Enabling Long-Range Large-Scale Channel Sounding at Sub-THz Bands: Virtual Array and Radio-Over-Fiber Concepts

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***Abstract*—Sub-Terahertz (sub-THz) (i.e., 100-300 GHz) communication is envisaged as one of the key building blocks for future communication systems due to its vast unexploited bandwidth. Knowledge of the radio channel characteristics is key to the design and development of new radio systems and air interfaces. Reliable channel sounding is essential to build accurate and realistic channel models. Virtual antenna array (VAA) has been a popular channel sounding strategy to obtain accurate directional characterization due to its low-cost and simple system implementation. However, this concept has not yet been realized for sub-THz bands in the state-of-the-art works due to difficulty in accurate phase control. The measurement range has been rather limited at sub-THz due to significant signal loss, especially in the radio frequency (RF) cables, compared to microwave or millimeter-wave frequencies. In this paper, we focus on vector network analyzer (VNA)-based channel sounders, highlighting frequency extension with sub-THz frequency extenders, measurement range extension with radio-over-fiber (RoF) schemes, and angular resolution improvement by VAA implementation with phase-compensation scheme. These techniques enable and enhance sub-THz channel characterization. The performance of the proposed long-range phase-compensated sounder is also experimentally demonstrated by the VAA-based channel measurements at 100 GHz in an indoor scenario.**

I. Introduction

RECENT fifth-generation (5G) standards have applied the (mmWave) frequency bands spanning from 24.25 GHz to 52.6 GHz (so-called frequency range 2). Sub-terahertz (sub-THz) communication technology, operating at even higher frequency bands up to 300 GHz, is foreseen to be one of the key enabling building blocks for the future communication systems, due to its huge unregulated bandwidth resources of up to tens of GHz and easy coexistence with other regulated and standardized frequency spectrum [1]. Furthermore, significant advances in THz front-ends and antenna design have led to the exploration of the sub-THz bands in recent years [2].

Accurate channel measurement and modeling is the foundation for designing and deploying the communication systems. Reliable channel sounders are essential to obtain accurate and realistic channel data. Specialized hardware is required to meet the specific requirements of sub-THz channel sounders, which can be summarized mainly as the following: 1) flexible carrier frequency setting and bandwidth to measure radio channels in the frequency bands of interest, 2) scalable measurement range with good signal dynamic range, 3) suitable sampling rate to cover channel dynamic characteristics, and 4) scalable antenna configuration to cover various multi-antenna schemes.

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Three main categories can be used to group the sub-THz channel sounders reported in the literature, i.e., pulse-based channel sounder [3], correlation-based channel sounder [4], [5], and vector network analyzer (VNA)-based channel sounder [6]–[8]. Pulse-based sounder, also named as THz time-domain spectrometer (THz-TDS), transmits a narrow optical pulse and down-convert to sub-THz frequency bands. THz-TDS offers the advantage of ultrabroad bandwidth up to several THz [3]. However, it suffers from low dynamic range and large size of the spectrometer, which limit its application for the channel measurements. Correlation-based channel sounders are among the most popular time-domain channel sounders, which transmit a pseudo-random noise sequence (PNS) over the channel, and correlate the received signal with the known PNS to obtain a good approximation of the desired channel response [1]. Due to the high sampling rate, real-time channel measurements can be achieved. The disadvantage is the small bandwidth, and the high complexity of system design and synchronization.

In addition to the two sounding techniques mentioned above, VNA-based channel sounder is based on a frequency-domain sounding technique that allows frequency sweeping over a large bandwidth. It has been widely employed for sub-THz channel sounding due to its easy calibration and general availability in radio frequency (RF) laboratories. The VNA based channel sounder can offer flexible carrier frequency and bandwidth setting, and high system dynamic range. However, VNA in its default setting cannot meet our objective to achieve long-range large-scale sub-THz channel sounding purposes due to the following limitations: 1) Commercial VNAs can typically perform frequency sweeping up to tens of GHz, which cannot meet the requirement of frequency and bandwidth setting required for sub-THz channel sounding. 2) Due to the fact that transmitter and receiver are co-located inside the VNA, we typically need to extend antennas connected to VNA via cables to support channel sounding in typical deployment environment. However, coaxial cables are excessively lossy at mmWave and sub-THz frequency bands, which significantly limits its measurement distance in practical channel measurements. 3) VNA ports are rather limited, which hinders its direct application for channel sounding for large-

