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Design and Validation of the Phase-Compensated Long-Range Sub-THz VNA-based Channel Sounder

Yejian Lyu, Allan Wainaina Mbugua, Kim Olesen, Pekka Kyösti, and Wei Fan

***Abstract*—This paper presents the first vector network analyzer (VNA)-based sub-Terahertz (sub-THz) phase-compensated channel sounder at 220-330 GHz using radio-over-fiber (RoF) techniques that could enable long-range phase-coherent measurements. The optical cable solution enables long-range channel measurements at sub-THz bands, since it can effectively minimize the cable loss. This paper also proposes a novel phase compensation scheme to stabilize the phase variations introduced by optical fiber of the channel sounder to enable its application in multi-channel/antenna measurements. This proposed channel sounder is validated in back-to-back measurements under two optical cable conditions, i.e., with presence of thermal changes and mechanical stress. The phase variation introduced by the cable effects in the system is shown to be over 400° in 220-330 GHz, compared to 15° at 220-288 GHz and 37° in 288-330 GHz after compensation, respectively, demonstrating the robustness and effectiveness of the developed channel sounder in practice. The developed system, which has a dynamic range of 106.7 dB, can support measurement range up to 300 m (limited by the optical cable length in our system and subject to over-the-air signal transmission loss in practical environment).**

***Index Terms*—Channel sounding, sub-Terahertz, radio-over-fiber, phase compensation**

I. INTRODUCTION

With the ever-increasing demand for higher data-rate for wireless communication, the exploration of unused sub-Terahertz (sub-THz) region (i.e. 100-300 GHz) has become a recent hot research topic [1]–[4]. Although sub-THz frequency bands provide an opportunity for higher data-rate, many challenges are faced in these frequency bands, e.g., high signal attenuation, vulnerability to blockage and other different propagation behavior compared to lower frequency spectrum [5], [6], which requires new channel sounding techniques and channel modeling studies at those sub-THz bands.

Due to the high signal attenuation at sub-THz bands, the long-range transmission has become a big challenge for sub-THz communication. Although the Vector Network Analyzer (VNA) is a popular channel sounding device in sub-THz channel measurements due to its ability to perform a frequency sweep over a large bandwidth [7], it suffers from high signal loss in cables at high frequency bands, which constrains VNA-based channel measurement to a short distance range. Recent solution to the range limitation is to exploit radio-over-fiber (RoF) techniques where the electrical-to-optical (E/O), optical-to-electrical (O/E) units, and optical fiber cables are used [8], [9]. Optical cables have the advantage of low signal loss and the use of the RoF solution can extend the measurement range to even 100 m at sub-THz bands [9]. However, the optical fiber cables are inherently sensitive to phase change due to the thermal changes and mechanical stresses [10].

Phase-coherent measurement is a prerequisite for multi-channel signal processing, e.g. virtual array concept as widely adopted in millimeter-wave (mmWave) channel sounding campaigns [11]. Besides, many sub-THz applications e.g., phase-sensitive detection, requires the system to be highly phase stable [12]. However, the phase of the current sub-THz channel sounder is often unstable. Thus, it is unable to conduct phase-coherent measurements by these kinds of channel sounders. Phase compensation schemes are applied to stabilize the phase of the VNA-based channel sounder at lower frequency bands [11], [13]. However, the phase compensation scheme in [13] is directly implemented using microwave circulators and radio frequency (RF) cables at sub-6 GHz bands, and using circulators and E/O and O/E conversion units for 30 GHz channel sounder [11], respectively. These approaches cannot be directly applied for sub-THz system, due to lack of suitable E/O and O/E units at these frequencies.

This paper proposes the first 220-330 GHz phase-compensated long-range VNA-based channel sounder. The concept of the phase compensation mechanism in our proposed channel sounder is based on the bidirectional signal transfer (i.e. forward and feedback link) on the same optical fiber cable by using two three-port optical circulators. With the feedback link, the impairments introduced by the thermal changes or mechanical stress of the cable can be de-embedded. To our best knowledge, this is the first channel sounder employing the phase compensation scheme that could enable the phase-coherent measurements at sub-THz frequency bands.

