Enabling VNA Based Channel Sounder for 6G Research: Challenges and Solutions

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Enabling VNA Based Channel Sounder for 6G Research: Challenges and Solutions

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***Abstract*—To support research and development for sixth-generation (6G) communication, it is imperative to understand the application needs and develop accurate and realistic channel models to meet the application needs. Several key radio technologies are identified for 6G research, including utilization of frequency bands ranging from sub-6 GHz to THz, antenna configuration covering simple single antenna to complicated gigantic multiple-input and multiple-output (MIMO) systems, and diverse deployment scenarios requiring various measurement ranges. This paper summarizes latest strategies to significantly extend the capabilities of current vector network analyzer (VNA)-based channel sounder, mainly radio-over-fiber (RoF) to enable long-range channel measurements, phase compensation to achieve accurate and coherent phase measurement, frequency extension to extend the carrier frequency and frequency bandwidth, and virtual antenna array (VAA) schemes to enable multi-antenna/link channel measurements.**

***Index Terms*—6G Channel sounding and modeling, Radio-over-fiber, Phase compensation, Frequency extension, Virtual array.**

I. Introduction

Sixth-generation (6G) will introduce new services on haptic and tactile communication, e.g. in Virtual Reality (VR) applications, to support remote surgeries and to enable holographic society. Furthermore, it is envisioned that we will have connectivity for all things. Some of the applications will necessitate extremely high data rates, extremely low latency, or ubiquitous connectivity. The communications will also gradually shift from human-centric communications to machine-human-centric communications. To support the 6G vision, several enabling radio technologies have been identified, including the utilization of extreme large-scale antenna systems (also known as massive multiple-input-multiple-output (MIMO), extreme-large massive MIMO or gigantic MIMO), utilization of the legacy sub-6 GHz, sub-millimeter-wave, millimeter-wave and Sub-Terahertz (sub-THz) frequency bands, utilization of ultra-wideband frequency bands, employment of reconfigurable intelligent surface, narrowband internet of things (IoT) radios, etc [1].

Realistic and accurate channel modeling is essential for the design and development of new radio technologies. Radio channel modeling, which characterizes how radio signals propagate between the transmitter and receiver, is essential for the development and performance evaluation of the wireless communication system. To develop accurate and realistic channel models, massive channel measurements in realistic deployment scenarios are performed. The channel sounder is the experimental platform employed in the channel measurements. It is essential that the channel sounder can support channel measurements in various deployment scenarios. Channel sounder system complexity will scale with the capability of the communication system. Therefore, there are several key requirements for channel sounder development to support 6G research: 1) scalable frequency range setting to cover from sub-6 GHz to sub-THz frequency bands along with both narrowband and ultra-wideband scenarios; 2) scalable measurement range to cover short-range and long-range communication scenarios; 3) scalable antenna configuration to cover simple single antenna as well as gigantic MIMO scenarios; 4) scalable sampling rate to cover static as well as dynamic propagation scenarios; 5) excellent system dynamic range to ensure good signaling conditions over deployment scenarios, etc. However, no channel sounders can fulfill all the requirements to our best knowledge.

The vector-network-analyzer (VNA) is a popular frequency domain channel sounder, due to its easy calibration, synchronization, and easy access in most antenna and radio frequency (RF) laboratories. It also offers an excellent system dynamic range. However, it has several limitations to support typical 6G scenarios:

- Constraint carrier frequency and bandwidth setting. VNA can support flexible frequency and bandwidth settings within the specifications. With the help of external frequency extenders, its bandwidth and carrier frequency setting can be extended to cover the promising sub-THz and THz frequency bands in 6G.
- Short measurement range. The VNA is used to record frequency responses between VNA antenna ports. We often need to use radio frequency (RF) cables to remote antennas for channel-sounding purposes in typical deployment scenarios. However, RF cables are very lossy, especially for millimeter-wave and sub-THz frequency bands. Consequently, the measurement range is typically rather small, due to dynamic range issues.
- Limited number of VNA ports. Most commercial VNAs offer only two ports, though some advanced models can offer a few more ports with additional cost. This significantly limits its capability to support multi-antenna/link research in 6G.