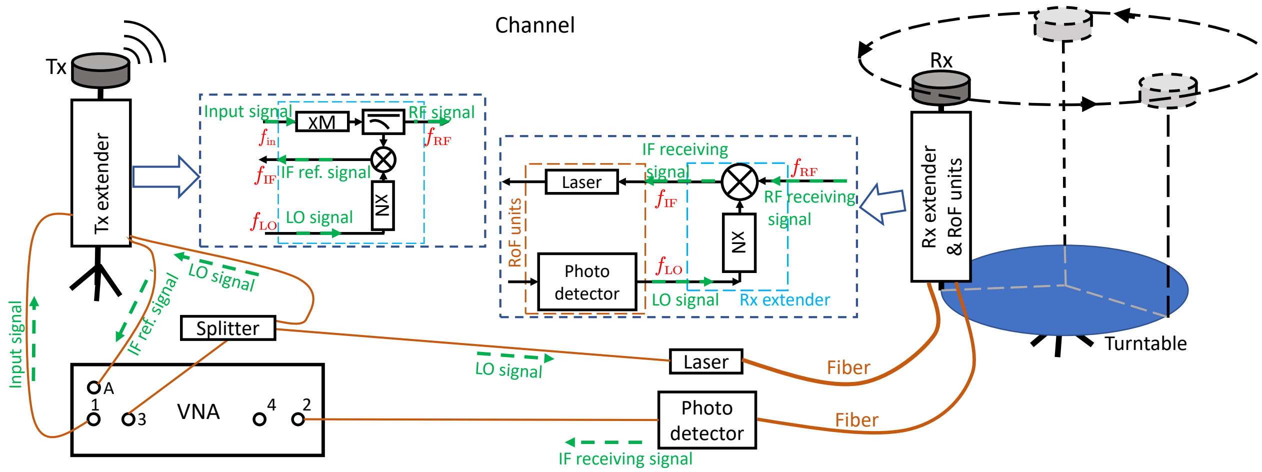


Fig. 1: An illustration of the VNA-based channel sounder using the frequency extension and RoF schemes.

scale antenna configurations.

Directional scanning scheme (DSS) with the help of mechanical turntable and directional antenna located in the turntable center is typically required at both communication ends to obtain channel spatial profiles. Alternatively, virtual antenna array (VAA) concept uses a single antenna to sound the channel in multiple preset spatial locations, forming the virtual array-based characterization. VAA is also a popular alternative in channel sounding since it can achieve a higher spatial resolution using proper array processing algorithms due to the implementation of virtual antenna arrays. However, phase-coherent measurements at preset spatial locations, which deemed crucial for VAA, has been seen challenging for sub-THz bands, since the phase performance of the sub-THz channel sounder is sensitive and hard to control [9]. Although the phase compensation scheme proposed in [8] shows the possibility of sub-THz phase-coherent measurements, no sub-THz VAA measurements have been reported in the literature yet. Furthermore, as the mechanical movement of the positioner, data acquisition, and frequency sweeping in the VNA is slow, the DSS and VAA schemes are constraint to static scenarios.

In this work, we aim to describe a VNA based channel sounder that can support long-range and large-scale VAA channel sounding at sub-THz bands. To achieve this objective, several strategies, i.e. frequency extension to sub-THz, radio-over-fiber (RoF) concept for long range transmission and phase-compensation scheme for virtual array, are introduced in Section II. Section III exemplifies the VAA-based channel measurements using the proposed channel sounder. Finally, we conclude the work and discuss the VAA application scenarios in Section IV.

II. VNA-based Channel Sounder with VAA

In this part, we introduce three schemes, i.e. frequency extension with sub-THz frequency extenders, measurement range extension with radio over-fiber technique, and VAA enabled by phase-compensation schemes, to make long-range large-scale channel sounding at sub-THz a reality. Then, capabilities of the realized sounder with the three schemes are summarized.

