

Key Metrology Requirements and Industrial Benefit Assessment for the 6G Communication Era

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Abstract. As research into 6G enters a critical window, Terahertz (THz) communication has emerged as a core enabling technology for the 6G physical layer, owing to its immense bandwidth and potential for integrated sensing and communication. However, the extreme frequency band introduces significant challenges for the existing metrological framework, including device non-linearity, near-field propagation effects, and measurement uncertainty in ultra-wideband signals. From the perspective of national metrological infrastructure supporting industrial development, this paper systematically explores the key metrology requirements for 6G THz communication across device characterization, spatial propagation, and system integration. Furthermore, it provides a quantitative assessment of the economic value that precise metrology contributes to shortening R&D cycles, enhancing manufacturing yields, and optimizing deployment costs. The research demonstrates that establishing a standardized and traceable 6G communication metrology system is a strategic cornerstone for overcoming commercialization bottlenecks, dismantling technical trade barriers, and achieving high-quality industrial development.

Keywords: 6G Communication, Terahertz, Communication Metrology, Industrial Benefits, Metrological Traceability.

1. Introduction

The rapid evolution of mobile internet, intelligent manufacturing, and integrated space-air-ground networks has brought the global wireless communication industry to a critical juncture, marking the transition toward the Sixth Generation (6G) of mobile communication. Compared to 5G, 6G imposes significantly more stringent requirements on transmission rates (reaching Tbit/s levels), latency (microsecond levels), and system reliability. The Terahertz (THz) band, characterized by its abundant spectral resources, is widely recognized by academia and industry as the pivotal enabling technology for the 6G physical layer. However, the industrialization of THz communication involves more than just a simple extension of frequency; it entails a multidimensional revolution in physical mechanisms, including signal generation, spatial propagation, and hardware integration.

In this technological paradigm shift, communication metrology—as the "yardstick" for high-quality national development—has evolved from traditional post-event inspection to proactive definition and full-lifecycle support. As communication systems migrate toward Extremely Large-Scale MIMO (XL-MIMO) and near-field propagation, existing measurement standards and traceability systems face unprecedented challenges. Critical questions persist: How can power consistency be ensured at extremely high frequencies? How can the non-stationary characteristics of complex spatial channels be quantified? And how can the gain performance of Intelligent Reflecting Surfaces (IRS) be precisely evaluated? These technical bottlenecks directly affect the deployment reliability and industrial cost-effectiveness of 6G technologies [1].

This paper systematically explores the key metrology requirements for 6G THz communication across device characterization, spatial propagation, and system integration. Beyond technical analysis, it provides a quantitative assessment of the economic value that a robust metrology system contributes to the communication industry chain. By implementing precise metrological evaluation, enterprises can significantly shorten R&D cycles, optimize process parameters, and enhance product yields, thereby establishing technological dominance based on metrological consistency in a highly

competitive international market. Through an investigation of the coupling mechanism between metrology, standardization, and industry, this paper establishes a strategic framework with engineering implications for the high-quality development of 6G.

2. Core Technical Architecture of 6G Terahertz Communication

2.1 THz Signal Generation and Reception Paths

Based on different physical implementation mechanisms, THz communication system architectures are primarily categorized into three paths: all-electronic, photonics-aided, and all-photonics. Each path imposes distinct metrology requirements for signal integrity. The all-electronic architecture relies mainly on solid-state electronic devices, such as Schottky barrier diodes or High Electron Mobility Transistors (HEMTs), to achieve signal up-conversion through frequency multiplier chains. This architecture offers high integration and strong compatibility with existing electronic systems. However, it faces the challenge of a sharp decline in output power as frequency increases, which demands extremely high sensitivity in the metrology of weak signal power [2].

The photonics-aided architecture is based on the principle of optical heterodyne beating, utilizing Uni-Traveling-Carrier Photodiodes (UTC-PDs) to convert two optical signals with a frequency difference into THz waves. This architecture boasts ultra-wide bandwidth and low phase noise, supporting the seamless integration of wireless links with existing fiber-optic backbones. It is currently the mainstream solution for achieving Tbit/s high-speed transmission. The core of the all-photonics architecture is the Terahertz Quantum Cascade Laser (THz-QCL), which can directly generate signals above 1 THz. This is suitable for specialized communication scenarios requiring ultra-high bandwidth, though it is currently limited by the need for cryogenic operating environments and difficulties in chip-level integration.

