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On the Phase-Compensated Long-Range VNA-based Channel Sounder for sub-6 GHz, mmWave and sub-THz frequency bands

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***Abstract*—This paper presents an overview of the vector network analyzer (VNA)-based phase-compensated channel sounder at sub-6 GHz, mmWave and sub-Terahertz (sub-THz) bands. The optical cable solution can enable long-range channel measurements for all these three bands, since it can effectively minimize the cable loss. The phase compensation architecture and principle are also discussed in this paper. The accurate phase measurement is enabled by the phase compensation scheme, which is essential for application in multi-channel/antenna measurements. We summarized the performance of the designed channel sounder under two types of cable effect condition, namely thermal changes and mechanical stress. Under these two cable conditions, the phase compensated channel sounders are validated in back-to-back measurements. The compensated phases demonstrate the robustness and effectiveness of these channel sounder for the frequency bands of 1-30 GHz, and 220-330 GHz.**

***Index Terms*—Channel sounding, phase-coherent, radio-over-fiber, phase compensation.**

I. Introduction

Phase stability is crucial in some phase critical applications, e.g. radio interferometry [1] and phase-sensitive detection [2]. Besides, phase-coherent measurement is a prerequisite for multi-channel signal processing, e.g. virtual array concept as widely adopted in channel sounding campaigns for millimeter wave (mmWave) frequency bands [3]–[5].

Vector Network Analyzer (VNA) is a popular channel sounding device due to its ability to perform a frequency sweep over a large bandwidth with high-fidelity performance [6]. However, it suffers from high signal loss in cables at high frequency bands, which is required to remote antennas in channel measurements. Hence, the VNA-based channel measurement is typically constrained to a short distance range. Recent solution to address the measurement 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 [7], [8]. The low signal loss in the optical cables indicates that the use of the RoF techniques can extend the measurement range. However, the optical fiber cables are inherently sensitive to phase change due to the thermal changes and mechanical stresses [9].

Phase compensation schemes can be applied to stabilize the phase of the VNA-based channel sounder at sub-6 GHz, mmWave and sub-Terahertz (sub-THz) bands [3], [10]–[12]. The phase compensation scheme in [10] 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 channel sounder at 1-30 GHz [3] and 1-50 GHz [11], respectively. In [12], the phase compensation scheme was further extended to sub-THz bands, i.e., 220 to 330 GHz. In these literature, the phase compensation schemes are proved to be a effective method to conduct the phase-coherent measurements.

In this paper, an overview of these phase compensation schemes are presented. The sounder architectures and principles are firstly discussed and compared. The phase changes of these channel sounders before and after compensation under both thermal change and mechanical stress cable conditions are then tested and analyzed.

The rest of this paper is organized as follows. Section II outlines the architecture of the channel sounders with the phase compensation schemes for sub-6GHz, mmWave and sub-THz frequency bands. Section III contains the detailed description of the validation measurements and analysis of the results. Finally, concluding remarks are presented in Section IV.

II. Overview on phase compensation scehmes

Fig. 1 illustrates the block diagrams of the phase compensation schemes used for stabilizing the phase of the VNA-based channel sounders at sub-6 GHz, mmWave, and sub-THz bands in [3], [10], [12]. The basic principle of the phase compensation scheme is to record the random and unpredictable phase behavior in the target cable, and de-embed these phase random changes in the post-processing. The system architecture and compensation principle are illustrated and explained below.