A. *Frequency extension scheme*

An exemplary structure of the frequency extenders is depicted in Fig. 1. The input signal at the frequency of f_{in} is converted to an RF signal at the frequency of f_{RF} by a multiplier with a factor of M and transmitted by the Tx antenna. Two synchronized local-oscillator (LO) signal at the frequency of f_{LO} are input to the extenders and converted by multipliers with a factor of N. We can then obtain the demodulated intermediate frequency (IF) signal with its frequency f_{IF}. After the Rx extender receives the RF signal, the received signal is demodulated into an IF signal and sent back to the VNA. The frequency responses could be obtained by dividing the IF receiving signal by the IF reference signal.

The employment of the frequency extension scheme enables VNA to conduct measurements at sub-THz frequency bands with a large bandwidth. The downside is that the frequency extension scheme has a rather high cost. The link budget is also affected by the noise figure of the frequency extenders. With the use of the multiplier in the extenders, the phase change in the RF cables is multiplied with the factor of the multiplier, which makes the accurate phase performance of the channel sounder more challenging. Besides, the frequency extender requires one additional VNA transmitting port for the LO signal and one additional VNA receiving port for the Tx reference signal, as shown in Fig. 1.

B. *RoF scheme*

The RoF scheme applies the optical fiber cable for the low signal loss in the wired transmission link, and hence realizes long-range channel sounding at sub-THz bands. For example, high quality signal mode fiber cable can exhibit a signal loss as low as 0.4 dB/km, while coaxial cable has a measured loss of 1.76 dB/km at 15 GHz (the input signal frequency of the 300 GHz extender, as an example) [8]. The RoF techniques, which contains electrical-to-optical (E/O) unit (i.e. laser), optical fiber cable, and optical-to-electrical (O/E) unit (i.e. photo detector), are employed and widely used [6], [7], [10]. Fig. 1 also illustrates the structure of the RoF scheme. E/O and O/E units support microwave and mmWave frequency bands are commercially available, as reported in [11]. However, such units are not commercially available for sub-THz system. To address this issue, the RoF scheme is implemented in the LO link before the frequency extender, which makes it possible to perform sub-THz long-range channel measurements using RoF units at mmWave bands.

The first disadvantage is the extra cost. The RoF components, i.e., laser and photo detector, at high frequency bands are costly. The other disadvantage is that the phase of the fiber is sensitive to the mechanical stress and thermal change, which indicates that the RoF scheme cannot be utilized in phase-coherent channel measurements directly.

C. VAA with phase-compensation scheme

1) Channel spatial profile measurement: As discussed, DSS and VAA are widely employed schemes for VNA based channel sounder to obtain the channel spatial profiles.

- **DSS**: To directly record the channel response at each rotation angle, this scheme mounts a highly directive antenna in the center of a turntable, which can be mechanically rotated in transmitter (Tx) and/or receiver (Rx). By doing so, we can directly obtain the channel spatial profiles. It has gained its popularity due to its simplicity, low-cost and offering high signal-to-noise ratio (SNR) measurements. However, it is rather slow and the spatial resolution is constraint by the employed directive antenna.
- **VAA**: A single omni-directional or directional antenna is mechanically moved to different locations by a positioner, which can be used to form arbitrary virtual array configurations. Channel frequency responses at different locations are recorded. Due to the realized antenna array, channel spatial profiles with a high spatial resolution can be obtained based on proper array processing algorithms. VAA is a popular and cost-effective scheme to obtain the spatial channel information. It is advantageous compared to DSS as better spatial resolution can be achieved. However, unlike the DSS scheme, it necessitates coherent phase measurement at each spatial location, since the processing operations for precise extraction rely on exact signal phase differences at different array elements. Besides, the inter-element spacing distance for the VAA scheme is reduced to the millimeter level (e.g., 0.5 millimeter (i.e. half wavelength) for 300 GHz) as the frequency increases to sub-THz bands, which means a highly accurate positioning stage or turntable is required for achieving VAA scheme.