2.2 High-Order Modulation and Constellation Shaping Technologies

To approach the Shannon limit within the finite THz spectrum, 6G systems have introduced more complex modulation and coding strategies. MQAM modulation is evolving from 16QAM to 64QAM and even 256QAM. As the modulation order increases, the Euclidean distance between constellation points is further compressed. Consequently, the system has an extremely low tolerance for Error Vector Magnitude (EVM) and phase noise, requiring the metrology system to provide higher precision in vector analysis.

Regarding constellation shaping technology, Geometric Shaping (GS) optimizes mutual information by altering the spatial distribution of constellation points. In contrast, Probabilistic Shaping (PS) maintains the constellation positions while reducing the frequency of high-amplitude points through non-uniform distribution. While these non-uniform signal characteristics effectively reduce the system Bit Error Rate (BER), they also present new challenges for the accurate measurement of the Peak-to-Average Power Ratio (PAPR). Precise metrology of these non-linear characteristics directly impacts the linearity evaluation of power amplifiers and the overall energy efficiency analysis of the system, serving as a critical link in guaranteeing 6G communication quality [3].

2.3 Evolution and Modeling of THz Channel Characteristics

The propagation characteristics of the THz band provide the physical basis for system design, and the accuracy of channel modeling directly determines the reliability of industrial deployment. Current channel modeling has evolved from traditional deterministic methods to hybrid modeling that combines deterministic and statistical approaches. Accurate channel models rely heavily on massive empirical measurement data. Supported by institutions such as the National Institute of Metrology (NIM), precise measurements of atmospheric absorption loss, material reflection coefficients, and multipath fading enable the establishment of traceable THz channel databases, providing scientific algorithmic input for 6G network planning.

Furthermore, because 6G extensively adopts Extremely Large-Scale MIMO (XL-MIMO), communication distances often fall within the Rayleigh distance, causing signals to exhibit complex near-field characteristics. This necessitates a fundamental shift from traditional far-field channel metrology models to spherical wave models. In such near-field non-stationary channel environments, accurately evaluating the pointing accuracy and spatial gain of beamforming has become a core technical problem that must be addressed in the field of modern communication metrology.

3. Industrial Benefit Assessment of 6G Communication Metrology

3.1 R&D Phase: A Multiplier for Cost Reduction and Efficiency

In the early stages of 6G development, exorbitant hardware costs and complex system designs represent core challenges for enterprises. A precise metrology system can directly enhance R&D efficiency through the standardization of parameters. Traditional communication system designs often necessitate substantial hardware design margins due to the lack of precise characterization of component parameters, such as non-linear distortion and thermal drift. By adopting standardized metrology specifications established by institutions like the National Institute of Metrology (NIM), enterprises can obtain accurate performance baselines for components. This capability allows for the precise optimization of design schemes, significantly reducing the redundancy of the Bill of Materials (BOM). Estimates suggest that comprehensive metrological support can shorten R&D and debugging cycles by 20% to 30%.

Furthermore, the complexity of 6G chips is immense, where failed tape-outs result in the loss of tens of millions in R&D investment. By integrating on-chip in-situ calibration and precision parameter measurement into the R&D process, enterprises can identify process defects at an early stage, effectively mitigating the costs associated with trial and error.

3.2 Production and Deployment Phases: The Anchor for Quality Consistency

The large-scale mass production and deployment of communication equipment impose rigorous demands on product consistency. As the benchmark for quality control on production lines, metrology directly determines product yield and subsequent maintenance costs. In automated production lines, the uncertainty of testing equipment directly impacts product qualification decisions. Establishing a unified traceability system ensures consistency across testing environments at different bases and production lines, potentially increasing the yield of terminal products by 3% to 5%, thereby directly optimizing the economic output of large-scale manufacturing.

Regarding infrastructure deployment, the coverage precision of base stations in THz and Intelligent Reflecting Surface (IRS) scenarios directly dictates network quality. The standard path loss models and beamforming calibration specifications provided by metrology systems ensure the success of initial base station deployment. This effectively reduces the need for additional base stations required for coverage hole-filling. Such precision coverage models can significantly decrease the total Capital Expenditure (CAPEX) and Operating Expenditure (OPEX) for network operators [4].

