THz Channel Sounding System for Dense Lab Environment (330 GHz – 500 GHz)

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Abstract

This paper presents a novel VNA-based THz channel sounding measurement setup that incorporates phase compensation, leveraging both power-adjustable radio-over-fiber (RoF) technology and a dedicated phase compensation mechanism for the 330–500 GHz range. The performance of system has been evaluated through a link budget analysis with optical fiber lengths of up to 600 m in a dense lab environment, along with radio channel sounding assessments at distances of up to 5.61 m.

***Index Terms*—Tera hertz channel sounding, Long-range channel measurement, 330 to 500 GHz**

1. Introduction

The increasing demand for ultra-fast data transmission is accelerating global interest in next-generation wireless communication technologies, driving advancements beyond fifth-generation (B5G) networks and laying the foundation for sixth-generation (6G) systems. Among these emerging technologies, 0.1-10 THz communication stands out due to its vast, underutilized spectrum, offering the potential to achieve ultra-high data rates[1]. As a result, sub-THz frequencies are expected to play a pivotal role in shaping the future of wireless connectivity.

Despite its promising benefits, sub-THz communication faces several challenges, primarily due to its high atmospheric attenuation, which is significantly more pronounced than in lower frequency bands. Additionally, as frequencies increase, sub-THz wavelengths become comparable in size to environmental particles such as dust and raindrops, leading to distinct propagation characteristics that differ from those observed in conventional lower-frequency communications. Overcoming these challenges is crucial for fully leveraging sub-THz technology in future wireless networks[2]. These challenges have sparked significant interest in studying sub-THz frequency bands, particularly in understanding their wireless radio propagation characteristics through channel sounding and modeling for future communication. Research efforts have been dedicated to developing propagation channel models for sub-THz frequencies in urban environments, focusing on deployments at 90 GHz and 300 GHz[3]-[4]. However, most of these studies have been limited to numerical and analytical modeling, with restricted consideration of environmental variables and parametric studies. Expanding these investigations is essential for developing accurate and practical models to support the real-world deployment of sub-THz communication systems[5].

Reliable channel data measurement is essential for the successful design of wireless communication systems, which makes channel sounders crucial for obtaining accurate measurements. These systems are typically divided into two categories based on their operating principles: time-domain channel sounders (such as correlation-based sounders) and frequency-domain channel sounders. Among the frequency-domain options, the vector network analyzer (VNA) is widely used due to its scalability in bandwidth and ease of calibration. However, the VNA relies on coaxial cable connections between the analyzer and remote antennas, and as frequency increases, signal loss through the cables becomes more pronounced. This leads to a reduced dynamic range and a limited measurement range, especially in the sub-THz frequency bands[6].

This paper presents a phase-compensated, dynamic-range-adjustable design for a long-range sub-THz VNA-based channel sounder system, operating in the 330 to 500 GHz range. The structure of the paper is as follows: Section II outlines the design principles of the channel sounder architecture, followed by a detailed description of the long-range sub-THz channel sounder system. Section III presents the measurement setup and evaluations of radio channel sounding conducted within a dense lab environment. Finally, the paper concludes in Section IV.

2. Channel Sounder Architecture

The proposed system is a VNA-based wideband channel sounder designed for precise sub-THz measurements. It features synchronized transmitters and receivers capable of sweeping across a broad frequency range, enabling accurate frequency response characterization. The collected data is processed to extract critical channel parameters, including the channel impulse response (CIR) and power delay profile (PDP). With its high dynamic range and wide bandwidth, the system achieves fine temporal resolution, making it well-suited for studying signal propagation in highly lossy sub-THz environments.

To address this limitation, RoF techniques are incorporated into VNA-based sounders. RoF uses electrical-to-optical (E/O)

