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Designing Low-Latency Terahertz Communication Systems for High-Capacity 6G Networks

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Abstract: To accommodate ultra-reliable, low-latency, and high-capacity wireless networks capable of meeting the low-latency demands of data-intensive applications like augmented reality (AR), virtual reality (VR), autonomous vehicles, industrial IoT applications, etc. Network needs such as these are targeted to be addressed by sixth-generation (6G) networks, based on terahertz (THz) communication, through unprecedented bandwidth, data transfer speeds, etc., overcoming challenges like severe propagation losses, energy inefficiency, hardware limitations, and scalability constraints. In this study, we propose a comprehensive framework for low-latency and energy-efficient THz communication systems for 6G networks, considering hybrid beamforming, ML-driven resource optimization, and renewable energy features including a solar-powered THz device and an antenna-based energy harvester, which will be included as a part of this framework. Additionally, real-world environmental factors such as molecular absorption and scattering, as well as atmospheric humidity and temperature, are considered in a novel channel model to guarantee the prediction of signal behavior in propagation. The results of the simulation show up to a 40% reduction in latency, 30% in energy efficiency, and spectral efficiency of 12 bps/Hz, much superior to baseline systems, and support the hypothesis for its applicability in various 6G use cases such as smart city infrastructure, communication for autonomous vehicles, and AR/VR applications. We conclude with these findings that establish the potential of the proposed framework to solve principal problems for scalability, sustainability, and reliability for future 6G networks and present future work on live network testing and large-scale deployment scenarios whereby the foundations of the framework can be developed in solving several core issues with the deployment of high-performance 6G communication systems.

Keywords: 6G Networks, Low-Latency System, Energy Efficiency, Terahertz Communication (THz), Nantenna Technology

1 Introduction

The establishment of 6G networks relies on developing new standards that will enhance data transmission speed while minimizing delay through higher spectral bands. Requirements evolve from applications needing large data volumes like autonomous vehicles and industrial IoT, respectively, alongside AR/VR deployments. Wide bandwidth abilities make terahertz (THz) communication advanced because they enable quick data transfer speeds. Signal degradation, excessive power costs, and insufficient transceiver execution are significant obstacles to THz band (0.1 - 10 THz) transmission operations, according to [4–6]. System designers require the implementation of contemporary optimization techniques with modern enhancement methods to optimize THz communication technology for 6G network functionality [7–9].

The research community has successfully created power-efficient THz communication systems that solve these problems. Array antennas combined with lenses enable powerful beam steering operations that improve the coverage range of terrestrial networks as well as satellite networks [10,11]. Research studies support the conclusion that combining joint antenna selection with beamforming methods enhances system performance while improving

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energy efficiency levels [12,13]. The application of power-efficient design methods for mmWave and sub-THz systems in indoor areas is explained through the research in [14]. An increase in the performance quality and energy savings for UAV communication systems occurs when users modify their parameters because it enables RF band adjustments for reduced energy consumption [15,16].

The combination of machine learning resources allows developers to build optimization solutions and management systems that advance THz communication advancement. Network transmission parameters automatically adjust whenever operational network conditions change in order to produce enhanced performance alongside energy-efficient operation [17–19]. The framework provides an organized integration of key scientific findings to tackle fundamental technical challenges that impact the THz-based networks for 6G, but the framework increases the latency efficiency, reduces power usage, and improves scalability capabilities. A full-fledged sustainable high performance communication system is realized through the combination of advanced channel models and adaptive hybrid beamforming together with resource management solutions based on machine learning functions [20,21].

The development of next-generation wireless communication systems builds its base on the current wireless communication breakthroughs that require innovative techniques in this framework. Real technical issues find solutions through this framework since it enables industrial IoT and autonomous vehicle system deployment in smart cities [22–26].The research in this study expands current methods to establish THz communication systems while supporting the sustainable development of 6G networks.

2 Literature Review

Progress in terahertz (THz) communication technology developments is steady because these networks deliver outstanding performance that fulfills next-generation network specifications regarding speed and bandwidth capabilities. The problem areas within THz communication persist despite major technological advancements because signal loss and system flaws for energy consumption and resource distribution still need solutions. This portion traces existing findings from research along with the new unique features incorporated into our study.

