dBi in the frequency range 240-330 GHz. A T-RIS is composed of a flat lens array consisting of 60×60 elements illuminated in the Fresnel-near-field region by a specific focal source. The unit cells of the flat lens impose a transmission phase modulation on the aperture, allowing for a controlled phase shift of the incoming electromagnetic EM wave.

The unit cell structure consists of three metal layers, separated by two dielectric spacers and a bonding film. Two orthogonal linear polarizers are placed on the outer surfaces, enabling nearly pure x-polarized waves to pass through the bottom side and y-polarized waves to pass through the top side. The inner layer, known as the rotator, is responsible for polarization conversion and phase control. The geometry of the rotator can be adjusted to tune the transmitted phase without significantly affecting the 90-degree polarization rotation or insertion loss.

Due to the frequency-dependent spatial phase delay, in the case of phase modulated T-RIS, one of the main drawbacks for large aperture designs is the trade-off between bandwidth and aperture efficiency. In this case, a wideband gain frequency response is achieved by illuminating the T-RIS with a 20 dBi horn pyramidal antenna located at a distance of 55 mm. An aperture efficiency of 47.2% has been demonstrated experimentally. Furthermore, the measured 1-dB gain bandwidth is approximately 56 GHz, from 264 to 320 GHz, which is approximately 19.0% of fractional bandwidth. In both principal planes, the half power beam width (HPBW) is approximately 2° in the 1-dB gain bandwidth.

B. R-RIS

Single-layer patch-based unit cells have been designed to achieve a passive R-RIS. The substrate is the dielectric Astra MT77 with a standard thickness of 0.75mm ensuring a sufficient mechanical strength of the surface. The remaining design freedom relies on the patterns of the top layer that will provide the required discrete set of phase states: 1) a squared metallic patch with size and 2) an outer metallic ring with thickness (see inset of Fig. 2).

At these frequencies, small fabrication imprecisions can significantly affect the unit cell response. For the presented design, a variation of $20\mu\text{m}$ can result in a phase variation up to 25° . Considering $20\mu\text{m}$ as the precision limit, a set of 6 unit cells can be modeled that provide a phase step close to 70° (similar to a 3bit phase quantization step). Using the

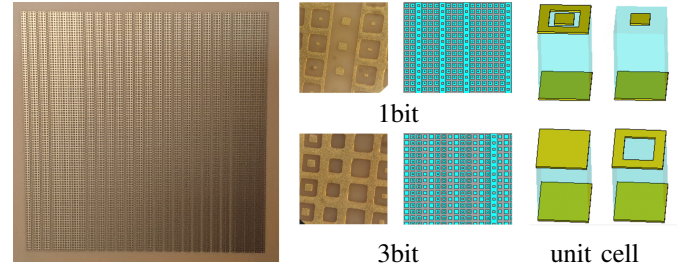


Fig. 2: Photo of R-RIS and the unit cell pattern of 1bit and 3bit RIS

set or sub-set of these unit cells, a total of three R-RIS, with different quantization steps (1,2 and 3bit) were manufactured. In all designs, the R-RIS will convert a normal plane into a tilted reflected wave at 30° .

III. T-RIS AND R-RIS MEASUREMENTS IN ANECHOIC CHAMBER

To precisely characterize each of T-RIS and R-RIS, the measurements were conducted using VNA in an anechoic chamber. This enables the suppression of any other external interference leading to highly accurate and repeatable measurements under the regulated and controlled environment.

A. Measurement Setup

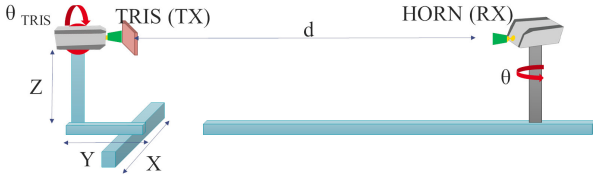
A specific setup was realized in anechoic chambers based on VNA and remote heads for up and down conversion to sub-THz. The measured band spans from 240 GHz to 320 GHz by step of 20 MHz. The Intermediate Frequency (IF) bandwidth is set at 1 MHz and the output power at -18 dB. On the transmitting side, a 20 dBi horn antenna is illuminating the T-RIS at the optimized focal distance. The T-RIS antenna is placed on a four-axis positioner (x - y - z - θ_{TRIS}) allowing a precision of 0.01 mm displacement and 0.1° in angle. On the receiving side, a 2-axis (d - θ) positioner with the same precision is employed. Two different setups have been implemented:

- *Setup 1* - on the receiving side a 20 dBi horn antenna is employed. The displacement is performed over d and θ_{TRIS} in order to measure the T-RIS gain pattern and the attenuation along distance (Fig. 3);
- *Setup 2* - on the receiving side a 20 dBi horn antenna is pointing the R-RIS placed at the 20 cm. The receiving horn antenna rotates along θ to measure the different orientation angles (Fig. 6).

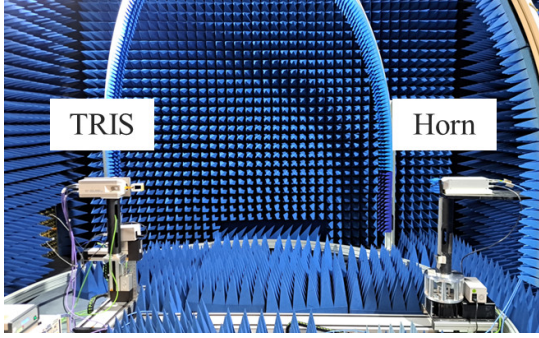
B. Measurement Results of T-RIS

In the first setup (*Setup 1*), the horn antenna was displaced along d . It is worth to notice that the measurement of T-RIS gain was not available in the far field condition due to the dimension of the anechoic chamber. The overall channel gain, i.e. including both TRIS and receiving horn factor, is presented in Fig. 4. Despite being below the Fraunhofer distance of the T-RIS, the attenuation is close to the theoretical one in the far

field. The discrepancy at the highest distance can be further justified by some misalignment that can be compensated.



(a) Setup



(b) Photo

Fig. 3: Measurement of *Setup 1* in anechoic chamber.

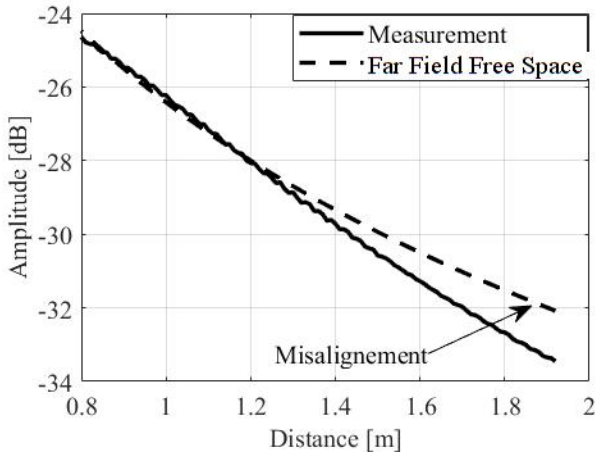


Fig. 4: Free space LoS measurement of T-RIS.

As a further verification of the T-RIS performance, the gain pattern is measured by moving θ_{TRIS} in (Fig. 3). The results for 280 GHz (i.e. the optimized one for the TRIS) and 304 GHz (i.e. the optimized one for the RRIS) are shown in Fig. 5. The maximum gain at this distance is estimated at 35.2 dBi.

C. Measurement Results of T-RIS and R-RIS

The objective of *Setup 2* is to evaluate the channel with the concatenation of T-RIS and R-RIS and to predict the expected outcome with greater precision in advance before conducting the indoor measurement scenarios.