The rest of this paper is organized as follows. Section II outlines the architecture of the proposed channel sounder. Section III contains the detailed description of the validation measurements and analyzes the results. Finally, concluding remarks are presented in Section IV.

II. CHANNEL SOUNDER ARCHITECTURE

A. Sounder Architecture

Fig. 1 illustrates the block diagram of the proposed sub-THz channel sounder. The types and working frequencies of

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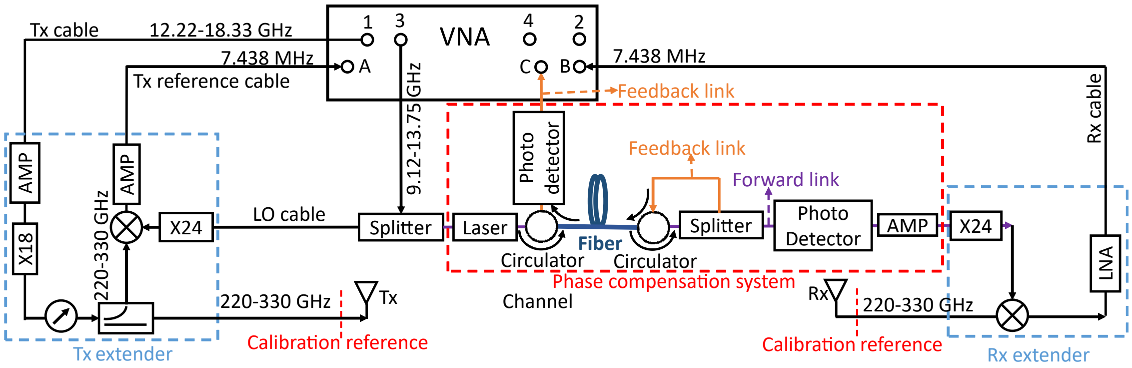


Fig. 1: Block diagram of the proposed RoF VNA-based sub-THz channel sounder.

channel sounder components are outlined in Table I. As shown in Fig. 1, the proposed channel sounder can be separated into two parts, i.e., sub-THz channel sounder and phase compensation system.

1) Sub-THz channel sounder: Signals at 12.22-18.33 GHz are sent from Port 1, multiplied by 18 times to 220-330 GHz band, and divided into two signals. One of the split signals is used to transmit through a directive antenna and the other is used to generate 7.438 MHz reference signal. The 9.12-13.75 GHz local oscillator (LO) signal is sent by Port 3 and split into two signals. The split LO signal is multiplied by a 24 times multiplier. At the Rx side, the received signal is demodulated to 7.438 MHz, amplified by a low noise amplifier (LNA) and sent to Port B.

Measurements were conducted to test the mechanical stress effect on the phase of the sounder by bending the cable into a circle with a 30 cm diameter. Note that calibration was performed before each cable bending. The objective is to determine the phase change introduced by the cable effect in the system and identify the main cables in the system that are susceptible to cable effect. We found that the main phase change is caused by the mechanical stress on the LO cable (up to 70.5° phase change introduced by cable bending), while the insignificant phase change on the Rx cable (up to 0.5°) could be ignored. Thus, the main idea of our proposed channel sounder is to compensate the phase change on the LO cable at the Rx side. Note that the phase stability of these Tx and Rx frequency extenders are ±6°.

2) Phase compensation scheme: The phase compensation scheme aims to remote the Rx antenna and stabilize the system phase when the Rx antenna rotates. The main difference in the proposed sub-THz system and previous works [11], [13] is explained below. Previous phase compensation schemes for sub-6 GHz and mmWave bands are implemented directly on the cable connected to the VNA receiving port. At sub-6 GHz bands, microwave circulators and RF cables are directly used. At mmWave bands, E/O and O/E units up to 50 GHz are used. This cannot be directly applied for sub-THz system, due to lack of such cost-effective conversion units at sub-THz bands. However, due to the introduction of frequency extenders in the sub-THz system and non-stable phase performance in the LO cable, the phase compensation scheme is implemented in the LO cable at the Rx side as shown in Fig. 1. This way, we can still utilize the same E/O and O/E conversion units at 9.12-13.75 GHz. Therefore, our work is an extension and novel application of the phase compensation scheme, which makes it suitable for sub-THz systems.

