**National Journal of RF Circuits and Wireless Systems**
Vol. 2, No. 1, Jan - Apr 2025, pp. 9-20
DOI: https://doi.org/10.17051/NJRFCS/02.01.02

# RF Performance Evaluation of Integrated Terahertz Communication Systems for 6G

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**Article Info**

***Article history:***

Received : 18.01.2025
Revised : 10.02.2025
Accepted : 19.03.2025

***Keywords:***

6G wireless networks,
Terahertz communication,
RF front-end,
Spectral efficiency,
Error vector magnitude (EVM),
Beamforming,
Channel modeling,
THz impairments,
High-frequency propagation,
Integrated THz systems.

**ABSTRACT**

6G wireless networks demand unprecedented data transmission speeds, extremely low latency and massive simultaneous connectivity, capabilities that conventional RF networks can't achieve by themselves. Utilizing THz radio frequency bands has potential because they provide enormous bandwidths and facilitate high-speed, short-range communications. We examine the RF characteristics of fully integrated terahertz radio systems for future 6G systems. The research examines THz transmitter and receiver design as well as channel modeling considering atmospheric propagation, impairments from phase noise, I/Q imbalance and challenges unique to the THz region such as molecular absorption and beam misalignment. An integrated simulation and analytical approach is used to characterize vital system performance metrics such as power efficiency, spectral efficiency, EVM and link reliability. It has been shown through simulation that in spite of promising data rates for THz systems, the choice of RF front-end design and beamforming algorithms significantly impacts the ability to control power loss and interference. This study identifies design considerations and offers system-level recommendations for effectively implementing integrated THz-RF systems in the emerging 6G wireless networks.

## 1. INTRODUCTION

Rapidly expanding interests in cutting-edge services including holographic communication, immersive XR, driverless vehicles and the global Internet of Everything are driving the need for wireless networks that can handle extraordinary capacities. 6G networks are expected to provide peak data rates of over 1Tbps, achieve latency as low as sub-milliseconds, enable reliable low-latency transmission and be able to connect over $10^7$ devices in one square kilometer. The sub-6 GHz and even millimeter-wave bands have restricted bandwidths and cannot support the advanced performance of nG networks.

The terahertz (THz) frequency band which ranges from 0.1 to 10 THz, has been identified as a vital technology for enabling 6G mobile networks. The THz band provides a virtually unbounded amount of highly continuous spectrum, enabling extraordinarily high capacity communication. Moreover, THz waves enable very small, powerful directional antennas that enable multiplexing and beamforming for extremely dense wireless networks. As a result, THz communication is well suited to short-distance, high-capacity transmissions in applications such as wireless backhaul, chip-to-chip communication and indoor ultrafast connections.

Employing THz bands in wireless communication networks requires overcoming a wide range of daunting obstacles. The combination of free-space attenuation and water and oxygen molecules absorbing THz signals severely degrades their reach and integrity. Designing low-noise, high-gain RF front-end devices, including THz amplifiers, oscillators, mixers and antennas, is challenging due to limitations and issues that arise when operating at these high frequencies. Aligning and keeping THz beams focused on the intended receiver can be challenging due to the exceptional directionality of these signals. Additionally, key RF impairments like phase noise, I/Q imbalance and non-linear distortions become more severe at THz frequencies, leading to deterioration of system performance indicators such as EVM, BER and spectral efficiency.

Conducting a rigorous RF performance study is essential to evaluate the practical prospects and constraints of integrated THz-band systems for next-generation networks. Our study seeks to fill this gap by evaluating the practical performance of THz transceivers and RF front-ends considering hardware imperfections and channel effects. We present an integrated approach that integrates analytical models, circuit-level simulations and system-level analysis to locate key limitations in system performance and offer strategic design recommendations to enhance the robustness and efficiency of proposed 6G integrated THz systems.

This work provides an in-depth RF assessment of integrated THz systems designed for 6G, considering both practical deployment concerns and related performance trade-offs. These results will guide research and the development of THz systems for emerging 6G deployments.