2) Unstable phase measurement at sub-THz band: Although VAA is highly valuable for precise extraction of channel spatial profile, VAA scheme has not yet been reported at sub-THz frequency bands due to the challenging nature of accurately and coherently measuring phase at multiple spatial locations [9]. In the following, we summarize main issues that affect the accurate phase measurements at sub-THz bands, which is required for VAA scheme:

- **Stability of the RF system**: The stability of the RF systems (e.g., VNA and frequency extenders) is fundamental to the phase-coherent measurements. According to our back-to-back measurement results in [8], [11], the RF systems are proved to be highly stable with 17 hours at 1-30 GHz bands, and 5 hours at 220-330 GHz bands.
- **Cable effects**: as explained, cables are required to remote antennas for VNA since Tx and Rx are co-located. However, cables are susceptible to phase changes due to mechanical stress and thermal variation in the environment. As shown in Fig. 1, using a turntable, the transmission cable that carries signals (either a coaxial cable or a fiber cable) connecting the VNA and Rx is mechanically stressed, which would introduce a random phase change in system. This issue is unfortunately unavoidable for measurement systems supporting VAA or DSS. The virtual antenna array or directional scanning scheme are rather time consuming. It might take up to several hours to complete one virtual antenna array measurement. As a result, the thermal change can also affect the phase in the cables, especially for the optical fiber cables. This issue can be solved by the phase-compensation scheme, which is described later.
- **Signal multiplication in the frequency extender**: The multiplier amplifies the input phase change by the corresponding multiplier factor (which depends on the manufacturer's design). Therefore, even a small input phase change will become severe after passing through the multiplier. For example, in the VDI WR 3.4 extender, the multiplier factor in the LO chain is 24, which means even a small phase change, e.g., 1° will be amplified to 24° [8].
- **Mechanical stability of the turntable**: As the frequency comes to sub-THz, the wavelength becomes millimeter scale. Therefore, even small vibrations of the turntable might have a serious effect on the phase. The mechanical stability of the turntable is thus a major issue for sub-THz channel measurements. This can be solved by using a highly stable turntable and carefully designing the waiting time for the stability of the turntable, however, this will increase the cost and measurement time.

3) Phase-compensation scheme: Fig. 2 depicts the structure of the phase compensation scheme. This scheme consists of two links, i.e., forward link and feedback link. The input signal travels through the fiber and suffers signal impairments (i.e. random phase changes). Using the optical splitter and two optical circulators, the signal travels back through the same fiber, experiencing the same impairments, and then is recorded in the VNA. Thus, the signal impairments through the fiber in the forward link could be recorded and hence compensated.

We can apply the phase-compensation schemes to either the RF chain or the LO chain, as depicted in Fig. 2. The phase-compensation scheme has been utilized at 1-50 GHz in [11] and at 220-330 GHz in [8]. At the sub-6 GHz and the lower bands of the mmWave frequency (up to 50 GHz), this scheme could be directly implemented on the RF chain. At higher frequency bands (e.g. sub-THz bands), due to the lack of the cost-effective components working in such a high frequency bands, the phase-compensation scheme cannot be

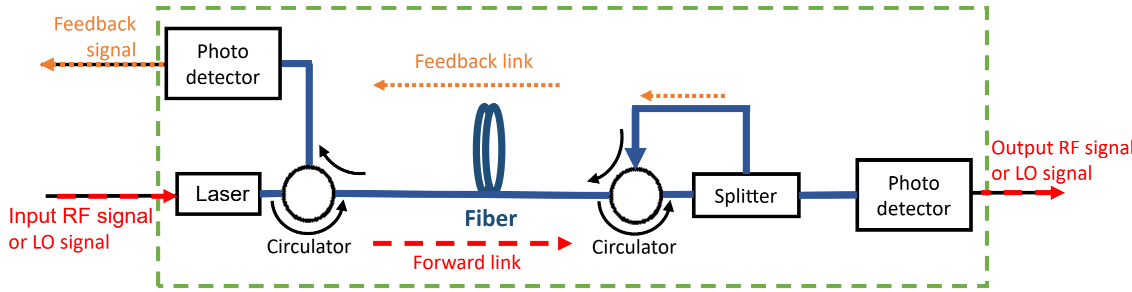


Fig. 2: The structure of the phase compensation scheme.

directly applied on the RF chain. Alternatively, we can implement the RoF scheme in the LO chain before the frequency multiplication. Furthermore, we demonstrarted in [8] that the main phase change of the channel sounder occurs on the LO chain. Therefore, the phase-compensation schemes can be applied on the LO chain.