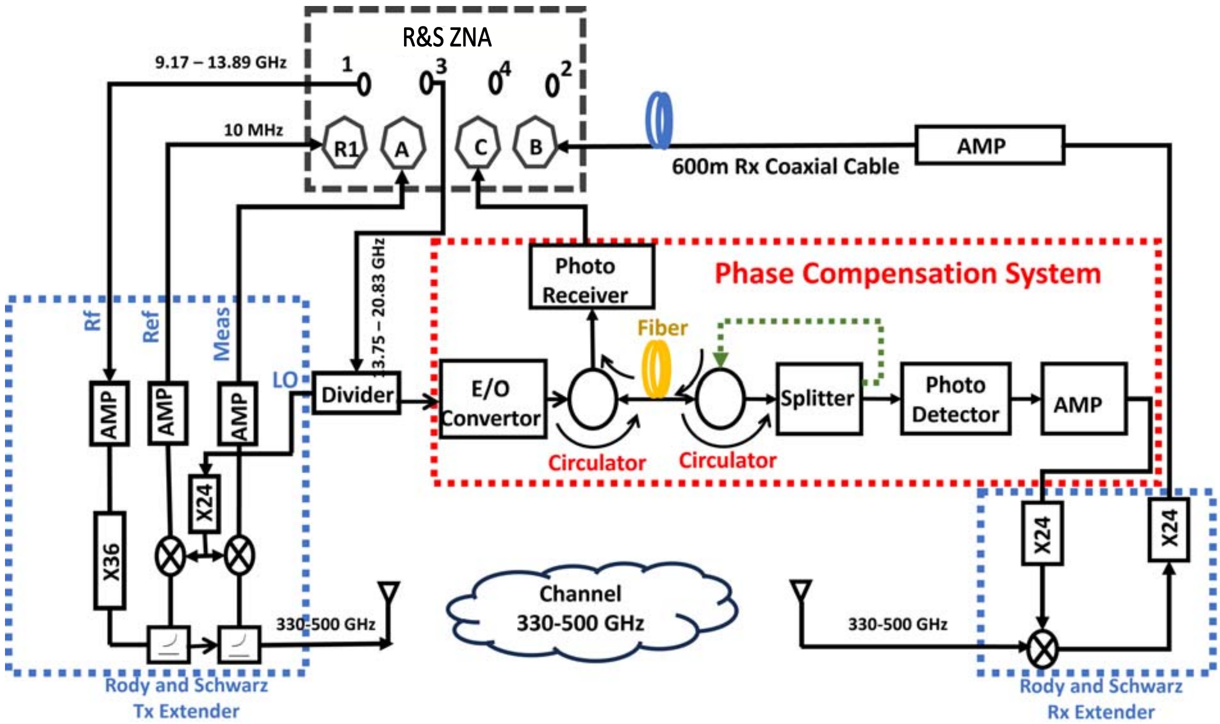


Fig. 1. Block diagram of the proposed 330 to 500 GHz RoF VNA-based sub-THz channel sounder.

and optical-to-electrical (O/E) units to convert electrical signals into optical signals, which are then transmitted through fiber optic cables that exhibit minimal signal loss. At the receiving end, the optical signal is converted back to an electrical signal. This approach significantly reduces signal degradation, extending the measurement range, and improving the accuracy of sub-THz channel characterization. These advancements in channel sounding technologies are vital for improving the reliability and precision of sub-THz communication models, facilitating their effective deployment in real-world applications.

The core of the RoF system is an electro-optical modulator (laser) that converts the electrical signal into an optical signal with a wavelength of 1550 nm. This optical signal is transmitted through a 300 m fiber optic link and is then reconverted into an electrical signal at the receiver end. In theory, this setup allows for a Tx-Rx separation of up to 600 m, opening up new possibilities for long-range THz channel sounding.

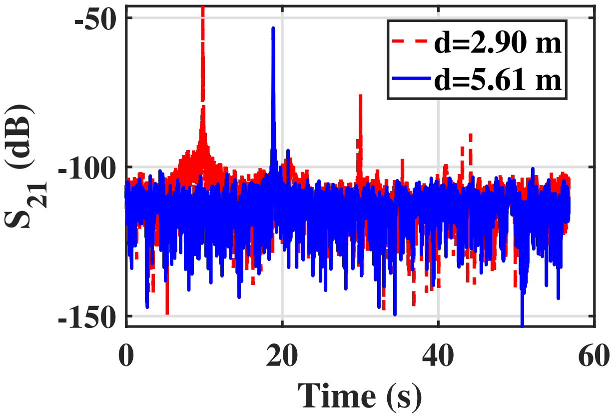
A. Long Range Channel Sounder Architecture

The long-range channel sounder setup is constructed using the Rohde & Schwarz four-port ZNA R&S®ZNA26, which operates up to 67 GHz in its coaxial configuration, as shown in Fig. 1. To extend the frequency range to 330–500 GHz, VNA frequency extension units R&S® ZC500 from Rohde & Schwarz are employed, along with LHA-HG-WR2.2 horn antennas from Antreal. These ZC500 units integrate essential components, including frequency multipliers, mixers, and filters, to facilitate signal conversion to the sub-THz range. However, the coaxial cables connecting the VNA to the extension units introduce significant signal losses, further limiting the measurement range of short-range setups.