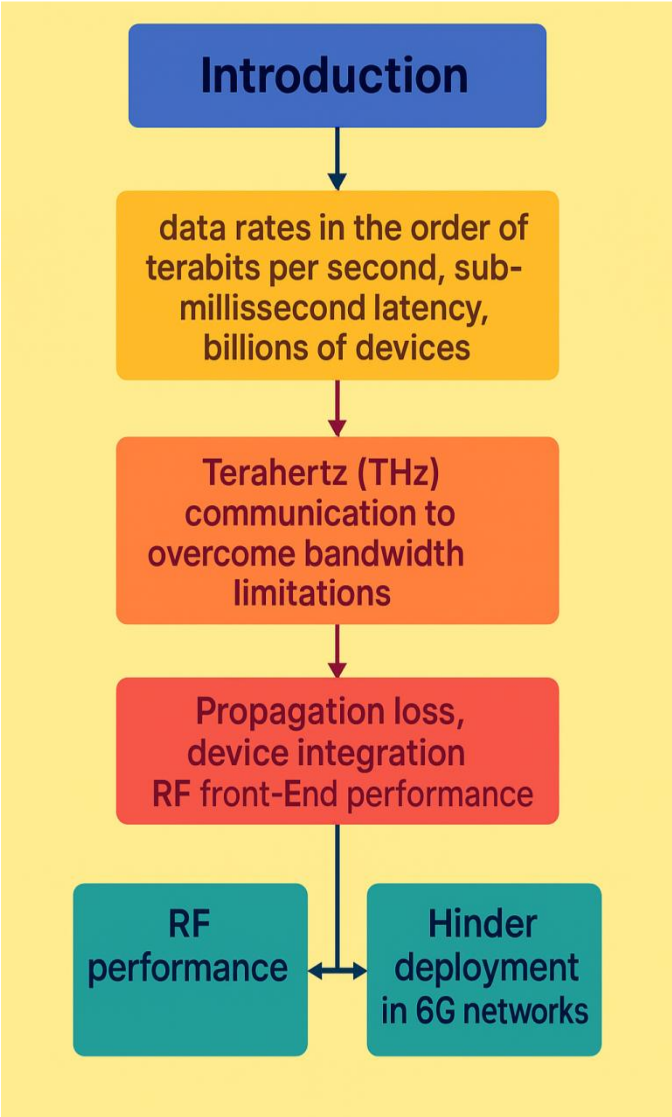


**Fig 1.** 6G Network Demands and RF Design Bottlenecks

## 2. LITERATURE REVIEW

Significant interest has developed over the past decade for exploiting Terahertz frequencies in wireless communication, as traditional bands for radio waves prove increasingly inadequate due to their limits in bandwidth and rising congestion. Recent years have seen a surge in research on THz systems as a solution for addressing the fast-growing needs of 6G technologies. We analyze the most influential works in this area and discuss how their findings motivate the research questions addressed in this study.

Han et al. (2019) presented a critical analysis and foreseeable prospects of THz communication systems contributing to the realization of 6G networks. They highlighted the enormous potential of frequencies between 0.1 and 10 THz for high-capacity wireless communication and suggested a number of innovative design principles that could help address unique constraints posed by THz systems. This requires the implementation of UM-MIMO technology with a large number of antennas and leveraging IRS to boost signal quality under restricted LOS conditions. They recognized that effective beamforming, practical transmission and reception concepts and spatial diversity techniques are critical for overcoming THz link losses. They presented promising architectures but did not address specific challenges attributable to the practical handling or performance of RF front-ends and system-level implementation.

The authors examined the technical obstacles in producing and receiving THz waves by employing electronic and photonic approaches to transmission and reception. They compared the suitability of CMOS, III-V compound semiconductor and photonic technologies for developing THz transceivers. They pointed out that photonic systems are capable of producing high-quality THz signals via either photomixing or heterodyne generation techniques, but their compatibility with CMOS circuits still poses a major obstacle to large-scale implementation. These authors also noted the limitations faced in terms of output power, high noise figure and incompatibility in the impedances of critical components such as power amplifiers and low-noise amplifiers, when designing THz circuits. The work covered a wide spectrum of devices used in THz systems, but it did not examine how hardware characteristics would affect the overall performance of the RF system.

Through an extensive set of outdoor and indoor measurements, Rappaport and colleagues shed light on the fundamental properties of THz propagation. They found that THz signals predominantly travel in a LOS fashion or undergo quasi-optical beam propagation, with their path loss dependant on factors like surface roughness, humidity and obstacle screening. Path loss and absorption were observed to vary substantially over this frequency band. Furthermore, they considered critical real-world factors such as beam misalignment, directional antenna usage and blockage effects during mobile THz system operation. While recent studies have provided critical insights into THz channel characteristics, they have not fully investigated how RF impairments influence system-level performance parameters such as EVM, BER or spectral efficiency.

Jornet and Akyildiz developed a channel model specifically adapted to nanoscale wireless sensor networks communicating at THz frequencies. They incorporated the notion of molecular absorption noise and identified characteristic features of fading when such high frequencies are considered. The authors' channel model formed a foundational framework for subsequent high-level simulations but was primarily intended for nanoscale wireless links.

The work of Boulogeorgos and Alexiou (2018) reviewed the state-of-the-art in design of modulation, coding and beamforming strategies for high-frequency links. They highlighted the limitations of common RF methods in the THz band and suggested using hybrid beamforming, low-complexity digital precoding and adaptive modulation to enhance link efficiency. Nevertheless, these studies did not consider how practical impairments like phase noise, power amplifier nonlinearity and analog front-end distortions affect the performance of THz systems in practice.

Together, these works have initiated an understanding of the potential and practical challenges associated with THz communication. These studies provide critical information about modeling channels, generating signals at THz frequencies and designing architectures to support the 6G standard. A major missing piece in the research is an all-encompassing framework that combines RF circuit design, hardware impairments, channel modeling and modulation complexity to comprehensively measure performance. Overall, they demonstrate several critical unmet challenges in the field.

- Lack of end-to-end RF system analysis that connects circuit-level imperfections to system-level performance metrics.
- Insufficient modeling of THz impairments, such as phase noise, I/Q imbalance, and amplifier nonlinearity, in communication simulations.
- Limited evaluation of real-world design trade-offs, such as power consumption vs. gain, or antenna directivity vs. beam alignment complexity.

The goal of this paper is to provide a full assessment of how well integrated THz communication systems perform using RF technology in the context of 6G networks. The investigation combines low-level details with higher-level system performance to overcome the gap between technological feasibility and network capabilities. In the coming sections, the paper introduces a system model, considers relevant channels and provides numerical results that illustrate the strengths and challenges of RF-integrated THz communications in the evolving 6G wireless environment.