2.1 Existing Research Contributions

2.1.1 Beam Steering and Antenna Design

The incorporation of antennas and lenses has improved beam steering in ground-satellite communication systems. The authors [10] noted how beam steering was used in a THz communication system to achieve minimum signal attenuation. The precision of beam steering determines signal attenuation, and the authors concluded that maintaining precision of the beam steering is very difficult in mobile operational environments, and the system they designed could not accommodate such a constraint. *et al.* [10].

A power-efficient beamforming and antenna selection method to stabilize communication was described by Zhang *et al.* in their work [12]. During sanctioned stationary procedures, the system performed at a higher level, yet it did not guarantee operational stability throughout real-time scenarios requiring dynamic environmental adjustments.

2.1.2 Energy-Efficient Designs for mmWave and Sub-THz Systems:

Efficient serial designs for mmWave and sub-THz systems have been made by researchers at Deng *et al.* [14], in which they work on indoor settings. Hybrid beamforming approaches proved useful to induce system stability, according to their team, while external environmental variability had to be optimized for proper implementation.

Heath *et al.* [6] produced fundamental works regarding energy-efficient 5G wireless technologies, which allowed future research to focus on mmWave and THz systems. Their research targeted the first steps of the implementation of 5G, but did not address issues that are unique to the operation of THz systems such as molecular absorption and inefficiencies in the hardware systems.

2.1.3 Resource Allocation in THz Networks:

Khalili *et al.* [15] set up a reactive RF band allocation system for UAV communication systems, which changes resources depending on the needs of the users. The suggested methodology improved power efficiency conjoined with service quality highly, but behave ineffective for developing toward general THz wireless implementations.

Zhang *et al.* [17] and Li *et al.* [19] used machine learning algorithms to realize optimization of resource allocation and hybrid beamforming. The combination of these techniques provided improved spectral and energy efficiency via the results they achieved, albeit with significant processing challenges for their purpose in real-time operations in power limited applications.

2.1.4 Energy Harvesting and Sustainability:

Guo *et al.* [25] reviewed nantenna-based energy harvesting solutions as sustainable power sources for IoT networks and THz communication. While the study highlighted their potential to reduce reliance on conventional energy, it lacked implementation details for large-scale systems.

Sharma *et al.* [23] introduced solar-powered THz devices to reduce environmental impact and improve network sustainability. Despite their promise, these solutions were limited to small-scale experimental setups and did not address integration into large 6G systems.

2.1.5 Latency and Scalability in 6G Networks:

Basu *et al.* [13] addressed latency reduction through resource optimization in IoT-based smart home systems, showcasing their potential for 6G applications in low-power environments. However, their scope was limited to small-scale, controlled IoT deployments.

Zhu *et al.* [16] proposed scalable designs for multi-hop relaying in 5G networks, laying the groundwork for future scalability in 6G. Nevertheless, the research did not address THz-specific issues, such as severe propagation losses and high energy demands.

2.2 Comparative Analysis of Existing Research and Our Work

2.3 Contributions of Our Research

Operational and resource management and energy efficiency-related issues of THz communication have been solved by research, which has already shown successful handling of beam steering issues. However, these approaches mostly focus on individual problems or operate under managed circumstances that restrict application possibilities in real situations. In this research, a solution has been proposed to these identified constraints; the proposed framework is an extensive solution.

–Combining Advanced Techniques:
–*Hybrid Beamforming*: In abnormal environments, such as that of the satellite, UAV, terrestrial, etc., it allows hybrid beamforming to be deployed to increase the beam steering precision with reliable communication.
–*Adaptive Resource Allocation*: Scheduling problems for bandwidth and power resources in a time scale that are being dynamically scheduled under machine learning algorithms to attain guarantees in real-time performance and energy efficiency.
–*Addressing Propagation Challenges*: Develops Next generation channel model that accounts for molecular absorption, scattering and environmental conditions of humidity and temperature for robust communication under all conditions.
–*Focusing on Sustainability*: It incorporates renewable energy resources and technologies that combine energy harvesting, antennas, solar devices, and other means to decrease ecological damage and enhance planetary sustainability.
–*Validating Through Realistic Simulations*: Using realistic parameters, the simulation in MATLAB, with carrier frequencies from 0.5 to 10 THz, a bandwidth of 10 GHz, and based on real-life conditions, also analyzes the practicality and scalability of the proposed framework.