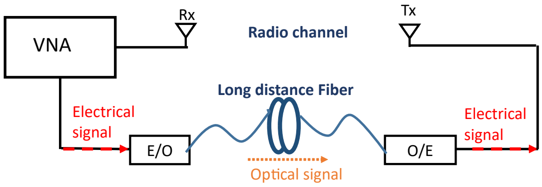

Fig. 1. An illustration of the RoF solution to extend measurement range for VNA-based channel sounder.

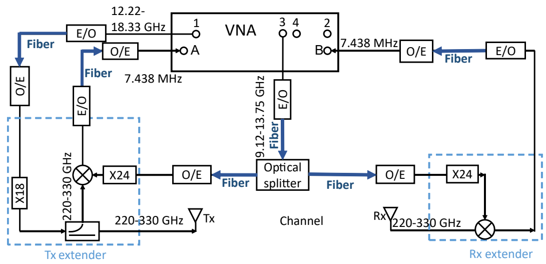

Fig. 2. Block diagram of the RoF enabled 300 GHz VNA-based channel sounder system.

Note that the VNA-based channel sounder also suffers from long measurement time compared to real-time correlative channel sounder. Frequency sweeping in VNA is slow, especially when a small intermediate frequency (IF) bandwidth setting in the VNA is preferred to ensure a high system dynamic range. Furthermore, the measurement time will be significantly prolonged if measurements at many antenna orientations (i.e. in the directional scanning scheme, DSS), or many spatial locations (i.e. virtual antenna array, VAA) are required.

In this work, we review and summarize strategies mainly radio-over-fiber, phase compensation, frequency extension, and VAA schemes, to tackle the above identified three research problems for 6G channel sounding.

II. Photonics enabled channel sounder

A. *Prolonging the measurement distance*

As discussed, one of the main limitations of using the VNA as a channel sounder is that the transmit and receive antennas must be connected to the VNA by cable connection. The tethered setup will result in severe signal loss over radio frequency (RF) cables especially at mmWave and sub-THz frequencies, leading to a very limited measurement range in comparison to the measurement range required to cover typical deployment scenarios in the communication link. To address this problem, the radio-over-fiber (RoF) solution has been widely adopted in the literature, as illustrated in Fig. 1. The electrical signal transmitted from the VNA can be converted to an optical signal, which can be carried by low-lossy optical cables, and then converted back to the electrical signals. Using this RoF scheme, we can solve the measurement range issue completely, at the expense of additional costs. The other disadvantage is that the phase of the fiber is sensitive to mechanical stress and thermal change, which indicates that the RoF scheme cannot be utilized in phase-coherent channel measurements directly. The phase-compensation scheme can be employed to achieve highly accurate and coherent phase measurements.

In [1], [2], a RoF-enabled VNA-based channel sounder at 28 GHz and 140 GHz was reported to investigate the spatial-temporal characteristics at these two frequency bands, and it was concluded that high similarity can be observed for these two bands. [3] investigated the possible sources of measurement uncertainties with the integration of RoF solution and frequency converters in a millimeter-wave VNA-based sounder, and it was concluded that disturbance of the cable only leads to phase variation, and the LO cable presented the worst phase response due to frequency multiplication in the LO chain. This further motivates the phase compensation scheme, which will be discussed later. In [4], a RoF-enabled channel sounder was reported to support urban measurement up to 300 meters at sub-6 GHz. An RoF-enabled channel sounder up to 200 m was reported to support channel measurements at 15, 28, and 60 GHz bands at the airport scenario in [5] and the street scenario in [6], respectively. In [7]–[11], an ultra-wideband double-directional RoF-enabled channel sounder with a measurement range of up to 67 GHz at 145-146 GHz was reported in a microcellular scenario. The RoF concept was also implemented by the commercial VNA, e.g., the distributed modular 2-port VNA, which supports measurement range up to 100 m and frequency up to 43.5 GHz [11].