After obtaining the measured responses of the forward link $S_{\mathrm{fw}}(f_{\mathrm{RF}})$ and feedback link $S_{\mathrm{fb}}(f_{\mathrm{LO}})$, we can get the accurate channel response $H(f_{\mathrm{RF}})$ by compensating the feedback response. The multiplier factor N in the extender ($N = 1$ if the phase-compensation scheme directly applied to RF chain) is a major factor that should be taken into account when calculating the phase compensation results in the postprocessing. The equations of the phase compensation schemes can be referred in [8], [11].

To sum up, the phase-compensation scheme can be utilized to solve the phase stability problem of the RoF scheme. It has a feedback link to record the phase change in the fiber during the channel measurements and it is used to compensate the phase variation in the forward link in post-processing. With the proposed phase-compensation scheme, we can achieve the phase-coherent measurements for the RoF scheme. However, the downside is that the phase-compensation scheme requires additional signal processing in post-processing. Moreover, the phase-compensation scheme also requires one additional VNA receiving port for the feedback link. The proposed scheme also suffers from the signal loss and cost of the additional components in the phase-compensation scheme, e.g., circulators and optical splitter.

4) Review on VAA measurements: At sub-6 GHz frequency bands, due to the high phase accuracy of the channel sounder, the accessibility of the omnidirectional antennas, and the low signal loss in the cables, VAA has been widely adopted in the channel measurements with a flexible measurement range [10], [12]. At mmWave bands, due to high propagation loss in the channel and high attenuation in the coaxial cables, the measurement scenarios with VAA schemes are mainly limited in the short-range scenarios, e.g. office and meeting room [13], [14]. The use of VAA at mmWave and sub-THz bands is hampered by the unstable phase performance of the channel sounder, which can be solved by our proposed phase-compensation scheme. The back-to-back results in [8], [11] demonstrates the feasibility of this scheme for phase-coherent measurements at mmWave and sub-THz bands. VAA validation measurements with omnidirectional antenna and directive antenna were conduct at 28 GHz in [11], [15] to validate the VAA concept at mmWave bands. In the following section, the exemplary sub-THz VAA measurements using the proposed phase-compensated channel sounder are validated and demonstrated first time in the literature.

D. Developed VNA-Based Channel sounder capability

The discussed schemes enables ultrawideband long-range phase-coherent measurements at sub-THz bands using VNA-based channel sounder with the following capabilities:

- **Scalable frequency range**: Using the frequency extender, the frequency range can be extended up to sub-THz with ultra-wide system bandwidth. For example, using the VDI WR3.4 frequency extenders, the frequency range can be extended to 220-330 GHz with 110 GHz system bandwidth.
- **Long-range capability**: The measurement range is physically limited by the length of the optical cable. Besides, the back-to-back dynamic range for the 100 GHz phase compensated VNA-based channel sounder at 100 GHz is experimentally shown to be 105.5 dB with 10 Hz IF bandwidth. With the use of the omnidirectional antennas at 100 GHz (the antenna gain is 4.5 dBi), the dynamic range can reach to 115.5 dB. However, in practical measurements, the measurement range may be affected by limiting factors, i.e., over-the-air free space propagation loss and antenna misalignment loss (e.g. antenna alignment and polarization alignment). Note that directive antennas are typically used to obtain higher signal power and hence higher SNR. This can support even longer measurement range.
- **Phase stability**: The phase performance of the proposed channel sounder has been tested and evaluated in the back-to-back connection at sub-6 GHz, mmWave, and sub-THz bands in [8], [11]. At sub-6 GHz and mmWave bands (i.e. 1-30 GHz), the phase without phase compensation varies over $50°$ and the deviation can be maintained within $2.5°$ after phase compensation [11]. At 220-330 GHz, the phase variation is much more severe than that at mmWave bands, exceeding $400°$. By using a phase-compensation scheme, the deviation can be retained within $15°$ [8]. Note that the phase change after phase compensation is mainly caused by the frequency extender due to the thermal change, which should be