The existing channel sounders using RoF techniques in [8], [9] only use the forward link and the phase variation caused by cable effects can be severe as shown in the Section below. Our proposed channel sounder on the other hand can support long range and highly stable phase measurements for sub-THz bands, with the proposed forward and feedback links. However, the scheme has a higher complexity and needs one additional VNA port. Note that although 220-330 GHz are aimed in this work, the principle can be applied for other frequency bands as well.

TABLE I: Channel sounder's components

Part	Name	Frequency/Wavelength
VNA	Keysight PNA N5227B	10 MHz-67 GHz
Extender	VDI WR 3.4	220 GHz-330 GHz
Laser	QMOD XMTQ-C-A-24	1550 nm
Photo detector	QMOD XMRQ-C-A-24	1550 nm
Optical splitter	JDS FFC-CKH12B105-003	1550 nm
Optical circulator	OZ FOC-12N-111-9/125-SSS -1550-55-SCASCASCA-1-1	1550 nm
RF amplifier	Picosecond 5828-108	9 GHz-14 GHz

B. Principle of Operation

The forward link and feedback link are recorded in the VNA as the S-parameter $S_{\mathrm{BA}}(f_1)$ and $S_{\mathrm{C3}}(f_2)$, respectively, where $f_1 = 7.438$ MHz and $f_2 = 9.12\text{-}13.75$ GHz. Note that the frequency points N_{f1} of the received signal is the same and one-to-one corresponding with that N_{f2} of the transmitted and LO signals. After using normalization procedure to eliminate the system response in the back-to-back setup, the response of the forward $S_{\mathrm{BA}}(f_1)$ and feedback $S_{\mathrm{C3}}(f_2)$ links are both normalized to 1. Replacing the back-to-back connection with suitable antennas in the actual channel measurements, the CFR $H(f_1)$ can be recorded in $S_{\mathrm{BA}}(f_1)$ as:

$$S_{\mathrm{BA}}(f_1) = 1 \cdot H_{\mathrm{fw}}(f_1) \cdot H(f_1), \tag{1}$$

where $H_{\mathrm{fw}}(f_1)$ denotes the frequency response caused by the mechanical stress and thermal changes on the optical fiber.

Similarly, the frequency response in the feedback link, which contains the cable effects, $H_{\mathrm{fb}}(f_2)$ is embedded in $S_{\mathrm{C3}}(f_2)$ as:

$$S_{\mathrm{C3}}(f_2) = 1 \cdot H_{\mathrm{fb}}(f_2) = \alpha_{\mathrm{C3}}(f_2)\exp(j\phi_{\mathrm{C3}}(f_2)), \quad (2)$$

where $\alpha_{\mathrm{C3}}(f_2)$ and $\phi_{\mathrm{C3}}(f_2)$ are the amplitude and phase of $S_{\mathrm{C3}}(f_2)$, respectively.

The bidirectional signal transfer on the same cable implies that the signal in the feedback link has undergone twice the phase change in the forward link due to mechanical stress and thermal changes on the optical fiber cable. Thus, the relationship between the response amplitude $\alpha_{\mathrm{LO3}}(f_2)$ and phase $\phi_{\mathrm{LO3}}(f_2)$ from the LO signal input port to Port 3 and those of $S_{\mathrm{C3}}(f_2)$ are:

$$\alpha_{\mathrm{LO3}}(f_2) = \sqrt{\alpha_{\mathrm{C3}}(f_2)} = \sqrt{|S_{\mathrm{C3}}(f_2)|}, \quad (3)$$