Our research develops an innovative approach to solve latency together with energy efficiency and scalability limitations in 6G THz communication systems that will enable their application across smart cities and telemedicine alongside industrial IoT applications and many others.

3 Problem Statement and Methodology

3.1 Problem Statement

During today's modern era, rising time-sensitive, data-intensive application demands lead to a decrease in the performance of the existing wireless networks. The requirements point out major possible network weaknesses because latency performance cannot meet the requirements, or enough capacity cannot be provided with the design, and the design efficiency is not sustainable. Although perfect high-speed connectivity is required for the AR/VR-based surgical robots, it is also critical for the implementation of very Reliable Low Latency Communication (URLLC) with milliseconds below 1 for collision prevention of autonomous vehicles in urban areas. However, molecular absorption and scattering cause severe propagation losses, resulting in unreliable networks such as in cities and places with distance in the terahertz (THz) frequency range, which has bandwidth capabilities. However, expansion on a large scale and worldwide deployment of THz networks are challenged by the huge amount of energy consumption and specialized hardware required. The main issue that arises is managing interference because network reliability must be increased in order to operate the dense smart cities and industrial IoT environments in resource-critical scenarios. Every geographical area, from the city to remote regions, has to meet the standard network performance. For the deployment of a sustainable 6G network over all regions, we need a new innovative system having hybrid beamforming adaptive functionalities along with machine learning-based resource organizations and renewable energy collection.

3.2 Methodology

The research methodology includes the use of enhanced channel modeling, simulative framework development, latency reduction innovations and energy performance boost enhancements to cope with THz communication systems problems. 6G networks benefit from separate

Table 1: Comparison of existing research and our contributions to next-generation communication systems

Aspect	Existing Research	Our Research
Beam Steering	Lens-array systems demonstrated beam steering precision but limited adaptability to dynamic scenarios [10,11].	Hybrid beamforming expands beam steering capabilities for terrestrial, satellite, and UAV communication systems.
Energy Efficiency	Designs focused on static setups and limited environmental variables [12–14].	Incorporates real-time optimization using machine learning and nantenna-based energy harvesting for scalable deployments.
Propagation Losses	Indoor models with simplified channel assumptions [6,14].	Advanced channel modeling accounts for molecular absorption, humidity, temperature, and scattering effects.
Resource Allocation	Reactive RF band allocation tailored for UAV systems with limited generalizability [15,16].	Adaptive resource allocation via machine learning ensures real-time performance across diverse applications.
Sustainability	Solar power and nantenna energy collection techniques have been suggested, but have never been put to use in massive systems. [23,25].	Our framework features renewable energy solutions for sustainable 6G networks to lessen the ecological footprint.
Latency Reduction	Methods showed latency reduction in regulated IoT ecosystems. [13,17].	Offers an extensive system to reduce latency that has been tested in practical simulations.
Scalability	Research that is centered on particular applications such as UAVs and indoor environments [14,15].	Intended for the large-scale use in smart cities and industry 4.0 IoT and beyond..

components that have been developed to resolve specific real-life problems of networking.

3.2.1 Channel Modeling

Molecular absorption, path loss, and scattering are included in the model for the THz channel. [5]. The total path loss $L(f,d)$ is expressed as:

$$L(f,d) = L_{\text{spread}}(f,d) + L_{\text{absorption}}(f,d) + L_{\text{scattering}}(f,d). \tag{1}$$

where:

–$L_{spread}(f,d)$: Free-space path loss, expressed as $L_{spread}(f,d) = \left(\frac{4\pi fd}{c}\right)^2$
–f: Carrier frequency in THz.
–d: Distance in meters.
–c: Speed of light (3×10^8 m/s) .

$L_{absorption}(f,d)$**:** Molecular absorption, modeled as:

$$L_{\text{absorption}}(f,d) = A = e^{\kappa(f)d}. \tag{2}$$

in which, $\kappa(f)$: Absorption coefficient, HITRAN database.