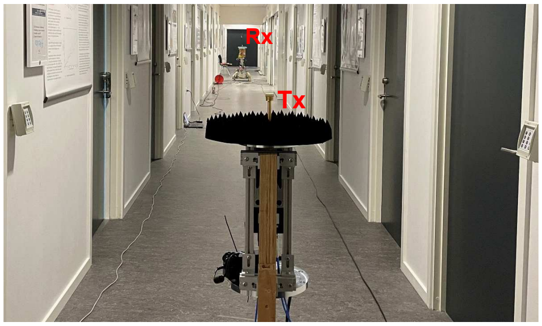


Fig. 3: Photo of the measurement scenario at 100 GHz.

further improved in future work. Readers could refer to [8], [11] for more details.

Large-scale antenna array: With the use of the VAA, we can form a (virtual) large scale antenna array for channel sounding. For example, in Section III, we formed a virtual uniform circular array (UCA) at the Rx with 360 array elements.

III. Exemplary VAA channel measurement at sub-THz bands

A. Measurement scenario

The exemplary VAA-based channel measurements were performed at 99-101 GHz in a corridor scenario with a size of $33.5 \times 2.0 \times 2.9\,\mathrm{m}^3$ (length $\times$ width $\times$ height). Photo of the proposed sounding system and the exemplary measurement scenario is depicted in Fig. 3. We used an omnidirectional antenna at the Tx side, and validated the VAA concept in two antenna type at the Rx side, i.e. omnidirectional antenna same as the Tx and directive antenna. The Tx is fixed on a wooden stick, while the Rx is mounted on a turntable, which is programmed to form a virtual UCA. The turntable rotates in steps of 1°, resulting in 360 VAA array elements for 360° turntable rotation. The Tx-Rx distance is set to 20 m. To calibrate the system response, a back-to-back normalization is carried out prior to the channel measurements.

To verify the correctness and show the priorities of the VAA measurements, the reference channel measurements are performed at the same location as the VAA measurements using a DSS, which mounts the same directive antenna on the center of the turntable at the Rx side to capture the spatial domain channel response. For all of the channel measurements, we consider a dynamic range of 30 dB relative to the line-of-sight (LoS) power. Table I illustrates the measurement configurations for the three VAA validation measurements.

B. Measurement results

Fig. 4 (a) depicts the channel impulse responses (CIRs) obtained at different virtual UCA array element positions using the omnidirectional antenna. Only two main paths can be observed in the noisy data and the dynamic range is rather limited, i.e. 22 dB. The spatial domain channel parameters can be extracted, based on beamforming algorithm or high-resolution parameter estimation (HRPE) algorithms. In this work, we employs the classical beamforming algorithm [12] for the omnidirectional VAA, and uses the modified beamforming algorithm in [15] for the directive VAA.

