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Channel Measurements Involving Passive RIS at 300 GHz

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Abstract—The ever growing demand for data rates motivates the exploration of the low terahertz (THz) frequency bands for mobile communications due to the large available bandwidths. To mitigate the reliance on line-of-sight (LOS), the concept of reflective intelligent surfaces (RIS) has emerged as a promising technology. By reshaping the electromagnetic environment, RIS modifies the channel, necessitating new approaches to model key parameters such as the path gain. This paper proposes the bistatic radar equation as a simple yet accurate model to predict the path gain of a link that includes a RIS, even below the Fraunhofer distance. Channel measurements at 300 GHz, incorporating a passive RIS, support the validity of this approach.

Index Terms—Terahertz (THz), path gain, reflective intelligent surface (RIS), near field, far field, measurements.

I. INTRODUCTION

The continuous demand of increased data transmission rates necessitates the advance to higher frequencies, such as the low terahertz (THz) region from 0.1 THz to 1 THz. With the large available bandwidth in this range, peak data rates in the terabits per second are expected to be achievable [1]. However, mobile communication at these frequency bands faces several challenges. For instance, signals experience significant attenuation upon wave propagation, which is typically mitigated by employing highly directional antenna structures [1]. Additionally, the absence of a line-of-sight (LOS) path between the transmitter (TX) and receiver (RX) at low THz frequencies can severely impact the communication link [1]. A promising technology that not only addresses this LOS dependency but also holds significant potential to enhance overall network performance and efficiency is RIS [2].

Consisting of numerous subwavelength tunable unit cells, a reflective intelligent surface (RIS) can control the phases of impinging electromagnetic waves that are to be reflected. This allows for the customization of the electromagnetic environment, e.g. via anomalous reflections [2]. For the effective implementation of RIS in a scenario, models predicting channel parameters such as the path gain are inevitable. The prediction of the path gain poses an obstacle as not a conventional link but a cascaded TX-RIS-RX link is present with participants possibly being in the near field of the RIS.

Many approaches to model the path gain for a RIS link, even below the Fraunhofer distance, exist in the literature. Observed drawbacks include high complexity of the models and missing verification by means of measurements, particularly in the low THz frequency range. For instance, models in [3]

and [4], which show good agreement with measurements in the millimeter-wave (mmWave) band, account for every individual unit cell, generating the need for detailed information for every unit cell such as power radiation pattern and reflection coefficients. In [5] a path gain model is derived using the vector generalization of Green's theorem, but not confirmed through measurements. Neither is [6], where a macroscopic, ray-based approach is proposed for efficient simulation.

This paper provides a validation of the radar equation as a simple yet sufficiently accurate path gain model for a link between the TX, a passive RIS, and the RX. This will be done by means of channel measurements at 300 GHz. In order to delineate the regions, where this approach is viable, measurements are conducted in the far field as well as in the near field of the RIS. Moreover, the impact of misalignments will be examined, i.e. when the RX is not in the main lobe of the RIS. In section II the used path gain model is introduced. Section III briefly describes the measurement equipment and scenario, while the measurement results are presented in section IV. Lastly, a conclusion is given in section V.

II. USED PATH GAIN MODEL

The bistatic radar range equation, often referred to simply as the radar equation, for polarization-matched and ideally aligned antennas with respect to the scatterer, is given by [7]:

$$P_{RX} = P_{TX} \cdot \sigma \cdot \frac{G_{TX}G_{RX}}{4\pi} \cdot \left(\frac{\lambda}{4\pi d_{TX,RIS}d_{RIS,RX}} \right)^2. \quad (1)$$

It describes the received power P_{RX} at the RX with receiving antenna gain G_{RX} , originating from a scatterer with the radar cross section (RCS) σ , such as a RIS, that is located at a distance $d_{RIS,RX}$. The TX radiates with the transmitting power P_{TX} and transmitting antenna gain G_{TX} towards the scatterer at a distance $d_{TX,RIS}$. The wavelength is denoted as λ . The RCS has to be known either through simulations or measurements. The path gain G in dB can be extracted from (1) by omitting the power terms and antenna gains. Unless otherwise stated, gains will be expressed in dB from here on.

$$G = 10 \log(\sigma) + 10 \log \left(\frac{1}{(4\pi)^3} \left(\frac{\lambda}{d_{TX,RIS}d_{RIS,RX}} \right)^2 \right) \quad (2)$$