$L_{scattering}(f,d)$**:** Losses from scattering, attributed to atmospheric particles and expressed with Rayleigh scattering concepts:

$$L_{\text{scattering}}(f,d) = C_S(f)d. \tag{3}$$

–$C_S(f)$: Scattering coefficient.

The model accounts for varying conditions of temperature (T), humidity (H), and pressure (P) when predicting the effect of signal propagation in the environment.[9].

3.2.2 Latency Optimization

Latency is an important performance measurement that is determined through the following equation:

$$T_{\text{latency}} = T_{\text{processing}} + T_{\text{transmission}}. \tag{4}$$

–**Processing Delay (**$T_{processing}$**):** Required time for processing signals and for the transmitters and receivers. These techniques are used in order to overcome this issue along with the hybrid beamforming algorithms by changing the phase and amplitude of antenna elements.
–**Transmission Delay (**$T_{transmission}$**):** Propagation time and number of retransmissions. Adaptive resource allocation is implemented at the level of power and bandwidth
allocation with the aim at real time adaptive power and bandwidth
allocation depending upon state of the network.

$$L_{\text{spread}}(f,d) = \left(\frac{4\pi fd}{c}\right)^2. \tag{5}$$

Key parameters for latency optimization:

–Carrier Frequency (f): 0.5–10 THz
–Bandwidth (B): 10 GHz

–Processing Speed: 1 ms of processing time for each data packet
–Propagation Delay Coefficient: Calculated from distance (d) and absorption losses [7,14].

Latency bottleneck prediction and optimal resource configuration
suggesting models are based on machine learning. These models
use reinforcement learning to deal with changing networks..

3.2.3 Multi-Objective Energy Optimization

Energy efficiency (η) is defined as:

$$\eta = \frac{\text{Throughput (bps)}}{\text{Power Consumption (W)}}. \tag{6}$$

Optimization is performed using a Lagrangian multiplier method:

$$\mathscr{L} = -\eta + \lambda \left(C_{\text{allocated}} - C_{\text{required}} \right). \tag{7}$$

where λ is the Lagrange multiplier [9].

Optimization Process: Gradient-Based Optimization refers to the maximization of the overall system efficiency (η) through the optimal adjustment of the system's transmission power and bandwidth, as determined by the real-time condition of the network. This method strives for a greater use of wireless resources both in a spectral and an energysustainable manner. In addition, the integration of renewable energy resources contributes to sustainability and decreases the operational carbon footprint. This is achieved through the utilization of the nantenna-based energy harvesting systems, solar powered THz devices, and a reduction in the utilization of the grid. Furthermore, with regard to the use of Machine Learning for prediction purposes, various supervised learning models are employed for the prediction and/or the forecasting of future power and demand traffic flow, which allows for the necessary advancements in resource allocation and overall network efficiency.

The Lagrangian multiplier method is used to solve the optimization problem:

$$\mathscr{L} = -\eta + \lambda \left(C_{\text{allocated}} - C_{\text{required}} \right).$$

where:

–$C_{allocated}$: Allocated capacity,
–$C_{required}$: Required capacity,
–λ: Lagrange multiplier ensuring constraint satisfaction [11].

3.3 Simulation Setup

Simulations are conducted in MATLAB using the following parameter values, which are illustrated in Table 2.

Table 2: Simulation parameters for evaluating the proposed framework

Parameter	**Value**
Carrier frequency (f)	5–10 THz
Bandwidth (B)	10 GHz
Distance (d)	10–100 m
Transmission power	0.1 W
Absorption coefficient	Derived from HITRAN
Processing delay ($T_{processing}$)	1 ms
Noise power (N_0)	-174 dBm/Hz
Humidity (H)	10–80%
Temperature (T)	0–40°C

3.4 Limitations and Future Refinements

Still, the proposed framework assumes, and has to overcome, limitations and assumptions that its advanced low-latency and energy-efficient THz communication would otherwise have. Molecular absorption data from the HITRAN database does not include sudden changes in the atmospheric composition, and the channel model assumes uniform temperature and humidity, i.e., no variability of real-world conditions. Static datasets are used to train the machine learning, which is resource optimized, and it will not be easily adapted to the dynamic network conditions or high density, while real-time optimization will incur computational complexity with delay. In addition, it is assumed that such advanced THz transceiver hardware is available and that energy already present in the environment is being made as available as possible. However, such limitations could be mitigated with the incorporation of emerging technologies. It enables real-time scalability and also allows prediction of the changes in the environment using AI-based predictive analytics, federated learning, and blockchain for secured resource allocation using smart contracts and decentralized authentication. However, quantum communication can be expanded further such that after improved security level (quantum key distribution, QKD) and optimized precision (quantum-assisted beamforming), the framework can be expanded. Due to these advancements and to address these challenges, which will cause the system to be refined for scalability, security, and adaptability, they need to exist in the system with a real-world 6G network.