A. Sounder Architecture

1) Sub-6 GHz phase-compensated channel sounder: The phase compensation scheme was firstly orignated in [10],

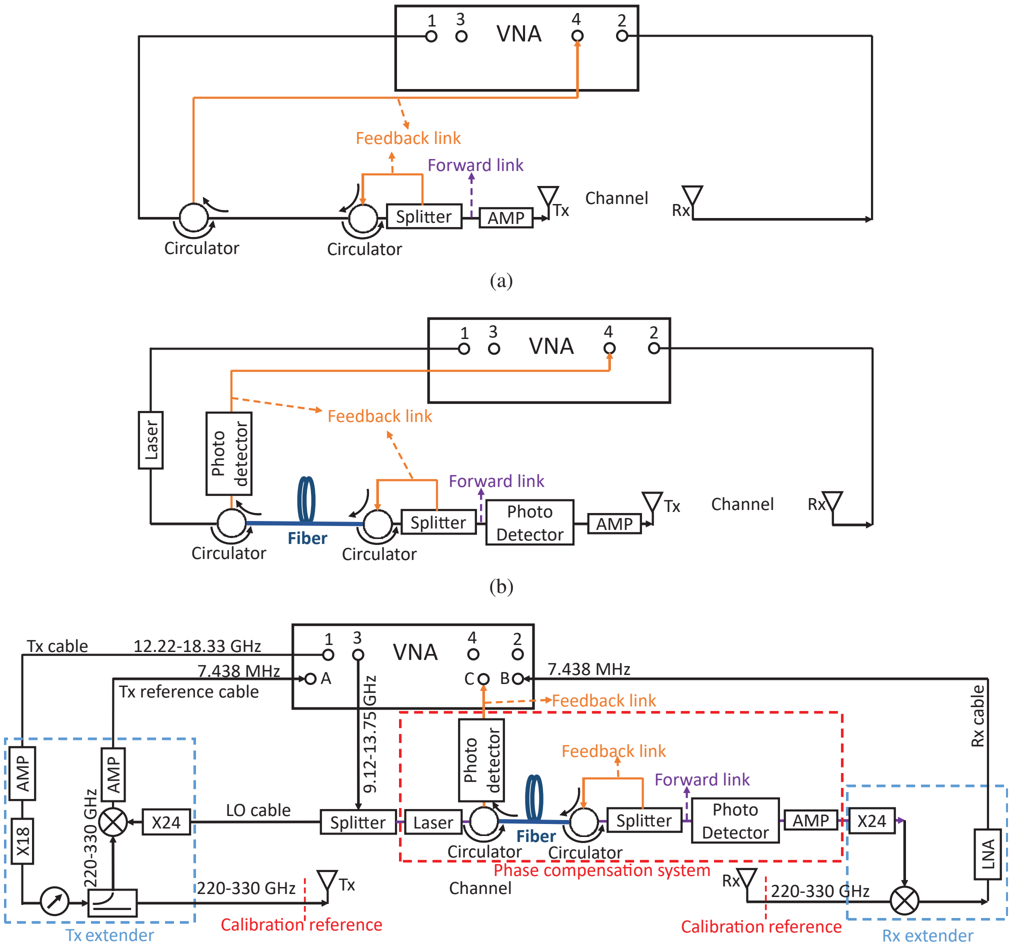


Fig. 1. Block diagram of the proposed RoF VNA-based sub-THz channel sounder: (a) Sub-6 GHz [10];(b) 28 GHz [3];(c) 300 GHz [12].