Henceforth, the path gain according to the radar equation refers to (2). The term bistatic refers to the different positions of TX and RX. Both the RCS and the Friis transmission equation,

which plays a key role in deriving the radar equation (1), are traditionally valid for the far field. The Fraunhofer distance serves as the conventional border between near and far field [7]:

$$d_{\text{Fraunhofer}} = \frac{2D^2}{\lambda}. \quad (3)$$

Small wavelengths combined with large geometric dimensions D of the RIS relative to the wavelength result in large values of the Fraunhofer distance, i.e. in a substantial near field region. Nevertheless, the path gain predicted by the radar equation (2) has been shown to be consistent with measurements even below the Fraunhofer distance [8]. This may be explained by the physically smooth transition between far field and near field contrary to the hard cut suggested by the Fraunhofer distance. Furthermore, the phase criterion in the definition of the Fraunhofer distance is both arbitrary and strict. In [9] it is demonstrated that RIS using conventional beam forming still function well below the Fraunhofer distance.

III. MEASUREMENT SETUP

This section comprises two parts, covering the used measurement equipment concisely before the examined scenarios will be described. The latter includes the ranges of varying parameters and the applied alignment procedure.

A. Measurement Equipment

The goal of the measurements is to obtain path gain values. For this, a correlation-based sub-mmWave channel sounder is used to measure the channel impulse response. The amplitude values are determined with an error tolerance of ± 1.8 dB [10]. During post processing, the path gain is extracted from the height of the correct peak, which can be identified by the delay. The used antennas are horizontally polarized, have a half-power beam width of 8.5° and a gain of 26.4 dBi. At the start and end of each measurement day, calibration measurements were conducted. These include back-to-back and LOS reference measurements. The channel sounder employs an ultra-wideband signal with 8 GHz bandwidth, ranging from 5.2 GHz to 13.2 GHz. This signal is upconverted to 304.2 GHz with frequency extenders. The clock frequency is 9.22 GHz. A filter limits the bandwidth to 4 GHz during post processing due to IQ imbalances. Further details can be found in [10].

The measured RIS is a 3 bit passive RIS designed for 304 GHz. 3 bit means that every unit cell can adjust the phase with a resolution of $360^\circ/2^3 = 45^\circ$ in theory. Practically, 60° phase shifts are possible due to limited fabrication precision. The 5 cm by 5 cm RIS consists of 100 by 100 unit cells, arranged with a $\lambda/2$ spacing, λ being the wavelength of the design frequency, i.e. 304 GHz. With the RIS diagonal $D \approx \sqrt{2} \cdot 5$ cm, the Fraunhofer distance (3) is approximately 10 m. Passive refers to the fixed state of the unit cells such that no reconfiguration is possible. The selected state reflects a boresight incident beam with an angle of 30° in the far field. For these directions and at 304 GHz, the simulated bistatic RCS is 16.7 dBsm and the reflected beam has a half-power beam width of 1.2° . Naturally, the RIS is object to the beam

squint effect [11]. The RCS is reduced to 14.4 dBsm and 12.4 dBsm at 300 GHz and 310 GHz, respectively.

B. Measurement Layout

A schematic overview of the measurement scenario is shown in Fig. 1. The Fraunhofer distance of the horn antennas used both at TX and RX is 12.5 cm. The distance between TX and RIS, denoted as $d_{\text{TX,RIS}}$, is 2.15 m, placing the RIS in the far field of the TX antenna. The RIS is illuminated perpendicularly by the TX. From the surface normal, the angle α denotes the direction in which the RX is positioned. Given perpendicular incidence at 304 GHz, the RIS has a main lobe at $\alpha = 30^\circ$. Thus, the RX is positioned at this angle for measurements with ideal alignment. To examine the path gain under misalignment conditions, the angle will be reduced by 2° and 4° for respective measurements.

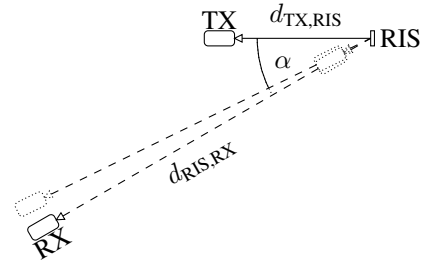


Fig. 1. Measurement scenario overview. TX illuminates RIS perpendicularly. RX is in main lobe of RIS or slightly misaligned at varying distances.