4 Simulation Details

The simulation setup, performance metrics, algorithms, and tools that are used to evaluate the proposed framework for THz communication systems are given in this section.

4.1 Environment Setup

In MATLAB R2023a, we create a simulation environment that tests the valid boundaries of the THz communication framework proposed in this paper. Below are the THz communication framework parameters and the environmental conditions we wish to simulate:

Core Simulation Parameters:

– Carrier Frequency (f): Ranges from 0.5 to 10 THz in a wide range of the terahertz spectrum to analyze system range.
– Bandwidth (B): 10 GHz, enough to facilitate high-speed data communication for next generation communication systems.
– Distance (d): 10 to 100 meters, includes short-range and medium-range THz communications.
– Transmit Power (P_t): 0.1 W, a good compromise for energy saving and reliable communication.
– Absorption Coefficient ($\kappa(f)$): from HITRAN database, provides realistic values of molecular absorption for different frequencies.
– Processing Delay ($T_{processing}$): 1 ms per data packet.
– Noise Power (N0): -174 dBm/Hz, thermal noise of the communication channel.

Environmental Parameters: Humidity (H) was varied from 10% to 80% to test the effect of moisture content in the air on molecular absorption and signal attenuation of THz Frequencies. The Temperature (T) was varied from 0°C to 40°C to maintain the normal operating conditions for the different climate zones. The Atmospheric Pressure (P) was kept at normal barometric pressure with a few changes to simulate high altitude/low pressure. These changes set the bounds to test the effects of environmental factors on signal propagation.

– Free-Space Path Loss ($L_{spread}(f,d)$): Models signal attenuation due to geometric spreading over distance.
– Molecular Absorption ($L_{absorption}(f,d)$): Derived from HITRAN data to simulate frequency-dependent signal losses caused by atmospheric molecules.
– Scattering Losses ($L_{scattering}(f,d)$): Includes Rayleigh and Mie scattering caused by atmospheric particles and other environmental factors.

4.2 Performance Metrics

To assess the effectiveness of the proposed framework, the following performance metrics are evaluated:

Latency ($T_{latency}$):

– Measures the end-to-end delay from transmission to reception.
– Calculated as: $T_{latency} = T_{processing} + T_{transmission}$
– Used to evaluate the system's capability to support real-time applications like autonomous driving and AR/VR [3].

Energy Efficiency (η):

– Defined as: $\eta = \frac{Throughput\ (bps)}{Power\ Consumption\ (Watts)}$
– Indicates the system's ability to balance high-speed data transmission with minimal power usage [13].

Spectral Efficiency (SE):

– Evaluates how efficiently the available bandwidth is utilized [17].
– Calculated as: $SE = \frac{Data\ Rate\ (bps)}{Bandwidth\ (Hz)}$

Bit Error Rate (BER):

– Measures the ratio of erroneous bits to the total number of transmitted bits.
– Used to assess the reliability of the communication system under varying conditions.

Optimization Convergence: Tracks how quickly the resource optimization algorithms stabilize to achieve minimal latency and maximum energy efficiency [2].

THz (terahertz) communication utilizes a spectrum that has such wide bandwidth, that it enables communication systems to transmit data at unprecedented speeds. However, a system will always be limited by a trade-off between the frequency it is operating at, and the range it is able to cover. The higher end of the THz frequency range will, indeed, support much higher data rates, but will suffer from even higher losses from propagation and atmospheric absorption. This will limit the distance over which communication is feasible. The figure below shows the classic capacity versus coverage trade-off for three examples of THz frequencies.