In practice, the R-RIS is placed at 1.92 m apart from the T-RIS. As shown above, the R-RIS is in a quasi-far field zone where the T-RIS beam is formed. On the other hand,

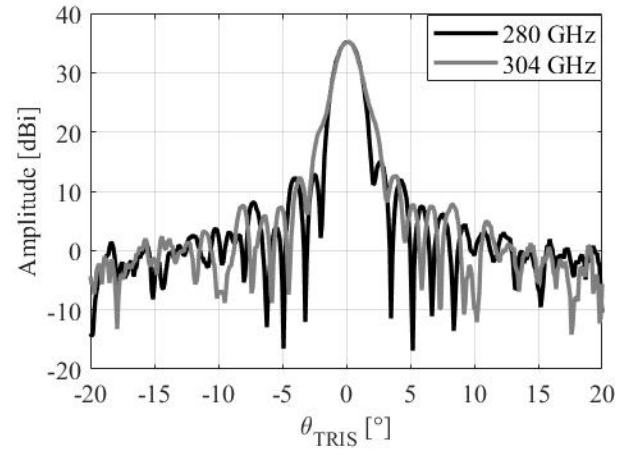
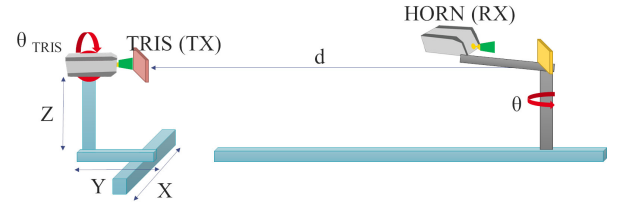


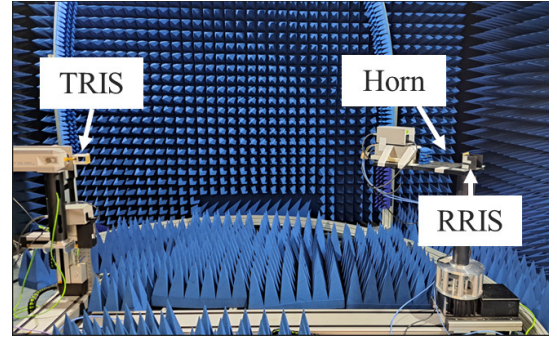
Fig. 5: Radiation pattern of T-RIS.

the receiving horn antenna is placed in the near field of the R-RIS at a distance of 20 cm apart from the R-RIS.

The normalized gain patterns for the 1-bit, 2-bit, and 3-bit are shown in Fig. 7. The results prove that the maximum gain by the R-RIS is obtained close to 30° and the phase quantization allows to reduce the side lobes.



(a) Setup



(b) Photo

Fig. 6: Measurement of *Setup 2* in anechoic chamber.

In Tab. I, the measured results were compared with those extrapolated from full-wave simulation in CST. In terms of Side Lobe Level (SLL) and overall channel gain, it was possible to observe a very good agreement for the three R-RIS with expectations. In particular, for the 3bit case, the discrepancy between the simulation and the measurement result was less than 1 dB, while a larger dispersion is found on the 2-bit.

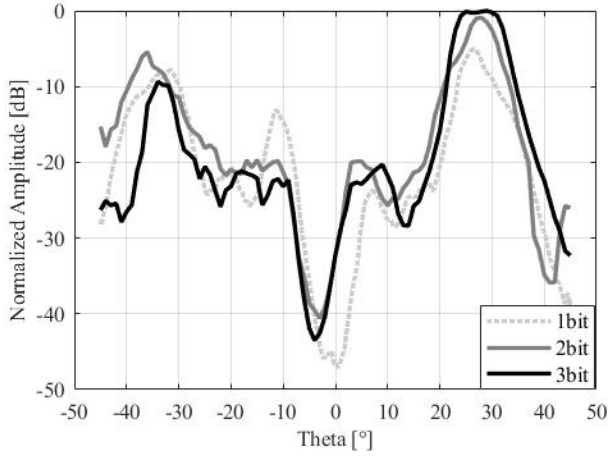


Fig. 7: Normalized measurement results of channel concatenated by T-RIS and R-RIS as a function of angle dependency.