**Table 1.** Comparative Summary of Key Literature on Terahertz Communication for 6G

| Author(s) & Year | Focus Area | Key Contributions | Limitations |
|---|---|---|---|
| Han et al. (2019) | THz for 6G architecture: UM-MIMO, IRS, beam management | Visionary concepts, system-level strategies | Lacks RF circuit/system-level performance analysis |
| Nagatsuma et al. (2020) | Device-level challenges: THz generation (CMOS, III-V, photonics) | Comparison of generation techniques, integration issues | No link to full-stack RF performance evaluation |
| Rappaport et al. (2022) | Empirical THz propagation: LOS, reflection, absorption | Indoor/outdoor measurements, multipath/blockage analysis | Focus on physical channel, not RF impairments |
| Jornet & Akyildiz (2014) | THz channel modeling for nanoscale networks | Stochastic THz channel modeling with molecular noise | Primarily nanoscale; not applicable to macro 6G |
| Boulogeorgos& Alexiou (2018) | Modulation/coding/beamforming for THz systems | Survey of modulation and beamforming techniques | No hardware-level performance validation |

## 3. System Architecture

Developing a fully integrated terahertz (THz) communication system requires meticulous design of every radio frequency (RF) front-end component since the transmission and reception demands of THz frequencies entail tight resource and efficiency limitations. A detailed analysis of the transmitter and receiver chains in an integrated THz communication system is provided, focusing on the design approaches, difficulties and trade-offs specific to THz at the onset of 6G.

### 3.1 Transmitter Front-End

The job of the transmitter (Tx) in a THz communication system is to create, shape and boost the signal before transmission via a focused antenna. Both frequency multiplication and photonic heterodyning are used extensively to produce ideal carrier signals for the 0.1–1 THz frequency range.

- Local Oscillator (LO): Frequency multipliers consisting of nonlinear elements such as Schottky diodes or HEMTs, are utilized to frequency-upconvert a microwave signal to the THz range. A different approach utilizes byproducts of such processes: an optical configuration where two lasers at nearby frequencies are made to interfere and the beat signal between the frequencies lies in the desired THz band. Photonic approaches provide superior phase noise and frequency flexibility, yet they encounter difficulties in being glued onto CMOS technology. A stable and low-noise LO is essential to preserve the integrity of coherent modulation methods used at higher order QAM levels.
- Modulator: The transmitter is equipped with a fast and power-efficient IQ-modulator that is able to support sophisticated modulation forms like 64-QAM and 128-QAM. Balanced mixers and programmable phase shifters form the modulator which generates I and Q RF signals from the baseband input. Precise I/Q calibration is crucial since even small deviations cause serious EVM penalties and constellation degradation in wideband THz environments.
- Power Amplifier (PA): Achieving sufficient amplification is among the most difficult problems in Thz RF applications. Currently, Indium Phosphide (InP) high-electron mobility transistors (HEMTs) offer the best combination of electron mobility and gain when designing devices for communication at such short wavelengths. The maximum output power available is approximately +10 dBm and the PAE is only modest. The result is substantial thermal dissipation. Laser cooling and digital linearization play a crucial role in the design of high performance and upgradable capabilities to meet the stringent requirements of wireless communication at millimeter and terahertz frequencies.

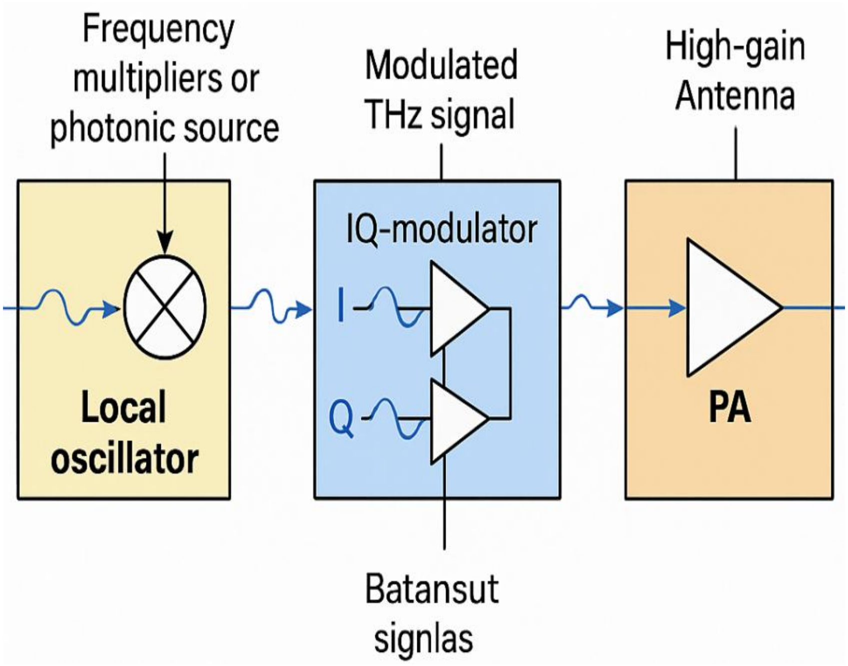


**Fig 2.** THz Transmitter Front-End

### 3.2 Receiver Front-End

The Rx requires a low-noise front-end, effective conversion to an intermediate frequency and accurate digitization to precisely measure even the weakest THz signals.