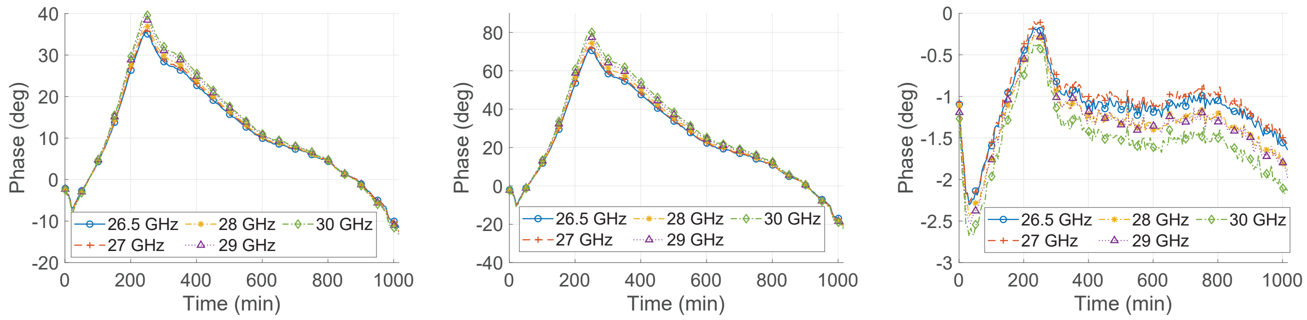
which is directly implemented using microwave circulators, power splitter, and RF cables at sub-6 GHz bands, as shown in Figure 1 (a). This bidirectional scheme was demonstrated to effectively mitigate the unexpected phase change, and was experimentally validated in a back-to-back measurement from 1.55 GHz to 2 GHz. Over the bandwidth, the compensated phase error is within $\pm 4^{\circ}$, which ensures the possibility to apply this phase compensation scheme in higher frequency bands.

2) Phase-compensated channel sounder for 1-30 GHz*:* The phase compensation method introduced in [10] was further explained and extended to optical fiber-based long-range channel sounder in [3], [11]. The block diagram of this phase-compensated long-range channel sounder is shown in Fig. 1 (b). The optical fiber-based phase compensation scheme is composed of a laser with a center wavelength of 1550 nm and two photo detectors, one of which is for the forward link and the other one for the feedback link. The transmitted signal is upconverted to optical signal by the laser and transmit through the single-mode optical cable of length 300 m. The optical power between the forward and feedback links is divided equally by an optical power splitter. Two nonpolarization-maintaining three-port optical circulators could enable bidirectional signal transmission on the same optical fiber. Before fed to the Tx antenna, the signal is amplified by an RF amplifier.

3) Sub-THz phase-compensated channel sounder: Fig. 1 (c) illustrates the block diagram of the sub-THz phase-compensated long-range channel sounder in [12]. The phase compensation scheme in this sub-THz channel sounder aims to stabilize the system phase. The split LO signal is up-converted to optical signal by the laser and transmitted through the optical fiber cable. The optical power of the signal is divided by a optical power splitter. One signal is transmitted to the photo detector on the forward link and the other is sent back to the port C through the optical fiber.

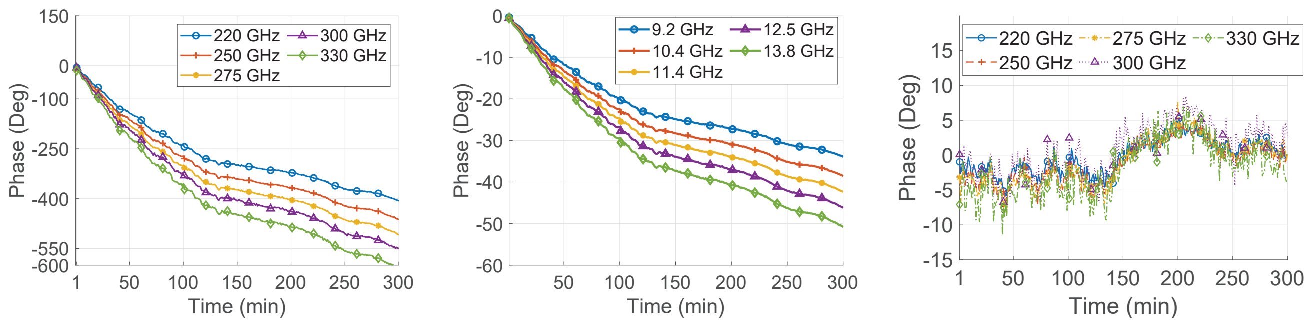
B. Principle of Operation

*1) Sub-*6 *GHz and mmWave:* The signal in the forward link and feedback link are recorded as S-parameter $S_{21}(f)$ and $S_{41}(f)$, respectively. After using the normalization procedure to de-embed the system response, the response of the forward $S_{21}(f)$ and feedback $S_{41}(f)$ links are normalized to 1. Similar as the sub-6 GHz and mmWave, after the normalization procedure, the response of the forward and feedback links



(a) (b) (c)

Fig. 2. Phase of the mmWave phase compensated channel sounder over a period of 17 hours. (a) The forward link; (b) The feedback link; (d) Compensated phase.