B. *Frequency extension for Sub-THz and THz bands*

We can employ the frequency extenders for the VNA to enable sub-THz and THz channel measurements with a scalar frequency bandwidth. The RoF scheme has to be employed to enable long-range channel-sounding measurements. To avoid high costs for electrical to optical (E/O) and optical to electrical (O/E) units at sub-THz bands [12], [13], the E/O and O/E conversion were performed at low-frequency bands in the LO before the frequency multiplication [14].

In [14], [15], a RoF-enabled channel sounder at 28 GHz with a measurement range of up to 300 m and at 300 GHz with a measurement range of up to 600 m were reported, with a focus on system design, link budget, and back-to-back and field measurements. Such schemes are also extensively employed in [16] to support the D-band channel measurements. Fig. 2 illustrates its block diagram.

Due to the introduction of the coupler and mixer inside the frequency extenders, the signal loss will be increased. However, the frequency extender also includes a low-noise amplifier to boost the signal level. Due to the use of the active devices in the frequency extender, e.g., the amplifier, the noise figure of those components influences the noise floor of the channel sounder, which would essentially lead to a reduction of the link budget. Frequency extenders are rather expensive. Moreover, the phase variation in the cables before the frequency multiplier will be multiplied by the factor of the multiplier, which makes the accurate phase performance of the channel sounder more challenging. Besides, the frequency

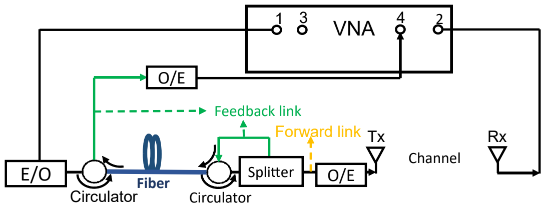

Fig. 3. An illustration of the phase compensated RoF enabled VNA channel sounder.

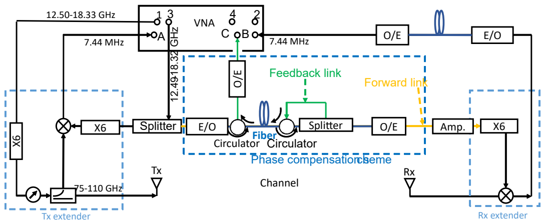

Fig. 4. long-range phase-compensated channel sounder for the W-band.

extender requires one additional VNA transmitting port for the local oscillator (LO) signal and one additional VNA receiving port for the Tx reference signal, which will further increase the system cost of the VNA.

C. Phase-coherent RoF enabled channel sounder

As discussed, at mmWave, the signal loss in the RF coaxial cable is very high, the RoF scheme is used to solve this problem. However, the phase in the fiber is sensitive to thermal change and mechanical stress, which limits the use of the RoF scheme in coherent phase channel measurement. In [17], a phase compensation scheme was proposed as illustrated in Fig. 3, where the basic idea is to exploit a feedback link to record the phase change in the cable. Since the same signal pathway is used in the feedback link and forward link, the random phase variation can be therefore removed in post-processing.

The phase compensation scheme was then extended to the sub-THz frequency bands in [18], solving one of the key issues in the community, i.e. coherent phase measurements at sub-THz bands. It was demonstrated the phase variation can be maintained within 15 degrees over 5 hours in the back-to-back measurements with cable bending effects from 220 to 330 GHz. The phase-compensation scheme only records the phase change in the optical fiber. The phase change after phase compensation is mainly caused by the frequency extender due to the thermal change.

The phase compensation scheme makes the VAA scheme at mmWave and sub-THz frequency bands feasible. In [19], a phase-compensated RoF-enabled channel sounder was proposed to implement the VAA scheme with directional antennas. The proposed VAA scheme with directional antenna elements was further employed to study the omnidirectional path loss [20].