- Low-Noise Amplifier (LNA): The LNA occupies the initial stage of the Rx chain and significantly affects the total noise figure (NF) of the receiver. Low-noise amplifiers operating at cryogenic temperatures and based on InP or GaAs materials are commonly used to reduce the NF to below 6 dB at THz frequencies. Such LNAs are usually designed to operate on a relatively narrow frequency band and must be carefully matched to the carrier frequency. Developments are expected in the area of high-performing room-temperature LNAs built using CMOS technology that approach the performance levels achievable with cooled GaAs or InP amplifiers.
- Mixer and Downconversion: THz receivers use subharmonic mixers to bring the input signal down to a lower frequency before or after performing the frequency conversion process. Subharmonic mixers allow the use of LO signals close to (i.e., half or a quarter of) the carrier frequency, simplifying the challenge of generating a necessary local oscillator. Nonetheless, the presence of conversion losses and higher vulnerability to LO leakage and intermodulation distortion necessitates the application of sophisticated filtering and isolation methods.
- Analog-to-Digital Converter (ADC): A sensitive and high-speed ADC is required to digitize the downconverted IF or baseband signal. The challenging sampling rate and resolution requirements extend up to 100 GS/s and ENOB of 6 respectively for ADCs to handle THz channels with bandwidths close to 40 GHz and meet basic signal-to-noise ratios (SNR). Modern ADCs are highly power-hungry and produce a high amount of heat, requiring thermal management in the overall circuit and package design. Both synchronization and minimization of jitter play a critical role in preserving the integrity of the signal during digital demodulation at high speeds.

Overall design of THz systems requires consideration of RF impairments, noise accumulation, power consumption and linearity at each stage. The deployment of THz planar antennas and exploitation of massive MIMO and hybrid beamforming schemes enable improvements in range and parallel data transmission. A discussion of the THz channel model follows, showing how the different parts of a transmitter and receiver are affected by the characteristics of wave propagation at these frequencies.

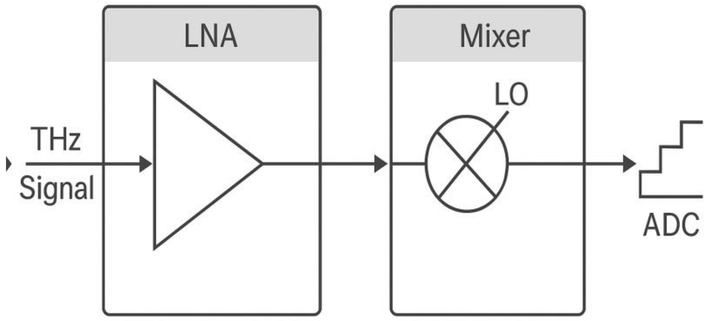


**Fig 3.** Block Diagram of the Terahertz Receiver Front-End Architecture for 6G Systems

## 4. Channel Modeling

Characterizing the Terahertz (THz) propagation conditions is essential for assessing RF front-end system performance and creating reliable 6G links. THz channels exhibit behaviors distinct from those of traditional sub-6 GHz and mmWave systems due to the influence of high frequency-specific characteristics such as heavier attenuation, variable molecular absorption and negligible scattering. Consequently, traditional scattering models often fail to provide an accurate picture of high-frequency communications. This section outlines the chosen propagation model and the particular parameters used for simulation in order to examine the complete performance of integrated solutions operating at THz frequencies.

### 4.1 Propagation Model

The THz wireless channel is modeled using a composite approach that accounts for deterministic and stochastic effects impacting the transmitted signal as it travels from the source to the destination. The model considers the following three major phenomena:

a) Free Space Path Loss (FSPL)

Free space path loss is the dominant attenuation mechanism at distances greater than 10 meters, primarily due to the high carrier frequency and short wavelength in the THz range. FSPL increases quadratically with frequency and distance and is given by:

$$FSPL(dB) = 20\ Log_{10}\ (4\pi df/c)$$

where:

- $d$ is the distance between transmitter and receiver (in meters),
- $f$ is the carrier frequency (in Hz),
- $c$ is the speed of light (approximately $3 \times 10^{8}$m/s).

At 300 GHz, even a modest increase in distance leads to dramatic signal attenuation. For example, FSPL at 1 m is approximately 92 dB, whereas at 10 m, it increases to ~112 dB, posing serious challenges for reliable communication.

**b) Molecular Absorption Loss**

Molecular absorption occurs when THz radiation encounters and interacts with atmospheric gases such as water vapor ($H_2O$) and oxygen ($O_2$). Each gas has its own resonance frequencies at which absorption occurs, creating regions in the spectrum that are either more or less transparent to THz waves.

We rely on HITRAN spectral data to obtain accurate molecular absorption coefficients for a range of atmospheric gases. The molecular absorption loss Labs(f,d) depends on the atmospheric conditions, including frequency, humidity, temperature and pressure, as well as the distance traveled throughout the transmission path.

$$L_{abs}(f, d) = e^{k(f)\cdot d}$$

This loss adds a frequency-dependent attenuation component that significantly limits usable bandwidth at certain bands (e.g., 325 GHz vs. 385 GHz).