$$\phi_{\mathrm{LO3}}(f_2) = \frac{\phi_{\mathrm{C3}}(f_2)}{2}, \quad (4)$$

After passing through the 24× multiplier and mixer, the amplitude $\alpha_{\mathrm{error}}(f_1)$ and phase $\phi_{\mathrm{error}}(f_1)$ of the error term $H_{fw}(f_1)$ can be written as:

$$\alpha_{\mathrm{error}}(f_1) \approx \alpha_{\mathrm{LO3}}(f_2) = \sqrt{|S_{\mathrm{C3}}(f_2)|}, \quad (5)$$

$$\phi_{\mathrm{error}}(f_1) = 24 \cdot \phi_{\mathrm{LO3}}(f_2) = 12 \cdot \phi_{\mathrm{C3}}(f_2), \quad (6)$$

Consequently, the error term $H_{\mathrm{fw}}(f_1)$ can be deembedded from the CFR $H(f_1)$ as follows:

$$H(f_1) = \frac{S_{\mathrm{BA}}(f_1)}{\sqrt{|S_{\mathrm{C3}}(f_2)|}\exp(j \cdot 12 \cdot \phi_{\mathrm{C3}}(f_2))} \quad (7)$$

C. Link Budget Analysis

Fig. 2 illustrates the link budget of the developed long-range phase-coherent channel sounder at 275 GHz as an example. At the Tx side, 5 m RF cables are used to connect the VNA with the Tx extender, while a 10 m RF cable and 300 m optical fiber cable are used at the Rx side to remote the Rx antenna. In order to ensure that the Tx extender works safely and prevent potential damage, the transmitted powers from Port 1 and Port 3 are 9 and 12 dBm, respectively. Also to ensure that the Rx extender works in its normal region, an RF amplifier operating at 9-14 GHz with a 10 dB gain and a 1-dB compression of 11 dBm is employed before the LO signal is fed to the Rx extender, which boosts the LO signal power to 2 dBm. The gains of the Tx extender and Rx extender are 2.6 and 15.3 dB, respectively. Note that the loss of the waveguide is included in the gains of extenders.

The obtained dynamic range is 106.7 dB for the back-to-back connection. As for conventional sounding system without RoF techniques, although the signal loss in the Rx cable at 7.438 MHz is low (below 0.2 dB/m [14]), the high signal loss in the LO cable at 9.12-13.75 GHz (i.e. 1.5-1.8 dB/m [14]) limits the measurement to a short range, i.e., several tens meters. However, in our proposed sounder, the signal loss in the optical fiber cable could be significantly reduced (i.e. 0.8 dB/km [11]) and the measurement range could be increased to 300 m (depend on the optical cable length in our sounding system and the over-the-air signal transmission loss in practical environment).

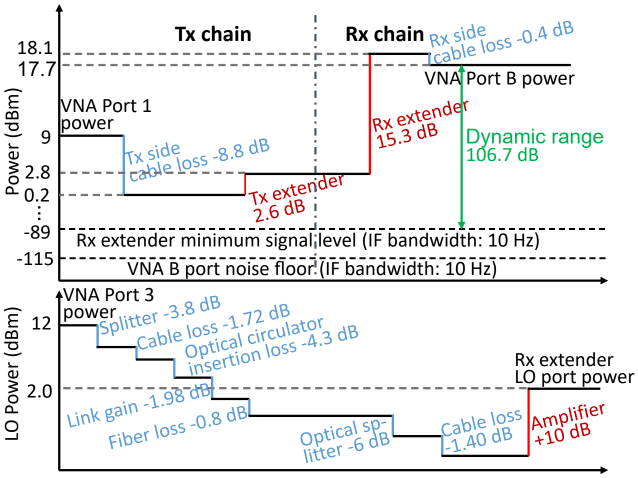
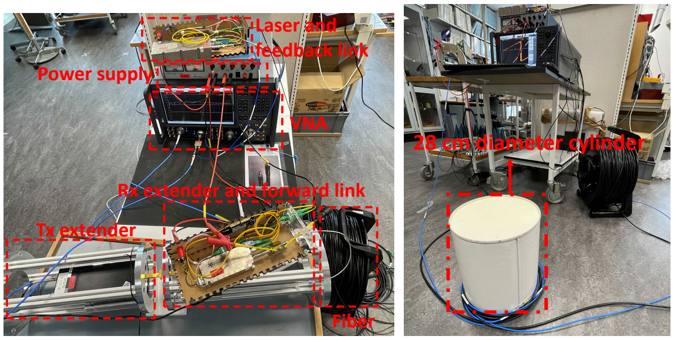