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 signal

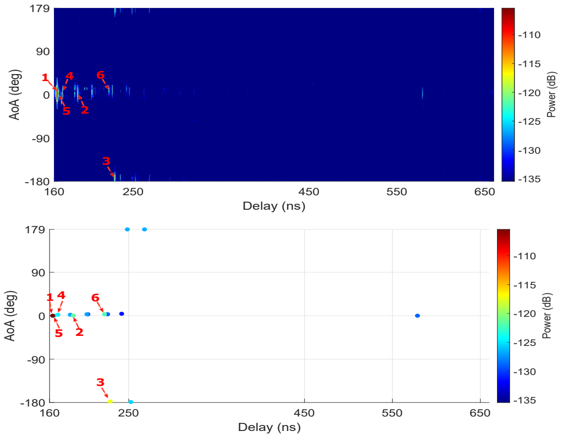

Fig. 5. (top) PADP using DSS and (bottom) PADP using VAA (with the FIBF and SIC algorithms).

loss and cost of the additional components in the phase-compensation scheme, e.g., circulators and optical splitter, are also disadvantages. Fig. 5 depicts the comparison of the power-angle-delay-profiles (PADP) using DSS method and VAA method (with frequency invariant beamforming (FIBF) with the successive interference cancellation (SIC) [21]). The DSS results is the reference to validate the VAA concept at W-bands. The MPC results using the two methods match well.

D. Multi-link RoF enabled channel sounding

As discussed, another limitation with VNA-based channel sounding is the limiting port resource on the VNA, which limits the number of transceiver chains in the sounding system. We can potentially employ a fast switch scheme to address this problem, as done in [22], which can significantly reduce the complexity and cost associated with multiple transceiver chains. However, this scheme can still not ensure simultaneous channel sounding for multi-links. Another possible structure is the utilization and optical delay line and combiner, as shown in Fig. 6. The combiner is used to combine multi-link signals to save the VNA ports. To be able to separate the signals in the multiple links, we can employ delay lines, where signals in different chains can be delayed and thus separated. It was demonstrated in [23] that the multiple channels could be measured simultaneously in one VNA port at sub-6-GHz bands. However, the unstable phase performance of the signals in the delay line at higher frequency bands (e.g., mmWave) limits the use of this scheme in phase-coherent measurements. In [24], [25], a multilink channel sounder that could achieve long-range phase-coherent measurements with minimal VNA ports was proposed, where the RoF technique is utilized to prolong the measurement range, and the mixer scheme is applied to down-convert the mmWave signal to lower frequency bands (i.e., 10–60 MHz) and delay line strategy is used to combine multiple received signals into one port, which saves the port resource of the VNA.

The proposed multi-link scheme was employed for an indoor channel measurement [25], where two Biconical antennas

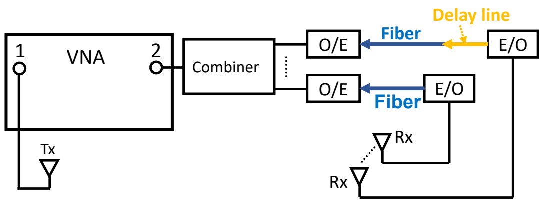

Fig. 6. Delay-line enabled multi-link VNA-based channel sounder.

were employed as two Rx antennas and one biconical antenna was used as the Tx antenna. A virtual uniform rectangular array (URA) (30×23 with 0.4 cm inter-element spacing) was formed at the Tx side using a scanner. The proposed scheme can be used to record channel responses for two links simultaneously.

E. Multi-antenna channel sounder based on the VAA scheme

Multi-antenna channel sounder is complicated and expensive at the sub-THz bands. In [26], the correlation-based channel sounder can support 2x2 multi-antenna measurements at 300 GHz. However, there has been no large-scale real antenna array (RAA) reported at sub-THz bands for this moment to our best knowledge. The main limitations are the hardware, e.g., power amplifier, analog-to-digital converter (ADC), the sub-THz antenna arrays, phase control, and the extremely high cost of the RF chains (i.e. frequency extenders). Analog beamformer structure, i.e. phased array-based channel sounder, is also challenging due to e.g. antenna packaging, phase shifter losses, array calibration, etc. [27]. A phased array, which offers fast electrical beam-steering capability, can be connected to the VNA port to measure the channel spatial profile. However, it is more expensive, and its extension to sub-THz has not been reported so far due to the complexity of the sub-THz phased array design.