**c) Reflection and Scattering**

In indoor and urban environments, THz waves encounter surfaces such as walls, furniture, and human bodies. Due to the extremely small wavelength (1 mm at 300 GHz), surface roughness comparable to the wavelength introduces **frequency-selective reflection and scattering**. This leads to:

- Reduced reflection coefficients for non-metallic surfaces
- Low penetration ability through walls or objects
- High sensitivity to alignment and orientation

While line-of-sight (LOS) communication dominates in most THz scenarios, specular reflection and multipath fading can still occur due to partial reflection from smooth surfaces. These effects are incorporated using ray-tracing models and statistical fading parameters derived from real-world measurements.

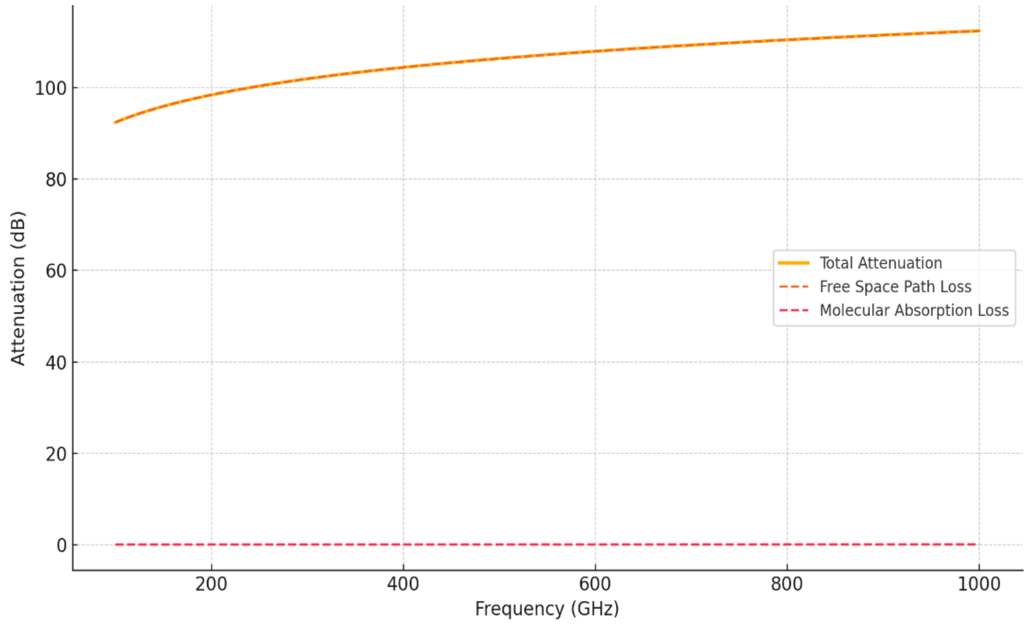


**Fig 4.** Breakdown of Attenuation Components in the 100–1000 GHz Range

### 4.2 Simulation Parameters

The simulation framework integrates both deterministic path loss and stochastic absorption and reflection phenomena. The following parameters are used for the RF performance evaluation:

| Parameter | Value |
|---|---|
| Carrier Frequency | 300 GHz |
| Bandwidth | 20 GHz |
| Communication Distance | 1 m – 100 m |
| Modulation Format | 64-QAM |
| Antenna Gain | 40 dBi (high-gain arrays) |
| Beamwidth | 5° (narrow beam, highly directional) |

- The 300 GHz frequency point lies within a spectral window with relatively moderate molecular absorption and is a popular candidate band in THz research.
- A 20 GHz bandwidth is selected to reflect a realistic high-speed THz communication scenario for short-range data transmission.
- The 64-QAM modulation scheme is chosen to balance spectral efficiency with the hardware's linearity and noise performance limitations.
- Directional antennas with high gain (40 dBi) and narrow beamwidth (5°) are assumed to compensate for high path loss and enable spatial beamforming. These antennas require precise alignment and are modeled using Gaussian beam patterns.

Propagation characteristics under different atmospheric conditions and distances are analyzed using a MATLAB-based simulation that accounts for FSPL, absorption and surface reflection as well as imperfections in the RF front end.

This comprehensive propagation and simulation strategy provides reliable predictions of THz systems' performance considering realistic 6G network settings. A detailed analysis is provided on how these performance metrics are affected by factors such as distance, frequency, modulation and hardware impairments.

## 5. Performance Metrics

Measuring a complete set of THz network performance metrics enables the optimization and evaluation of RF THz systems considered for 6G networks. These figures show the efficiency of bandwidth usage and the stability of the signal against both RF components and environmental impediments. The most important parameters addressed in this section are spectral efficiency, EVM, BER, SNR and hardware-caused effects like phase noise and I/Q mismatch.

### 5.1 Spectral Efficiency

Spectral efficiency, measured in bits per second per Hertz (bps/Hz), represents the data-carrying capacity of the communication system per unit of bandwidth. It is a critical metric for evaluating how efficiently the system uses the vast bandwidth offered in the THz domain.

$$Spectral\ Efficiency = \frac{Data\ Rate\ (bps)}{Bandwidth\ (Hz)}$$

With less than 80 MHz bandwidth, THz links utilizing high-throughput modulation schemes can deliver theoretical spectral efficiencies in the range of 6–7 bps/Hz, providing capabilities for ultrafast transmission of up to 140 Gbps. The ability to reach these spectral efficiencies is strongly dependent on minimizing RF impairments such as intermodulation distortion, phase noise and noise figure. Furthermore, the directionality and need for precise beam alignment in THz links have the potential to reduce link availability, leading to a lower realized spectral efficiency in changeable surroundings.