(a) (b) (c)

Fig. 3. Phase of the sub-THz phase compensated channel sounder over a period of 5 hours. (a) The forward link; (c) The feedback link; (d) Compensated phase.

are normalized to 1. In the actual channel measurements, the channel frequency response (CFR) $H(f)$ and the frequency response $H_{\text{fw}}(f)$ caused by the mechanical stress and thermal changes on the target cable are recorded in $S_{21}(f)$ as:

$$S_{21}(f) = 1 \cdot H_{\text{fw}}(f) \cdot H(f), \tag{1}$$

Similarly, the frequency response in the feedback link, which contains the cable effects, $H_{\text{fb}}(f)$ is embedded in $S_{41}(f)$ as:

$$S_{41}(f) = 1 \cdot H_{\text{fb}}(f), \tag{2}$$

The signal in the feedback link has undergone twice the phase change in the forward link due to the bidirectional signal transfer on the same cable. Thus, $H_{\text{fw}}(f)$ can be expressed as:

$$H_{\text{fw}}(f) = \sqrt{H_{\text{fb}}(f)} = \sqrt{S_{41}(f)} \tag{3}$$

Finally, the error term $H_{\text{fw}}(f)$ can be deembedded from the CFR $H(f)$ as follows:

$$H(f) = \frac{S_{21}(f)}{\sqrt{|S_{41}(f)|} \exp(j \cdot \frac{1}{2} \cdot \phi_{41}(f))}, \tag{4}$$

where $\phi_{41}(f)$ represents the unwrapped phase of the $S_{41}(f)$.

2) *Sub-THz:* The principle of the sub-THz phase compensation is similar with those at sub-6 GHz and mmWave bands. The forward link and feedback link are recorded in the VNA as the S-parameter $S_{\text{BA}}(f_1)$ and $S_{\text{C3}}(f_2)$, respectively, where $f_1 = 7.438\,\text{MHz}$ and $f_2 = 9.12\text{-}13.75\,\text{GHz}$. The frequency points of the received signal at 7.438 MHz is one-to-one corresponding with that of the transmitted and LO signals. In this sub-THz channel sounder, the LO signal will pass through a $24\times$ multiplier, thus, the relationship between the phase of the error term $\phi_{fw}(f_1)$ and the phase of the feedback link $\phi_{fb}(f_2)$ is $\phi_{fw}(f_1) = 12 \cdot \phi_{fb}(f_2)$. Consequently, the phase compensation can be performed as follows:

$$H(f_1) = \frac{S_{\text{BA}}(f_1)}{\sqrt{|S_{\text{C3}}(f_2)|} \exp(j \cdot 12 \cdot \phi_{\text{C3}}(f_2))} \tag{5}$$

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

III. Channel Sounder Performance Validation

Phase stability is fundamental if the channel sounder is to faithfully record the phase characteristics of the channel [3]. These channel sounders are validated using back-to-back measurements. The phase change introduced by the following two conditions and the amplitude and phase stability after compensation are tested:

1) signal drifting over time (thermal change)

2) cable bending (mechanical stress)

A. Signal Drifting over Long Measurement Time

Practical virtual array or directional scanning measurements could take several hours to record the channel responses. Thus, the measurement system are required to ensure there is no significant signal drift during the entire measurement period. However, signals in fiber optical cable undergo significant phase changes due to small changes in ambient temperature [9]. To verify the robustness of the phase compensation channel sounder, a back-to-back measurement needs to be conducted. After the VNA and the RF amplifier are warmed up, a normalization procedure is carried out to de-embed the system response. The measurement times for the mmWave and sub-THz phase compensated channel sounder are 17 and 5 hours, respectively. The other measurement configurations are demonstrated in Table I.