Fig. 2: Link budget of the proposed channel sounder and the phase compensation system at 275 GHz and 11.5 GHz.



(a) (b)

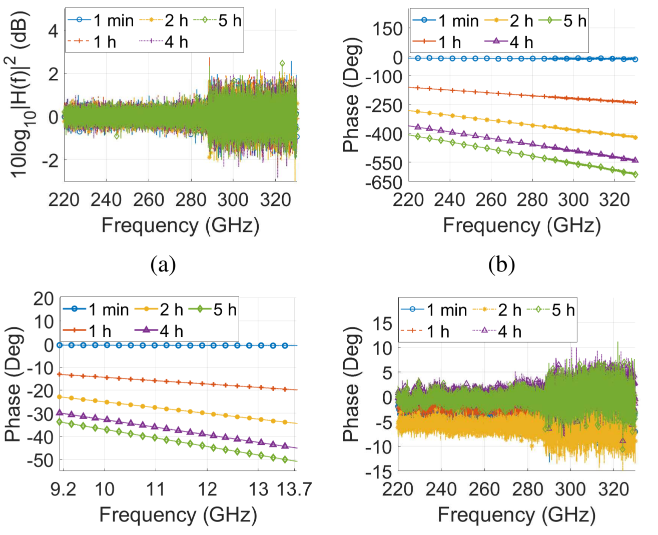
Fig. 3: Photograph of the back-to-back and the cable bending measurements. (a) Back-to-back measurement;(b) Mechanical bending of the optical fiber and Rx coaxial cables.

III. CHANNEL SOUNDER PERFORMANCE VALIDATION

Amplitude and phase stability are fundamental if the channel sounder is to faithfully record the characteristics of the channel [11]. The proposed channel sounder is validated using back-to-back measurements. The amplitude and phase stability under the following two conditions are tested by the back-to-back measurements, i.e. signal drifting over time (thermal change) and cable bending(mechanical stress).

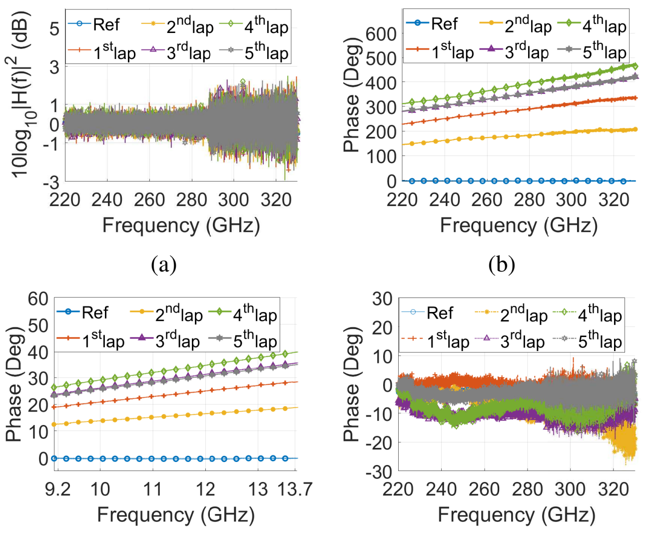
A. Signal Drifting over Long Measurement Time

In practical directional scanning measurements both at the Tx side and Rx side, it could take several hours to record the channel responses due to the narrorw beamwidth of the sub-THz frequency bands and sequential search procedure at the Tx and Rx side. It is essential to ensure that there is insignificant signal drift in the measurement system during the entire measurement period. However, according to [10], the subtle changes in the ambient temperature will cause a significant phase change to the signal in the optical fiber cable. To verify the robustness of our proposed channel sounder, a back-to-back measurement is conducted, as illustrated in Fig. 3 (a). Note that the VNA and the RF amplifier are firstly



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

Fig. 4: Amplitude and phase of the proposed channel sounder over a period of 5 hours. (a) Compensated amplitude;(b) Phase of the forward link; (c) Phase of the feedback link; (d) Compensated phase.