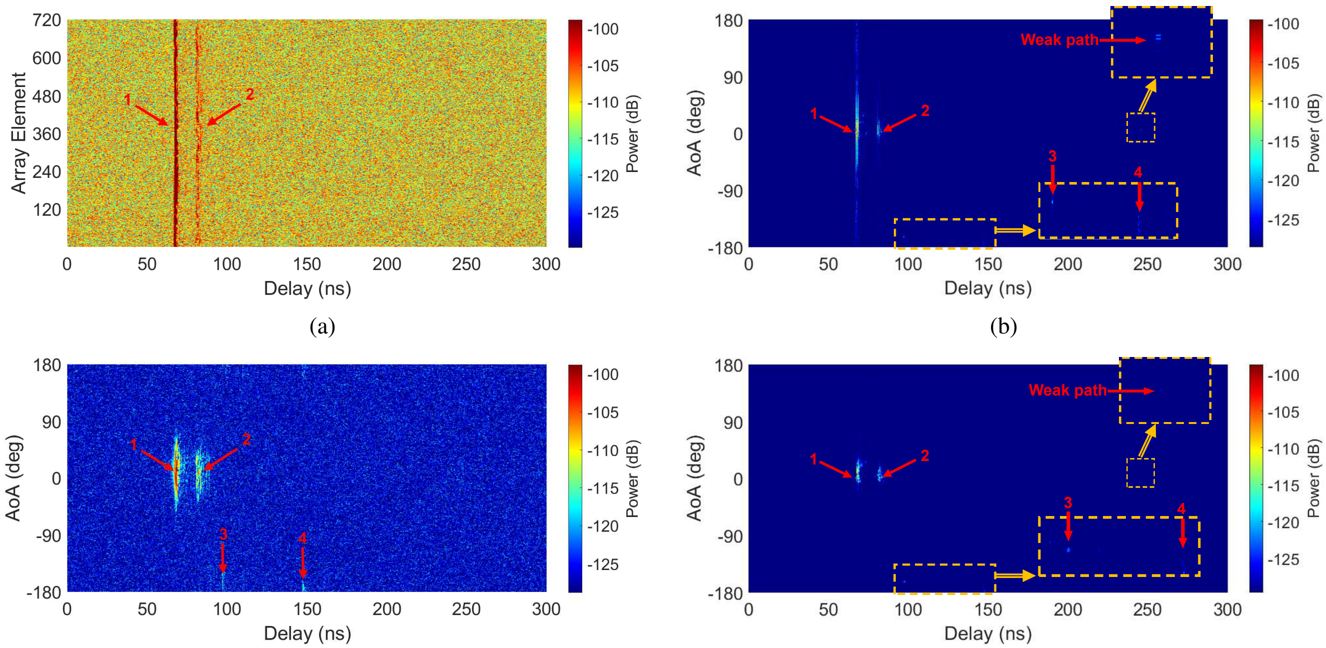
TABLE I: VAA validation measurement configuration.

Parameter	Omnidirectional element VAA	Directive element VAA	DSS
Frequency	99-101 GHz		
Number of frequency points	1001		
Transmitted power	10 dBm		
VNA IF bandwidth	500 Hz		
Antenna height	1.25 m		
Tx-Rx distance	20 m		
Antenna type	SAO-7531140230 -10-S1	ASY-CWG-S-750	
Antenna gain	5 dBi	13.5 dBi	13.5 dBi
HPBW	omnidirectional	45°	45°
Rotation range	$[-180^\circ, 180^\circ]$		
Rotation step	1°	1°	1°
Offset to the rotation center	5 cm	5 cm	0 cm

Fig. 4 (c) depicts the power-angle-delay-profile (PADP) using the DSS scheme. Thanks to the gain of the directive antenna, we can observe four paths in the results. However, the wide HPBW of the antenna leads to a low angular spatial resolution. Fig. 4 (b) and (d) describe the PADPs with the omnidirectional antenna and the directive antenna-based VAA, respectively. Four dominant paths can be identified for both measurement results. Path 1, i.e. LoS path, is observed to have an angle-of-arrival (AoA) of 0° and a delay of 67 ns (corresponding to 20.1 m), as expected. The LoS path for the omnidirectional VAA and directive VAA (removing the antenna gains) are -99.8 dB and -100.2 dB, respectively, which is close to the Friis free space path loss calculation result, i.e., 98.5 dB. Moreover, a weak path on a delay of 245 ns, equivalent to 74.5 m, can still be seen in the PADP result. Compared with the DSS results in Fig. 4 (c), the four main paths are found to be well-matched, validating our measured results using VAA concept. Besides, the PADPs with the VAA scheme can provide a higher angular resolution. Furthermore, the beamforming results in Fig. 4 (b) and (d) illustrates that the VAA has SNR improvements, i.e., 17.3 dB for omnidirectional VAA and 11.9 dB for directive VAA, compared to those of the original CIRs and the DSS results, respectively. The trajectory of the MPC paths is illustrated in Fig. 5. The identified delay and AoA information of the MPCs match well with the path trajectory, which demonstrates the effectiveness of the proposed channel sounder.