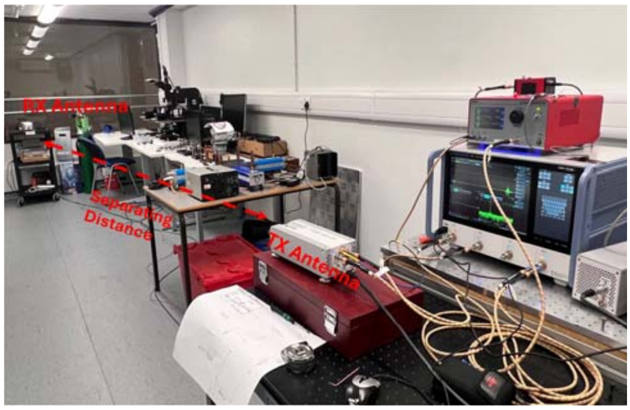
To ensure precise phase stabilization in long-range sub-THz frequency-domain radio-over-fiber (RoF) systems, a dynamic range-adjustable optical-power phase-compensated electro-optical system is implemented at the receiver. This advanced setup integrates power-adjustable EO and OE converters, with a 600 m fiber optic cable serving as the transmission medium for the LO signal. A robust phase compensation mechanism, incorporating two three-port optical circulators, enables bidirectional signal propagation (forward and feedback) through the same optical fiber. This feedback loop effectively mitigates impairments caused by thermal fluctuations and mechanical stress in the fiber, thereby preserving signal integrity and phase coherence.

To meet the input power requirements of the frequency extender's LO input, the output amplitude from the OE converter in the LO forward path necessitates amplification. For this purpose, a ERZA-LNA-1000-27-30-4 amplifier, operating within the 10–27 GHz range with a typical gain of 28 dB, is incorporated. This ensures adequate power levels for subsequent signal processing stages.

Furthermore, the intermediate frequency (IF) measurement signal must be transmitted across a 600-meter distance. Given its IF of 10 MHz, transmission over a coaxial cable remains



(a)



(b)

Fig. 2. Channel impulse responses (CIRs) at the LOS distances of 2.90 m and 5.61 m (b),Experimental setup for VNA-based channel sounder system

feasible with manageable signal attenuation. To this end, an RG58U coaxial cable is selected, which introduces approximately 25 dB of attenuation over the given distance. To compensate for this loss and maintain the system's dynamic range, an additional amplification stage is employed using a Mini-Circuits ZFL-500LN+ amplifier, which operates over the 0.1–500 MHz range and provides a typical gain of 28 dB. This ensures signal fidelity and robustness, thus optimizing system performance for precise and reliable sub-THz channel characterization.

TABLE I
LONG-RANGE SYSTEM MEASUREMENT PARAMETERS

	Parameter
IF Bandwidth	50 Hz
Points	25001
f_{start}	330 GHz
f_{stop}	500 GHz
Meas. cable length (Rx)	600 m
LO cable length (Rx)	600 m
Range	10 m
Dynamic Range	90 dB

3. Measurements

The long-range measurement setup was carefully designed to ensure high precision in characterizing sub-THz propagation over extended distances. The RX extender head was connected via a 600-m RoF link and coaxial cables, requiring an advanced calibration approach. To address this, the enhanced response method was employed, effectively shifting the reference plane to the waveguide test ports to mitigate systematic errors. The Thru-Reflect-Line (TRL) calibration standards were measured within the local Tx unit, which was connected to the VNA via 1.2-m cables. To compensate for expected free-space path losses, SGH-26-WR2.2 horn antennas were integrated into the setup. Additionally, a laser alignment system was used to ensure a clear line of sight (LOS) between the transmitter and receiver antennas.

A comprehensive frequency sweep spanning 330 GHz to 500 GHz was conducted, capturing 25,001 discrete frequency points with an IF bandwidth of 50 MHz [see Table I]. The VNA recorded the measured S-parameters, which were subsequently transformed into the time domain for further analysis. The performance of the setup was evaluated by taking measurements at incremental antenna separations from d= 2.90 m to 5.61 m,

As illustrated in Figure 2(a), the results demonstrate a gradual increase in signal propagation delay with greater antenna separation—an expected outcome due to the constant velocity of electromagnetic wave propagation. Additionally, the signal amplitude decreases as the separation increases from d=2.60 m to 5.91 m, primarily due to the cumulative effects of free-space path loss. A notable difference in noise levels around the signal peaks is observed, likely resulting from the inclusion of additional active components, such as optical converters and amplifiers, in the long-range system. The highest peak corresponds to the LOS, whereas the remaining peaks represent reflections and scattering for each separation distance due intense Lab environment[see Fig. 2(b)] . These additional components introduce extraneous noise, affecting the overall measurement clarity. However, despite these variations, the impact of noise remains minimal, as the primary signal peaks remain well above the noise floor.

4. Conclusion

This paper presents a novel VNA-based THz channel sounder developed for the 330 GHz to 500 GHz frequency range. The system incorporates phase compensation system and utilizes power-adjustable RoF technology to enable long-range measurements. Preliminary sub-THz channel sounding experiments were conducted in a dense lab environment for distances ranging from 2.90 m to 5.61 m, demonstrating the system's potential for sub-THz communication applications

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