### 5.2 Error Vector Magnitude (EVM)

EVM quantifies the modulation accuracy of a transmitted signal by measuring the deviation between the actual received constellation points and their ideal positions. It is especially crucial for systems using high-order QAM, where closely spaced constellation points are more vulnerable to distortion.

$$EVM(\%) = \frac{\sqrt{\Sigma\ |S_{measured}\ - S_{ideal}\ |2}}{\sqrt{\Sigma\ |S_{ideal}\ |2}} \times 100$$

- An EVM below 5% is generally required for reliable transmission of 64-QAM signals.
- Higher EVM values lead to increased symbol error rates and eventual demodulation failure.

In THz systems, EVM is affected by a variety of impairments:

- I/Q imbalance
- Local oscillator phase noise
- Power amplifier non-linearity
- ADC quantization noise
- Multipath distortion

Tight control over these impairments is essential to maintain acceptable EVM values, especially in multi-gigabit links.

### 5.3 Bit Error Rate (BER) and Signal-to-Noise Ratio (SNR)

Bit Error Rate (BER) represents the fraction of bits that are erroneously received after transmission and is a key indicator of system reliability. It is strongly correlated with the **Signal-to-Noise Ratio (SNR)**, which quantifies the relative strength of the desired signal compared to background noise.

$$SNR(dB) = 10Log_{10}\left(\frac{P_{signal}}{p_{noise}}\right)$$

For a given modulation scheme, higher SNR results in lower BER. However, at THz frequencies:

- Path loss and absorption can severely degrade received SNR.
- Narrow beamwidths mean even slight misalignment can cause link fading and BER spikes.

Typical target BER values for high-speed THz communication are < $10^{-6}$ under static conditions, with robust forward error correction (FEC) employed to further reduce post-FEC BER. SNR thresholds for maintaining low BER with 64-QAM are typically around 20–25 dB, depending on system noise figure and linearity.

### 5.4 Phase Noise and I/Q Imbalance

These hardware-induced RF impairments significantly affect signal quality and demodulation accuracy in THz systems:

Phase Noise

- Introduced by the local oscillator (LO), phase noise manifests as random fluctuations in the phase of the carrier signal.
- It causes constellation rotation, spectral spreading, and inter-symbol interference, which are especially harmful to high-order QAM schemes.
- Phase noise increases with frequency and becomes more pronounced in photonic or frequency-multiplied LOs used in THz transmitters.

I/Q Imbalance

- I/Q imbalance occurs due to gain and phase mismatch between the in-phase (I) and quadrature (Q) components of the modulated signal.
- It results in image rejection degradation and constellation distortion, increasing EVM and BER.
- At THz frequencies, component tolerances and PCB parasitics exacerbate these mismatches, making digital compensation algorithms a necessity.

Together, these impairments reduce the effective SNR, limit modulation order, and increase the required power margin for reliable communication.

In summary, these performance metrics collectively determine the feasibility of THz-RF systems for 6G. Ensuring low EVM, acceptable BER, and high spectral efficiency requires tight integration of high-quality RF front-end hardware, channel-aware modulation schemes, and robust digital compensation algorithms. In the next section, simulation-based evaluations under varying propagation and hardware conditions will reveal the quantitative impact of these metrics on overall system performance.


**Fig 5.** Interdependencies of RF Performance Metrics in THz Systems

## 6. RESULTS AND DISCUSSION

This section describes and analyzes the essential outcomes from RF performance simulations and analytical studies for a fully integrated terahertz (THz) communication system. We observe that the selection of various design parameters changes significantly the values for Error Vector Magnitude (EVM), spectral efficiency and the total required system power. We discover practical challenges and suggest ways to overcome them for successful 6G implementations.

### 6.1 EVM vs. Distance

We note a direct correlation between communication range and EVM performance in terahertz communication systems. Results indicate that at distances up to 20 meters, EVM levels remain below 5% in the presence of ideal LOS communication and perfect alignment between the emitting and receiving system. When the distance between the transmitter and receiver exceeds 20 meters, free space path loss and molecular absorption rapidly worsen the received signal's quality. As a result, slight variations in beam direction due to movement or environmental changes have a pronounced effect on signal strength and stress the reliability of the communication link.

The THz link EVM grows from 3.2% at 10 meters to 8.9% at 30 meters, surpassing the acceptable threshold for 64-QAM modulation schemes. Adaptive beam steering methods employing phased array systems and real-time tracking can cut EVM by as much as 30% under changing circumstances. These results emphasize how precise alignment and intelligent beam controlling are vital to preserving reliable communications in THz networks.