IV. Conclusion and Discussion

In this work, we discuss the solution of VNA-based channel sounder for the sub-THz channel measurements that enables extracting crucial propagation characteristics for communication research and standardization. We introduce several enabling solutions, i.e. the frequency extender to extend the carrier frequency and bandwidth for sub-THz application, RoF scheme to extend measurement range, phase-compensation scheme for VAA implementation. Besides, we experimentally demonstrate the results from the VAA-based channel measurement campaign and analysis at a Tx-Rx distance of



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

Fig. 4: Measurement results at 100 GHz. (a) CIRs recorded at different UCA elements with omnidirectional antenna. (b) PADP with omnidirectional VAA using classical beamforming. (c) PADP using DSS scheme. (d) PADP with directive VAA using the algorithm in [15].

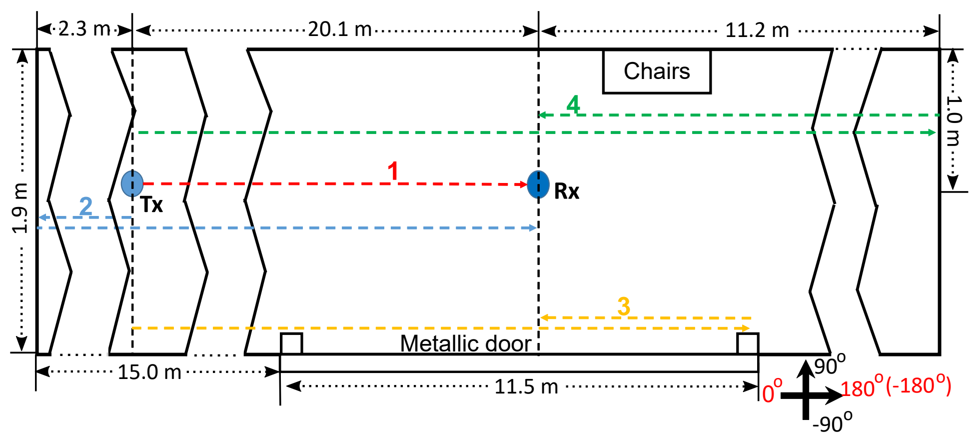


Fig. 5: Relationship between the detected paths and the geometry of the corridor scenario.

20 m at 100 GHz bands. The introduced techniques will be used extensively in planned channel measurements at sub-THz frequency bands (e.g. 300 GHz) and in a variety of practical deployment scenarios.

The proposed phase-coherent VAA scheme, whose advantages have been demonstrated in the previous measurements, can have promising applications in the following scenarios at sub-THz bands: 1) **SNR improvement**: Using the beamforming algorithm, signal received at array elements can be constructively summed by canceling the phase difference introduced by the array geometry and impinging path directions. Noise, however, cannot be constructively summed. Therefore, we would observe an increase in the SNR. 2) **Antenna de-embedding**: Directive antennas are applied in channel measurements to combat the high propagation loss at higher frequency bands (e.g. mmWave). However, the antenna response is embedded with the propagation channel response. Antenna de-embedding is desirable for obtaining the pure propagation channel response. Simulations or measurements for the design and analysis of the communication systems should be repeated for different employed antenna types without de-embedding procedure, which will increase the work load of the engineers and decelerate the deployment process. VAA is capable of forming an array pattern with extremely narrow beamwidth and low sidelobes with appropriate post-processing algorithm and large array aperture. Whatever directive antenna employed in the VAA scheme, a pencil-beam can be synthesized. 3) **Omnidirectional path loss**: In the conventional omnidirectional path loss computation for the DSS scheme, all the powers above the noise floor at each rotation angle are summed, which will be inevitably affected by the non-ideal beampatterns of the directional antenna. With the accurate phase and the high angular resolution of the VAA by using proper algorithm, more precise path parameters can be obtained, which makes it possible to obtain a more accurate omnidirectional path loss. 4) **Other application scenarios**: Other sub-THz applications such as near-field antenna measurements, localization, and sensing, which require phase-coherent measurements at multiple locations, RF channels and antennas can be supported by this sub-THz VAA scheme.

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