TABLE I
VALIDATION MEASUREMENT CONFIGURATION

Parameter	mmWave	sub-THz
Thermal change		
Frequency	26.5-30	220-330
Number of points	1501	20001
Measurement time	17 hours	5 hours
Time interval	5 minutes	1 minutes
Cable bending		
Frequency	1-30	220-330
Number of points	4001	20001

The phase results of the mmWave and sub-THz channel sounders are demonstrated in Fig. 2 and Fig. 3, respectively. Fig. 2 (a) shows that the system phase varies over $40°$ without phase compensation. As demonstrated in Fig. 2 (a) and Fig. 2 (b), the phase of the feedback link is observed to be approximately twice that of the forward link. The compensated phase deviation for the period of 17 hours is maintained within $3°$, which proves the stability of the phase compensation scheme at 30 GHz bands within 17 hours. As for the phase of the sub-THz scheme, the phase of the forward link can be seen to vary over $550°$ in 5 hours, which illustrates that the phase change due to the thermal change at 300 GHz band is much more severe than that at 30 GHz. Comparing Fig. 3 (a) and Fig. 3 (b), the phase of the forward link is approximately twelve times that of the feedback link. After compensation, the phase is observed to be within $15°$, which indicates the robustness of this sub-THz phase-compensated long-range channel sounder in 5 hours. Note that due to the effect of the $24\times$ multiplier, even a small phase error variation will become 24 times larger. Besides, Fig. 3 (c) also shows that the fluctuation at 300 and 330 GHz is seen to be much larger compared to that at 220, 250, and 275 GHz, which is possibly caused by the multiplier and mixer inside the Rx extender.

B. Cable Bending

In practical directional scanning measurements, mechanical stresses on the optical fiber are inevitable due to the movement of the antenna positioning stages. We use two ways to characterize the phase change effect introduced by the mechanical stress of the cable and test the stability of the phase compensation scheme:

1) Use a rotation table to mount the cable and rotate together, as illustrated in [3], the cable was mounted on the rotation table and rotate $360°$ to check the stability of the channel sounder.
2) Use a cylinder to bend the cable to mimic the mechanical stress effect in the directional measurements. In [12], cable bending responses are measured for a total of 5 bends around the cylinder at 300 GHz bands. Note that in this paper, we only bent the optical cable.

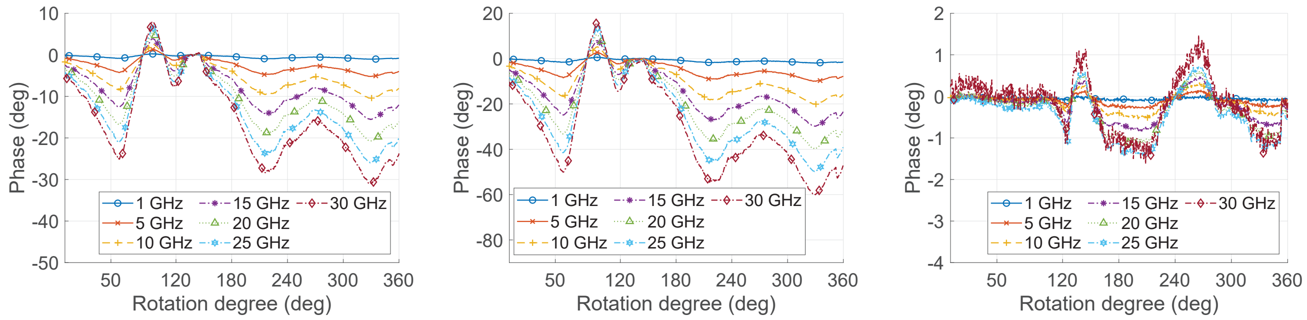
Fig. 4 and Fig. 5 illustrates the mechanical stress phase results at 1-30 GHz and 220-330 GHz bands, respectively. As for the mmWave phase compensated channel sounder, the phase of the forward link is observed to be half that of the feedback link. As illustrated in Fig. 4 (c), the phase change is maintained within $4°$. With respect to the sub-THz phase compensated channel sounder, the phase of the forward link is observed to be unstable as it varies over $400°$. Compared with Fig. 5 (a) and Fig. 5 (b), the phase of the forward link is approximately twelve times the phase of feedback link. After the phase compensation procedure, the system phase is observed to be maintained within $15°$ at 220-330 GHz.