TABLE I: R-RIS SLL and Channel Gain of Concatenation of T-RIS and R-RIS

RRIS	SLL [dB]		Channel Gain [dB]	
	Sim.	Meas.	Sim.	Meas.
1 bit	-1.8	-2.8	-36.47	-34.5
2 bit	-5.6	-4.4	-29.3	-33.5
3 bit	-7.2	-9	-31.3	-31.7

IV. CHANNEL MEASUREMENT ENVIRONMENTS

To characterize the sub-THz propagation channel through the use of multiple RISs, the measurements were conducted in an empty lecture room using the channel sounder, which is less regulated and controlled conditions, yet closer to realistic environments.

A. Measurement Equipment

For the measurements, The channel sounder operating at 300 GHz [10] was used to measure the channel impulse response (CIR) in the time domain by employing the correlated ultra wide band (UWB) pseudo-random signal. The channel sounder operates with the parameters detailed given in Table II.

TABLE II: Parameters of the channel sounder.

Parameter	Value
Center frequency	304.2 GHz
Clock frequency	9.22 GHz
Bandwidth	8 GHz
Chip duration	108.5 ps
Sequence length	4095
Sampling factor	128
Measurement rate	17,590 CIR/s

B. Measurement Scenario

A photo of the measurement setup in a profile view is presented in Fig. 8. Here, transmitter (Tx) was positioned perpendicular to the R-RIS, while receiver (Rx) was positioned to $+30^\circ$ and -30° with respect to R-RIS to achieve the radar cross section (RCS) of the designed angle and the opposite angle. Thereby, the measurements were completed by varying

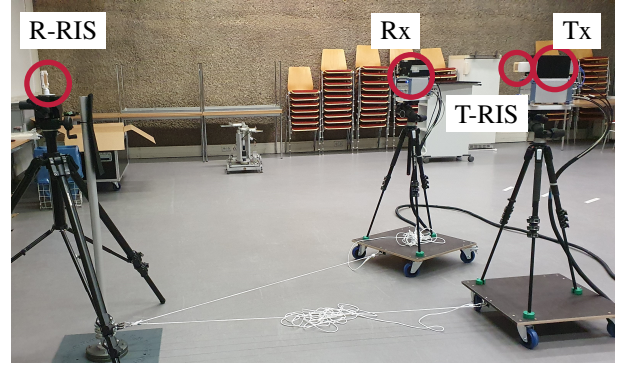


Fig. 8: Photo of the measurement setup illustrating the concatenated channel of Tx, T-RIS, R-RIS, and Rx.

the distance between R-RIS and Rx from 2.15 m to 6.5 m, while the distance between T-RIS and R-RIS is fixed as 2.15 m.

V. INDOOR CHANNEL MEASUREMENTS

The measurement results are evaluated in terms of path gain, which has been obtained by post-processing to exclude the impact of the antenna radiation pattern to focus solely on the propagation channel including RCS of RIS.

First of all, Fig. 9 visualizes the measurement results for various configurations solely using R-RIS. Here, each graph shows the measurement results of path loss normalized by the 3bit R-RIS measurement at 30° with the shortest measurement distance, which demonstrates the highest RCS value among all. In the case of 1bit R-RIS, the measurement values for $+30^\circ$ and -30° showed mostly the same value across all distances comparing square and round solid lines, as it is expected to show the behavior due to a symmetrical RCS. In addition, for 3bit R-RIS cases, approximately 15 dB of differences, yet it fluctuates from 9.3 dB to 16.8 dB, was observed between the target angle and the opposite angle ($+30^\circ$ and -30°). This value aligns with the 15 dB of the predicted difference between $+30^\circ$ and -30° considering a more focused beamforming efficiency of 3bit R-RIS at the target angle.

In addition, the fluctuation of the normalized path loss was observed for the case of 3bit at 30° in Fig. 9. This can be contributed by the imperfect alignment between RIS and Rx. This misalignment causes changes in the RCS value, which is optimized for the angle at $+30^\circ$. Consequently, this results in fluctuating path loss rather than consistently increasing values as a function of distance.