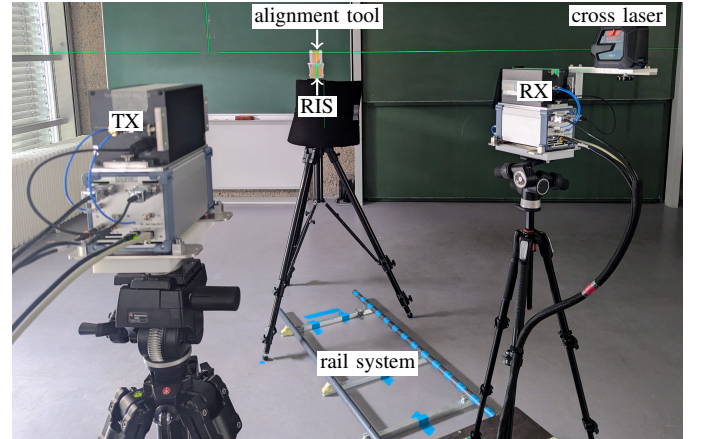


Fig. 2. Photo of TX, RIS and RX. The cross laser and the alignment tool help during the alignment process.

The distance between RIS and RX, denoted as $d_{\text{RIS,RX}}$, spans a wide range, with a higher resolution closer to the RIS, as for larger distances approaching the Fraunhofer distance, the radar equation for path gain prediction has already been verified [8]. The measured distances are as follows:

$$d_{\text{RIS,RX}} \in \{0.2, 0.3, \dots, 2, 2.15, 2.75, 3.5, 4.5, 5.5, 7.5, 10, 11\} \text{ m}. \quad (4)$$

The repeated execution of measurements at numerous distances was only possible due to the rail system on which the RX was mounted. This can be seen in Fig. 2 and allowed varying the distance between RIS and RX without having to repeat the cumbersome alignment process.

IV. MEASUREMENT RESULTS

Six series of measurement data with an ideal alignment of TX, RIS and RX, i.e. the TX illuminating the RIS perpendicularly and the RX being in the main lobe of the RIS at 30° , were recorded in total. To ensure credibility, each of these measurements was conducted at different points in time, with separate alignment processes and calibration measurements. The path gains resulting from these measurements, along with the path gain predicted by (2), are presented in Fig. 3. Two main observations can be made. Firstly, a high qualitative similarity between predicted and measured path gains can be seen as long as the distance between RIS and RX is not too small. Secondly, an almost constant offset between expected and measured path gains is present.

From the Fraunhofer distance onwards, the predictions and measurements should theoretically agree. To enforce this, the measurement curve with the highest path gains, i.e. measurement 4, is considered. With the Fraunhofer distance being 10 m, the differences between the measurements and the expected path gain values at 10 m and 11 m are averaged, resulting in 6.01 dB. Regardless of the origin of this difference, which will later be classified as a systematic error, the curve belonging to measurement 4 is shifted upwards by this value and shown in Fig. 3 as well. The very high agreement of prediction and measurement, from 1 m onwards, then becomes easily recognizable. If all measurements are shifted upward by 6.01 dB, the average difference between them and the expectation is below 3 dB for distances greater than or equal to 0.9 m. The minimum distance between RIS and RX yielding an agreement with an average deviation smaller than 3 dB, is 0.9 m. This corresponds to approximately one-tenth of the Fraunhofer distance and roughly 13 times the RIS diagonal.

Below this distance, the qualitative trend indicates an overestimation of the path gain by the bistatic radar equation. This aligns with [12], where a lower path loss exponent closer to the RIS is derived.