3.3 Trade and Standardization Dividends: The Passport for International Competitiveness

In the context of economic globalization, metrology serves as the fundamental gateway for communication equipment to enter international markets, with its economic benefits manifested through the elimination of technical trade barriers. The global market access for China's communication industry is highly dependent on Mutual Recognition Arrangements (MRAs). Relying on the national traceability system, corporate products can obtain internationally recognized performance certifications. This not only eliminates the exorbitant expenditures required for repetitive testing of basic parameters in export destinations but also reduces market entry costs by over 30% for individual products, substantially strengthening the international competitiveness of domestic communication equipment.

Moreover, metrology provides the essential support for the formulation of standards, while standards lead industrial development. By translating China's scientific achievements in THz metrology into international standards, the nation's communication enterprises will secure greater pricing power and ecological definition rights in the 6G era. This transition from a follower to a standard-setter represents the ultimate economic dividend generated by metrological advancement.

4. Key Technical Challenges and Metrology Bottlenecks in 6G Terahertz Communication

4.1 Precision Metrology and Characterization Issues for Core Devices

To meet the demands of 6G ultra-wideband signal processing, baseband devices such as ADCs and DACs must achieve synergistic optimization between high-speed sampling and high-precision quantization. Current research primarily focuses on increasing sampling rates to support wideband transmission, yet it faces persistent issues at high frequencies, including limited resolution, significant quantization noise, and rapid power consumption growth. From a metrology perspective, existing measurement equipment struggles to maintain consistency and traceability across hundreds of GHz of bandwidth. Furthermore, the heterogeneous integration of III-V semiconductors and CMOS processes poses severe challenges for on-wafer parameter metrology and thermal characteristic assessment; the lack of unified evaluation standards directly limits the iteration efficiency and large-scale application of heterogeneous chips.

4.2 Complex Spatial Measurement for Extremely Large-Scale MIMO

Extremely Large-Scale MIMO (XL-MIMO) achieves high-dimensional spatial multiplexing through the integration of hundreds or thousands of antenna elements, but it faces severe physical constraints in the THz band. As antenna scale and operating frequency increase, systems readily enter the near-field propagation region, rendering traditional far-field channel models inapplicable. In such non-stationary near-field environments, spatial parameters are highly correlated and non-uniformly distributed across sub-arrays, making the construction of accurate and generalizable channel models a technical difficulty. From a metrological standpoint, the absence of metrology specifications for near-field spatial power distribution based on spherical wave models results in significant uncertainty in beamforming pointing accuracy evaluation. Additionally, distributed baseband processing architectures impose extreme requirements on picosecond-level time-frequency synchronization between nodes, and quantifying the impact of residual phase noise on system capacity remains a prerequisite for the commercialization of XL-MIMO [5].

4.3 Testing and Engineering Bottlenecks of Intelligent Reflecting Surfaces (IRS)

Intelligent Reflecting Surface (IRS) technology enhances links at low power by adjusting the phase and amplitude of incident electromagnetic waves, representing a critical path toward "Green 6G." However, its engineering deployment faces numerous bottlenecks. Current measurement of phase control precision for large-scale passive elements remains subject to significant uncertainty, limiting deployment accuracy in complex environments. In the THz band, electromagnetic properties of reflecting materials, inter-element coupling effects, and environmental factors exert significant influences, yet reliable, traceable experimental data remain scarce. Establishing standard reflection efficiency evaluation models and Over-the-Air (OTA) test environments is essential for assessing the coding and diversity gains of IRS. Without precise metrological evaluation, a significant gap between theoretical gains and actual commercial performance will persist, hindering the integration and standardization of IRS within existing cellular network architectures.

5. Summary

This paper provides a comprehensive review of the technical challenges in 6G Terahertz communication and highlights the pivotal role of precision metrology in facilitating the transition from laboratory research to industrial application. The research demonstrates that establishing a standardized and traceable 6G communication metrology system is essential not only for overcoming bottlenecks in device characterization and near-field measurement but also for generating substantial economic and trade benefits by optimizing R&D cycles, enhancing manufacturing yields, and promoting international standardization.

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