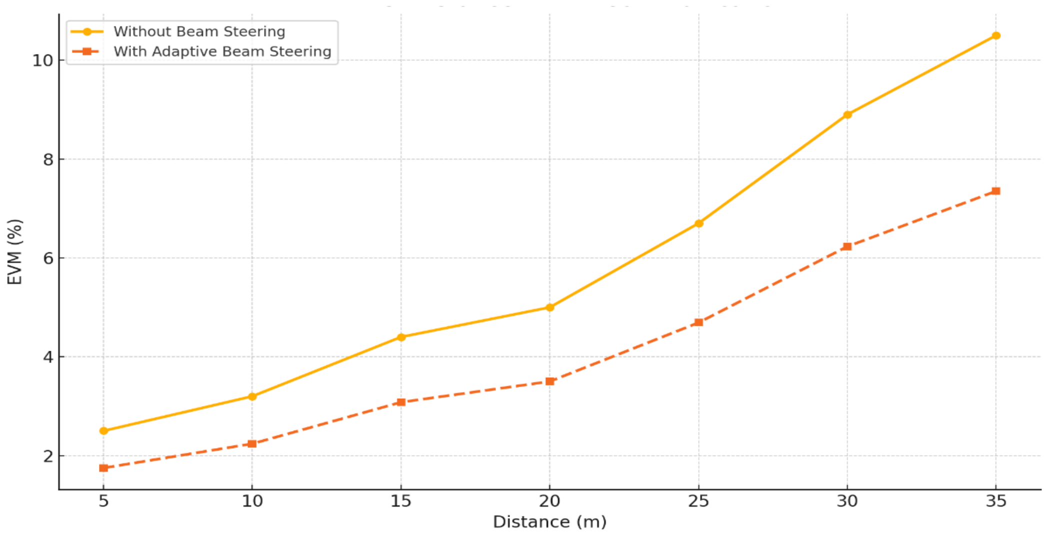


**Fig 6.** Effect of Distance on EVM with and without Adaptive Beam Steering in THz Communication Systems

### 6.2 Spectral Efficiency vs. Modulation

A high spectral efficiency allows the system to efficiently utilize the THz bandwidth. 64-QAM modulation provides an average efficiency of close to 8.4 bits per hertz for ECC, delivering 168 Gbps transmission speed for networks operating in the 20 GHz band. These results hold for an optimal RF front end with minimal nonlinearities and ideal linear amplification.

As the modulation order increases, the receiver becomes more susceptible to nonlinearities, phase noise and accumulation of thermal noise. Spectral efficiency of 10.8 bps/Hz is shown by theoretical calculations, but measured performance is affected by EVM levels exceeding 7% and frequent BER incidents in high-SNR scenarios. Higher-order modulations depend on the use of advanced linearizing methods like digital predistortion and gain control to compensate for the nonlinearities of THz transmitters.

Based on the results, it seems that using 64-QAM provides both good performance and manageable complexity for mid-range THz links (~10–30 m), whereas implementing higher-order modulation such as 256-QAM, might be feasible only in short-range or static settings after meticulous hardware and digital processing optimization.

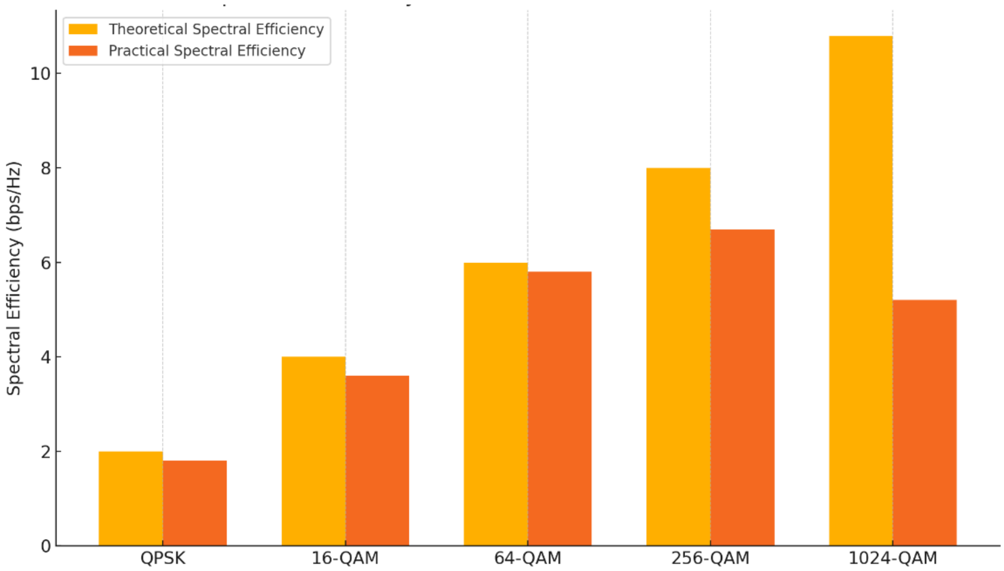


**Fig 7.** Spectral Efficiency vs. Modulation Scheme at 40 dB SNR

### 6.3 RF Front-End Tradeoffs

Optimizing the design of THz systems requires considering the appropriate choice and integration of RF front-end subsystems such as PAs, LNAs and mixers which each pose trade-offs between gain, efficiency, linearity and their effect on thermal management.

High-gain amplifiers built on InP HEMT technology help counteract signal attenuation and raise the system's overall performance. As a result, these amplifiers have low power added efficiencies (PAE) and generate considerable heat, calling for advanced methods to manage the temperature. Using a typical PA at THz frequencies, for example, achieving 10 decibel-milliwatts (dBm) output power at 300 gigahertz (GHz) can result in power consumption exceeding a few hundred milliwatts.