A similar offset of 4 dB to 6 dB between expectation and measurements was observed in a previous measurement campaign, where it was justified with measurement inaccuracies and misalignments [8]. Despite the more sophisticated alignment process here, misalignments certainly cannot be ruled out. This is because the alignment process still is done manually at the beginning of each measurement, creating a possibility for errors. Therefore, a part of the offset is expected to be due to misalignments. The normalized scattering gain of the RIS for different angles and distances, given perpendicular incidence, displayed in Fig. 4 shows, that a 1° misalignment can result in a 10 dB loss at 304 GHz, confirming that even small misalignments may be responsible for the observed path gain discrepancies. Seeing that the 6.01 dB offset corresponds to the measurement series with the highest measured path gain and six series were conducted in total, misalignment is a particularly suitable explanation for the variation between the measurements themselves. The previously mentioned beam-squint effect plays a role as well. For example, perfect alignment of 30° at 304 GHz will cause a slight misalignment at the upper and lower border of the bandwidth, which will have an influence on the measured path gain. Therefore, a part of the shift is inevitable. Another possible cause for at least part of the offset is a mismatch between the RCS values of the fabricated RIS and the simulation. This could be due to differences in the material parameters as well as slight deviations in production. This possibility is currently object of further investigations. Of course the measurement inaccuracy of ± 1.8 dB of the channel sounder accounts for part of the discrepancies as well. For distances greater than 20 cm the difference between the highest and lowest measured value across all measurement is under 7.1 dB. This order of magnitude can be easily explained by the combination of misalignments and measurement inaccuracies already mentioned, thus indicating

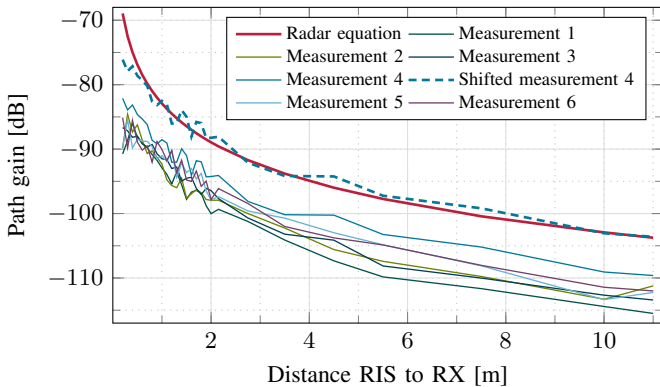


Fig. 3. Measured path gains for TX-RIS-RX link over distance between RIS and RX for the six measurements, measurement 4 shifted by 6.01 dB, and path gain predicted by (2).

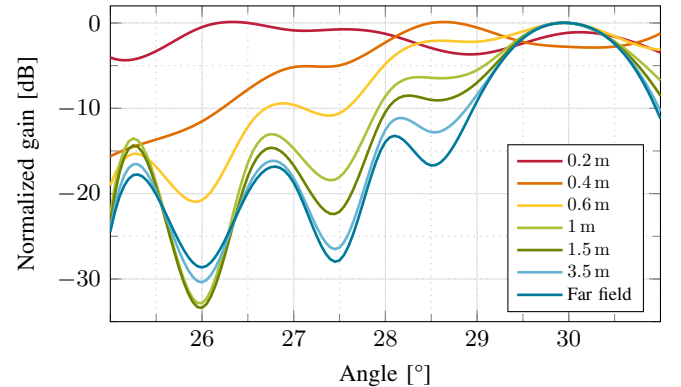


Fig. 4. Simulated normalized scattering pattern G_{pat} of RIS at 304 GHz given perpendicular incidence at some distances. Provided by the Institute of Telecommunications, University of Lisbon.

good reproducibility and credible results.

The high qualitative agreement overall, together with the high quantitative agreement after the correction of the systematic error, between prediction and measurement confirms the suitability of the bistatic radar equation for predicting the path gain of a TX-RIS-RX link even in most of the near field of the RIS. Precise alignment is both mandatory and challenging.

In addition to the case of ideal alignment, the path gain for 2° and 4° misalignments between RIS and RX was examined over varying distances between RIS and RX. Theoretically, these correspond to angles of $\alpha = 28^\circ$ and $\alpha = 26^\circ$. The measured path gains along with the path gain predicted by (2) can be seen in Fig. 5. The path gain belonging to the ideal alignment behaves as previously discussed, displaying an offset. For the misalignment cases, the path gains at 0.2 m start just below the ideal case. After this point the path gains drop rapidly by 20 dB within the next 80 cm for the 2° misalignment, and within 20 cm for the 4° misalignment. For the remaining distances both curves follow a similar progression to the ideal alignment curve, albeit with a gradually increasing gap relative to the ideal case.