Furthermore, using T-RIS in Fig. 10, similar results to those in Fig. 9, yet more consistent with the expectation, were observed. The measurement values of 1bit R-RIS for $+30^\circ$ and -30° showed nearly identical values, except at 5.5 m, yet slightly reduced RCS value than simulation. This discrepancy can be attributed to the inherent challenges associated with aligning T-RIS, particularly when considering 2° of HPBW. In the case of 3bit R-RIS, approximately 15 dB of constant differences was observed between the target angle and the

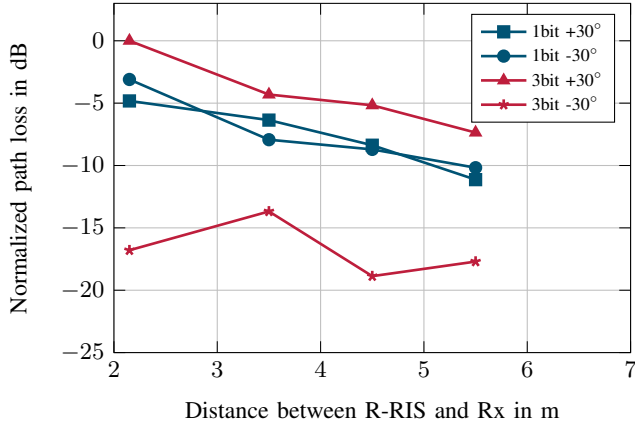


Fig. 9: Normalized measurements results for various configurations: types of R-RIS (1bit and 3bit), anomalous reflection angles (+30° and -30°), without using T-RIS

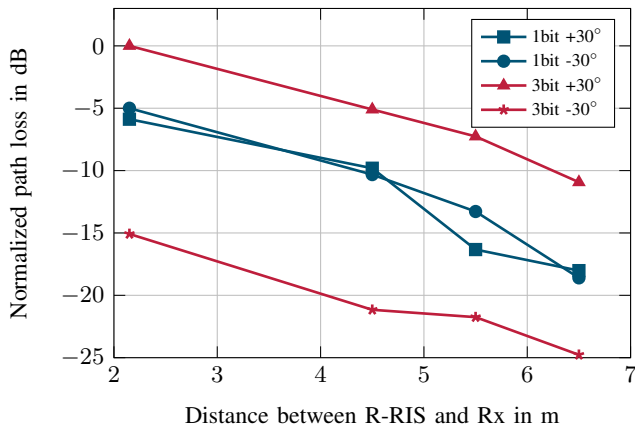


Fig. 10: Normalized measurements results for various configurations: types of R-RIS (1bit and 3bit), anomalous reflection angles (+30° and -30°), with using T-RIS

opposite angle (+30° and -30°). Thereby, less impactful fluctuation in the range between 13.9 and 16 dB was observed.

In any case, even under less regulated and controlled conditions, the indoor measurement results exhibited a strong similarity to the simulation results and the results in an anechoic chamber demonstrating the feasibility of sub-THz communication supported by the concatenation of RISs.

VI. CONCLUSION

This paper presents the measurement results of the propagation channel concatenated by T-RIS and R-RIS at 300 GHz. The measurements were conducted in an anechoic chamber with a VNA and an indoor environment with a channel sounder to cover a range of various measurement environments from a more regulated and controlled condition to a more realistic environment. Regardless of the measurement environments, the measurement results in both the anechoic chamber and the indoor environment exhibit a strong agreement with the expected values for the angular behaviors of the different types

of R-RIS, as shown by the RCS values of R-RIS through the full-wave simulation. The measurement results proved that sub-THz links can be established through the sequential concatenation of the multiple RISs and their performance can be predicted by using a straightforward bistatic radar model. Nevertheless, given the narrow HPBW of both T-RIS and R-RIS, achieving perfect alignment was challenging in a realistic measurement environment. Even a slight misalignment introduced significant deviations in channel gain, which ultimately may result in an insufficient data rate requirement for future sub-THz communications. This fact underscores the importance of introducing reconfigurability into THz communications to ensure optimal channel quality. The future work includes the measurement campaign using fully operating RISs to analyze their beamforming performance and to investigate the potential for coverage extension.

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