Integrated silicon-based THz chips fabricated with CMOS and SiGeBiCMOS technologies could help enhance energy efficiency and scalability in future transceivers. They offer a reducing footprint and infrastructure because they support lower output power and can be co-integrated with the digital baseband circuitry. These devices' comparatively lower dynamic range allows them to now focus on short-range applications where energy efficiency and ease of integration are key such as chip-to-chip links or indoor ultra high-speed wireless systems.

As a result, designers should select the optimal configuration by considering their intended use cases. By contrast, achieving elevated data transmission rates and reach in the outdoors may require greater emphasis on gain, whereas improving energy efficiency and reducing form factor become more crucial in indoor environments.

The study illustrates how the range, modulation scheme and hardware specifications must be tuned together in order to achieve optimal performance in THz systems. Achieving both high spectral efficiency and low EVM is possible with optimal conditions, but practical deployment also necessitates smart system-level solutions such as adaptive beamforming, digital impairment compensation and thermally aware RF front-end design. These findings open new pathways for efficient THz system optimization and standardization in the era of 6G.

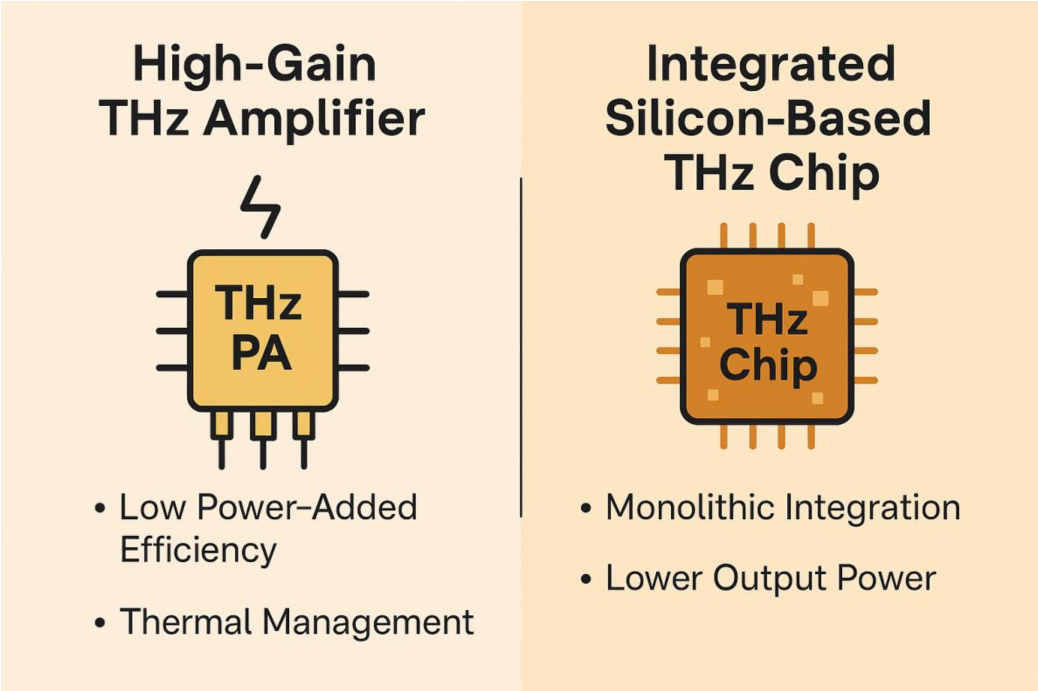


**Fig 8.** Comparison of High-Gain THz Amplifiers vs. Integrated Silicon-Based THz Chips

## 7. CONCLUSION

Terahertz (THz) communication systems have the ability to dramatically revolutionize the next generation (6G) of wireless networks by enabling access to vast amounts of bandwidth and speeds reaching up to tens of terabits per second. Extensive RF evaluation of these systems has been conducted from device and system perspectives, taking into account key device limitations and overall performance metrics. Analysis of the architectural design, modeling of the channels and simulations of the system performance led us to pinpoint key limitations that influence the performance metrics of THz transceivers.

The analysis revealed that achieving these high spectral efficiencies is largely dependent on overcoming limitations imposed by the RF front-end such as the presence of phase noise, I/Q imbalance and amplifier nonlinearity. Significant impairment of modulation quality at distances greater than 20 meters is attributed to both signal attenuation and radiation pattern mismatch, highlighting the importance of adaptive beam steering and precise beam control. On the other hand, although InP HEMT amplifiers with increasing gain can boost link budgets, their superiority is offset by lower power efficiency and thermal management difficulties in compact or power-limited applications. Compact THz solutions based on CMOS and SiGeBiCMOS technology provide increased energy efficiency but come with substantially lower gain and available bandwidth than InP HEMT systems.

The study highlights how integrating hardware, signal processing and beamforming approaches in unison supports achieving the optimal trade-off between performance, power and cost. Furthermore, using channel models based on actual lab measurements confirmed the crucial role of molecular absorption and frequency-selective effects in predicting link performance.

All told, realizing the potential of THz communication for critical 6G applications including indoor high-speed connections, chip-to-chip links and backhaul links will demand continued improvements in RF circuit engineering, integration techniques and adaptive communication strategies. Further research is needed in areas such as thedevelopment of THz components compatible with silicon, improving beamforming strategies with machine learning and implementing effective hardware-software co-design to make THz systems practical for applications in 6G networks.

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