Overall, the phases of these phase compensated channel sounders are observed to be very stable at 30 GHz and 300 GHz bands, and the results indicate the robustness and effectiveness of the phase compensation scheme in these two frequency bands.

IV. CONCLUSION

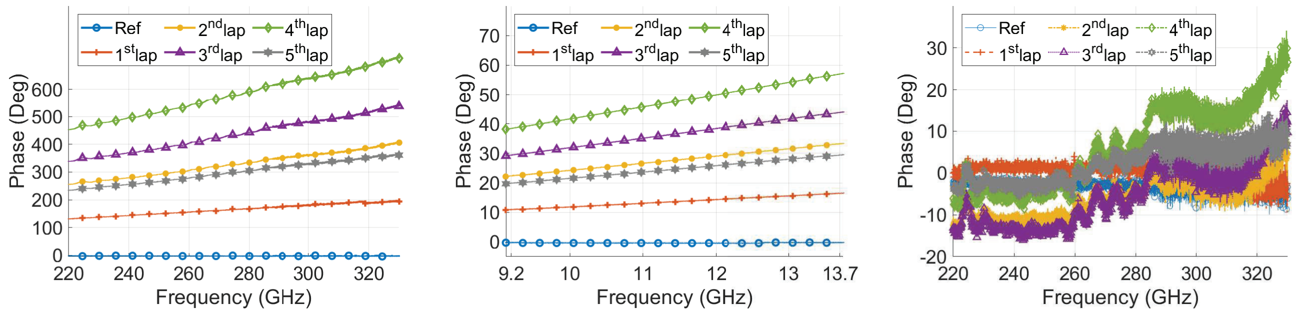
In this paper, an overview of the VNA-based long-range phase compensated channel sounders developed in Aalborg University Denmark is presented. By using the RoF technique and phase compensation scheme, the long-range phase-coherent channel measurement could be conducted. The robustness of these novel channel sounders is validated and specified for the frequency range at 1-30 GHz and sub-THz (i.e. 220-330 GHz) bands by back-to-back measurements. Compared to the phase change introduced by the cable effect of over $40°$ and $600°$ at 30 and 300 GHz bands, respectively, the compensated phase could be maintained within $3°$ and $15°$, respectively, which could enable phase coherent measurements at both frequency bands.

To sum up, these channel sounders could achieve long 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), high dynamic range, and scalable frequency and bandwidth. Besides, due to the phase compensation scheme, the virtual array measurements could be performed by these channel sounders. However, due to the long frequency sweeping time of the VNA, these channel sounders are limited to static scenarios. Our future work plans to perform phase-coherent measurements and verify the virtual array concept at sub-THz bands.



(a) (b) (c)

Fig. 4. Cable bending results of the mmWave phase compensated channel sounder from 26.5 to 30 GHz. (a) The phase of the forward link; (b) The phase of the feedback link; (d) Compensated phase.



(a) (b) (c)

Fig. 5. Cable bending results of the sub-THz phase compensated channel sounder from 220 to 330 GHz. (a) The phase of the forward link; (b) The phase of the feedback link; (d) Compensated phase.

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