The difference of the measured path gains $\Delta G_{\text{meas}, 2^\circ \text{misalign}}$ and $\Delta G_{\text{meas}, 4^\circ \text{misalign}}$, between ideal alignment and the 2° as well as 4° misalignments, respectively, are shown in Fig. 6. These differences do not match the expected values based on the normalized scattering gain patterns G_{pat} , shown in Fig. 4. This can be seen, since the normalized gain at 30° is 0 dB from 0.6 m onwards, so that the differences of the measured path gains should correspond to the normalized gain at the respective angles. For 28° and 26° in the far field this would be approximately -15 dB and -28 dB. However, this particularly contradicts the behaviour of $\Delta G_{\text{meas}, 4^\circ \text{misalign}}$, which is barely 15 dB below the ideal curve, resulting in a 13 dB gap. To demonstrate that the measurements do match the simulated patterns to some extent and to support the suspicion that misalignments, i.e. a mismatch between assumed and actual orientations, are an issue, the following approach is taken.

The angle α_{real} corresponds to the actual angle of the

supposedly ideal alignment and is presumed to be between 29° and 31° . By subtracting the pattern gain values $G_{\text{pat}, \alpha_{\text{real}}}$ at this angle from the pattern gain values at all angles, for all distances, the adjusted gain patterns $G_{\text{pat}, \text{adj}, \alpha_{\text{real}}}$ are obtained:

$$G_{\text{pat}, \text{adj}, \alpha_{\text{real}}} = G_{\text{pat}} - G_{\text{pat}, \alpha_{\text{real}}} \quad (5)$$

Given the assumed angle α_{real} , the adjusted gain patterns $G_{\text{pat}, \text{adj}, \alpha_{\text{real}}}$ describe the expected difference between the path gain in direction α_{real} and the path gain in any other direction. For a given angle α_{real} and another direction β , the expected difference in gain is denoted as $\Delta G_{\text{pat}, \alpha_{\text{real}} - \beta}$. Similar to the assumed ideal angle α_{real} , the possible angles $\alpha_{\text{real}, 2^\circ}$ and $\alpha_{\text{real}, 4^\circ}$ for the 2° and 4° mismatch range from 25° to 27° and 27° to 29° , respectively. The angular resolution is 0.05° .

The objective is to find the angular combination within these ranges yielding expected differences $\Delta G_{\text{pat}, \alpha_{\text{real}} - \beta}$ that best match the measured differences $\Delta G_{\text{meas}, 2^\circ \text{misalign}}$ and $\Delta G_{\text{meas}, 4^\circ \text{misalign}}$. Additionally, the difference between the ideally aligned measurement and the path gain predicted by (2), denoted as $\Delta G_{\text{meas}, \alpha_{\text{real}}}$, is considered. One approach to assess the agreement of expectation and measurement over the non-equidistant distance samples is a weighted mean. However, this can result in good scores even with high local deviations, which is an undesired behavior. The chosen metric solves this problem by giving back the highest deviation. The task of finding the best fit then becomes identifying the angles $\alpha^* = (\alpha_{\text{real}}^*, \alpha_{\text{real}, 2^\circ}^*, \alpha_{\text{real}, 4^\circ}^*)^\top$ belonging to the curve with the lowest maximal deviation over the distance $d_{\text{RIS}, \text{RX}}$ between RIS and RX:

$$\alpha^* = \arg \min_{\alpha} \left(\max_{d_{\text{RIS}, \text{RX}}} \left(|\Delta G_{\text{pat}, \alpha_{\text{real}} - \alpha_{\text{real}, 2^\circ}} - \Delta G_{\text{meas}, 2^\circ \text{misalign}}| + |\Delta G_{\text{pat}, \alpha_{\text{real}} - \alpha_{\text{real}, 4^\circ}} - \Delta G_{\text{meas}, 4^\circ \text{misalign}}| + |\Delta G_{\text{meas}, \alpha_{\text{real}}}| \right) \right) \quad (6)$$

This approach of connecting path gain values with angles by means of a gain pattern over an angular domain is taken from [13]. The angles best explaining the measurement values

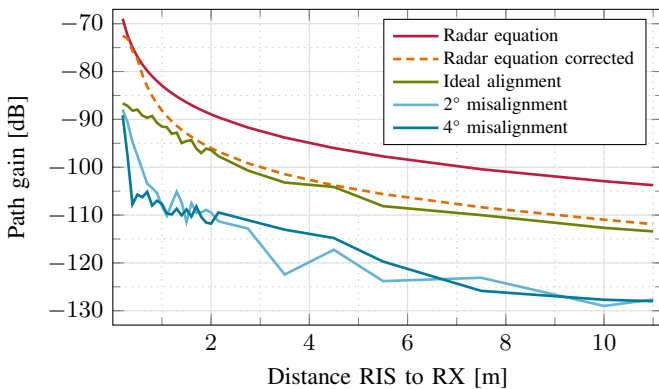


Fig. 5. Measured path gains for TX-RIS-RX link over distance between RIS and RX in case of ideal alignment, 2° and 4° misalignment. Path gain predicted by (2) with/without correction by normalized scattering gain at 29.05° .