Due to the limited ports, several schemes have been reported in the literature to measure the channel spatial profile, e.g. the directional scanning scheme (DSS), and the virtual antenna array (VAA) scheme. The most popular scheme in the state-of-the-art for spatial channel measurements at the sub-THz is the DSS scheme. In the DSS scheme, a directive antenna in the center of a turntable is mounted on a turntable and we directly record the channel response at each rotation angle. By doing so, we can directly obtain the channel spatial profiles. It has gained popularity due to its simplicity, low cost, and high signal-to-noise ratio (SNR) measurements. However, the spatial resolution is constrained by the employed directive antenna.

In the VAA scheme, a single antenna (e.g. omnidirectional or directional antenna) is mounted on a positioner, and the antenna is mechanically moved to predefined spatial locations, thereby forming arbitrary virtual array configurations. The channel frequency responses (CFRs) are recorded at each virtual array element location. Due to the realized virtual antenna array, channel spatial profiles with a high spatial resolution can be obtained based on proper array processing algorithms. The VAA scheme is attractive since it is simple and cost-effective. Furthermore, compared with real antenna arrays, the undesired antenna effects, e.g., mutual coupling, are not present among virtual array elements. VAA is advantageous compared to DSS as better spatial resolution offered by the virtual antenna array aperture can be achieved. Furthermore, better SNR, which is critical for sub-THz frequency bands, can be realized with the VAA. The multipath signal responses at different VAA elements are strongly correlated, with additional phase differences related to the VAA configuration. Using the beamforming algorithm to compensate the phase differences, the signal responses can be coherently boosted, which would realizes an increase of $10{\cdot}\log_{10}(M)$ in dB in the SNR in principle.

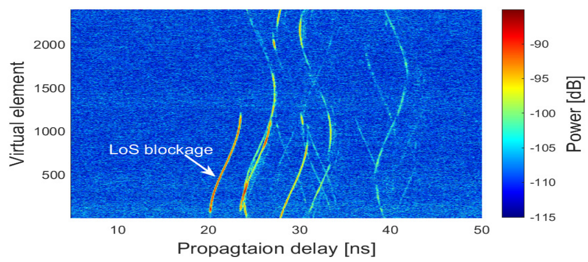

Fig. 7. Multi-antenna channel measurement based on the VAA scheme at the sub-THz band.

However, unlike DSS, the VAA scheme 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 as the frequency increases to sub-THz bands, which means a highly accurate positioning stage or turntable is required for achieving VAA scheme. The VAA scheme requires the channel to be static while measuring. Thus, it is not suitable for dynamic scenarios. For the VAA scheme, a coherent phase is seen as essential, though mechanically and electrically difficult at the sub-THz. The discussed phase-compensation scheme is the enabling solution to achieve this objective.

Fig. 7 illustrates a multi-antenna channel measurement result based on the VAA scheme at 100 GHz [28]. The discussed phase-compensated channel sounder (i.e., Fig. 4) is adopted where a single omnidirectional antenna is mechanically rotated to realize a 2400-element VAA. As observed, channel multipaths are detected with 's'-alike curves across the antenna array. It is due to the high delay resolution from the ultra-wide system bandwidth (10 GHz) and the near-field spherical propagation effect introduced by the large-scale array. Besides, the line-of-sight (LoS) path is observed with a partial curve onto the array, demonstrating spatial non-stationarity [29].

III. Conclusion

VNA is by default a frequency-domain radio channel sounder, which has been extensively utilized in the state-of-the-art for channel measurement purposes. However, its application for 6G is limited. In this paper, we summarize various schemes to significantly extend the capabilities of the VNA-based channel sounder to support 6G research. More specifically, 1) the RoF technique can solve the measurement range limitation issue with the VNA; 2) the phase compensation scheme is an effective solution to track the random phase problem with the optical cable, and it has been demonstrated to be highly effective for sub-6 GHz, mmWave, and sub-THz frequency bands; 3) the frequency extender scheme can be employed to extend the system's operating frequency and range; 4) the delay line can be introduced to support multi-link/multi-user channel measurements simultaneously; and 5) the VAA scheme is a highly effective solution for static propagation channels, which can offer extreme spatial resolution and improved SNR. The enhanced VNA-based channel sounder will be a valuable instrument to support 6G research.

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