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

Fig. 5: Amplitude and phase of the proposed channel sounder with cable bending. (a) Compensated amplitude;(b) Phase of the forward link; (c) Phase of the feedback link; (d) Compensated phase.

turned on and warmed up for 30 minutes before the measurements. A normalization procedure is then carried out to deembed the system response before the measurements, which effectively shifts the phase reference from the VNA ports to the calibration reference plane, as shown in Fig. 1. During the measurements, a frequency sweep from 220 to 330 GHz with frequency points of 20001 is executed continuously for a period of 5 hours at a interval of 1 minute.

The amplitude and phase results with the RF amplifier included over a period of 5 hours are demonstrated in Fig. 4. The amplitude at the frequency range of 220-288 GHz varies within 1 dB. However, the amplitude at 288-330 GHz varies in the range of $[-2.8, 2.4]$ dB. In the phase of the forward link, i.e. without the compensation scheme, it is observed that the phase varies over 500° and is approximately twelve times the phase of the feedback link, as demonstrated in Fig. 4 (b) and Fig. 4 (c). The compensated phase deviation for the period of 5 hours is maintained within 12° at 220-288 GHz and 37° at 288-330 GHz, respectively, as illustrated in Fig. 4 (d). Besides, the phase noise at 288-330 GHz is seen to be much larger compared to that at 220-288 GHz, which possibly caused by the multiplier and mixer inside the Rx extender (which unfortunately subjects to manufacturer designs). Note that even a small phase error variation will become 24 times larger due to the effect of the multiplier. The real error of the phase compensation system is much lower (e.g., 1.5° phase error before the 24 times multiplier corresponding to 36° after it). These results indicate the robustness of this proposed phase-compensated channel sounder in 5 hours.

B. Cable Bending

In practical directional scanning measurements, at the Rx side, mechanical stresses on the optical fiber and Rx coaxial cables are inevitable due to the movement of the antenna positioning stages. To characterize the cable bending, a 28 cm cylinder is used to bend the cables, as shown in Fig. 3 (b). Then cable bending responses are measured for a total of 5 bends around the cylinder.

Fig. 5 illustrates the mechanical stress amplitude and phase results. As shown in Fig. 5 (b), the phase of the forward link is observed to be unstable as it varies over 400°. Compared with Fig. 5 (b) and Fig. 5 (c), the phase of the forward link is approximately twelve times the phase of feedback link. After the phase compensation procedure, the phase due to mechanical stress is observed to be maintained within 15° at the frequency range of 220-288 GHz and within 30° at the frequency range of 288-330 GHz, respectively, as depicted in Fig. 5 (d).

IV. CONCLUSION

In this paper, a novel sub-THz VNA-based long-range phase compensated channel sounder at 220-330 GHz is proposed. The dynamic range of this channel sounder could be improved to 106.7 dB for the back-to-back connection at 275 GHz to support the long-range channel measurements. By using the RoF technique and phase compensation scheme, the long-range phase-coherent channel measurement could be conducted. The robustness of this novel channel sounder is validated and specified for the frequency range from 220 to 330 GHz by back-to-back measurements. The phases after compensation at 220-288 GHz and 288-330 GHz are within 15° and 37°, respectively, compared to over 400° phase change introduced by cable effect at 220-330 GHz. In the future work, we plan to conduct phase-coherent measurements and validate virtual array concept at sub-THz, which has not be achieved so far due to unstable phase response in the measurement system.

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