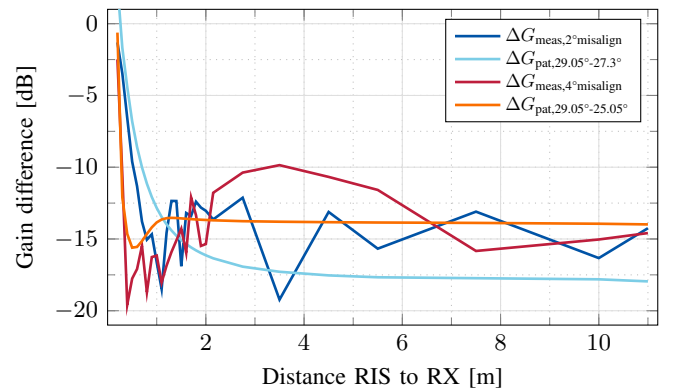


Fig. 6. Measured gain differences $\Delta G_{\text{meas}, 2^\circ \text{misalign}}$ and $\Delta G_{\text{meas}, 4^\circ \text{misalign}}$ between ideal alignment and 2° as well as 4° misalignment, and pattern gain curves best explaining the progressions.

here are $\alpha_{\text{real}}^* = 29.05^\circ$, $\alpha_{\text{real},2^\circ}^* = 27.3^\circ$ and $\alpha_{\text{real},4^\circ}^* = 25.05^\circ$. This implies alignment errors of 0.95° , 0.7° and 0.95° . For 2° and 4° misalignment, the maximum difference between expectation and measurement then is 5.02 dB and 4.92 dB, respectively, which is a significant improvement compared to the previous 13 dB. The associated curves are shown in Fig. 6. The normalized scattering gain at the angle $\alpha_{\text{real}}^* = 29.05^\circ$ in the far field of the supposedly ideally aligned link, lies 8.15 dB below its maximum. At the same time, the average difference between measurements and predictions in the far field is 9.71 dB. In Fig. 5, the orange curve shows the path gain according to the radar equation corrected by the scattering pattern gain for the angle α_{real}^* . This yields a significantly improved match.

The observable qualitative agreement of the curve progressions in combination with the reasonable quantitative agreement lead to the conclusion that misalignments are indeed present. This confirms the earlier suspicion of misalignments being one of the reasons for the constant offsets as well as for the deviations between theoretically identical measurements. Notably, with the theoretically determined angles α^* , basically no offset is present. Since the angles cannot be confirmed, this does not contradict the earlier offset analysis. However, it suggests that misalignments likely are the dominant factor. Another takeaway is the usefulness of (simulated) scattering gain patterns for distances both in near and far field. If the direction and the distance of the RX from the RIS is known, these patterns may be applied to adjust the predicted path gain, similar to how they were used to determine the actual angles here.

V. CONCLUSION

A comprehensive measurement campaign at 300 GHz, examining the path gain of a link between TX, passive RIS and RX, has been conducted. The parameters under investigation included the distance between RIS and RX as well as the angle at which the RX was positioned relative to the RIS.

Based on the measurement results, the bistatic radar equation is deemed a suitable tool for path gain prediction. A strong qualitative agreement of measurement and prediction up to a tenth of the Fraunhofer distance was observed. A constant offset, that was already seen in previous measurements, was present. Despite a meticulous alignment process, this offset most likely originates from misalignments, as confirmed in the second part, and the beam squint effect. Additionally, the possibility of a discrepancy between the simulated and real RCS values of the RIS is currently under investigation. Nonetheless, this does not undermine the suitability of the radar equation for path gain prediction.

Besides the necessary RCS, the normalized scattering gain patterns of the RIS at different distances and angles, given a certain angle of incidence, provide valuable information when confronted with the task of path gain prediction. They can

be used to adjust the path gain depending on distance and direction of the RX relative to the RIS. A more detailed analysis of this topic may be part of future works.

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