As the frequency is higher, the data rates can increase for the nearby but reduce fast for the farther ranges. For example, 10THz can be used for very high data rates within a very few meters making it suitable for short range, high density applications, while 0.1THz can be used for more stable performance over longer range. These results highlight the importance of the adaptive frequency choose and beamforming to obtain performance under different implementation circumstances.

4.3 Algorithms

The simulation framework consists of a number of intelligent algorithms, integrated in order to optimize the allocation of the resources and performance of the overall system. A gradient-based optimization technique is applied for adjusting transmission power and bandwidth distribution and beamforming control parameters

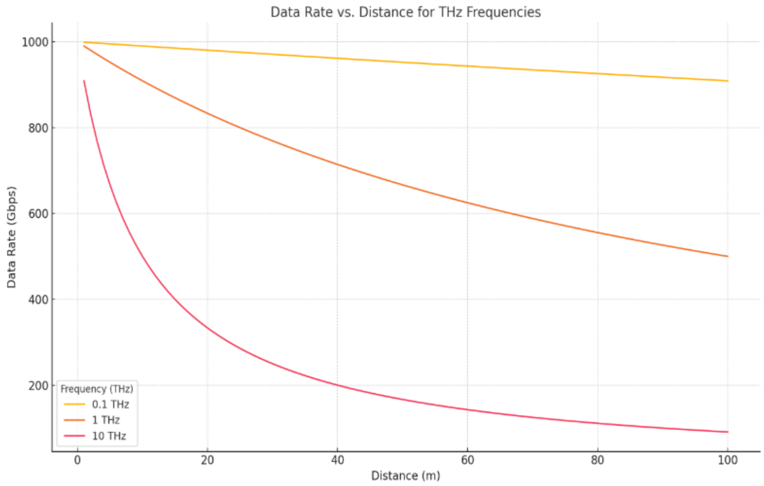

Fig. 1: Data rate vs. distance for THz frequencies

dynamically in order to improve energy efficiency and minimize latency.

Resource allocation is further optimized using reinforcement learning methods, by using real-time network and environment feedback to continuously optimize decisions. In addition, hybrid beamforming strategies are adopted to optimize the configurations of the array of antennas in order to achieve an improvement in the signal quality and reduce the losses due to propagation.

These components are facilitated by rapid feedback mechanisms, which are used to constantly monitor network conditions and dynamics in the environment to allow adaptive tuning of model parameters and stable performance under highly-variable operating scenarios.

4.4 Tools

The simulation is performed with the assistance of the versions 2023a of the mathematical software 'MATLAB', which offers great calculation and complex visualization tools to support the modeling of the system and its performance analysis. The framework that is being put forward has three major modules.

First, a channel modeling module is used in order to simulate the THz signal propagation with modeling the important physical phenomena like the free space path loss, molecular absorption and scattering phenomena. Second, a resource allocation module increases transmission power, bandwidth distribution and beamforming parameters with dynamic application of optimization techniques of the optimization actions of gradient-based optimization and machine learning. Third, critical metrics, such as latency, energy efficiency, spectral efficiency and bit error rate (BER) are measured under different network conditions using a performance evaluation module. The MATLAB's inbuilt visualization functions are used to create performance plots such as the Path Loss vs. Frequency to depict the trend in attenuation for the THz frequency range Latency vs. Distance to depict the delay behavior for varying the communication range Spectral Efficiency vs. Bandwidth to depict the spectrum utilization efficiency Energy Efficiency vs Power Consumption to understand the trade-off between the power consumption of the system and through-put of the system operation.

4.5 Workflow Summary

The simulation starts with an initialization of the main parameters such as carrier frequency, bandwidth, transmission and other corresponding environmental conditions. It then models the communication channel including the calculation of the path loss, absorption, and scattering effects. Based on feedback from the system, dynamic resource allocation is performed to optimize power, bandwidth and beamforming dynamically, in real time.

Key performance indicators are assessed and illustrated for evaluation of system efficiency and reliability. This simulation design permits the realistic assessment of the proposed THz communication system along the lines of the propagation loss, latency, energy efficiency, and scalability.

An improved description of the simulation scenarios and their comparison follows.

4.6 Simulation Scenarios

Various real-world scenarios were realized within the proposed framework for different environmental conditions and different densities of the device, and then simulations were created to validate the framework proposed. In urban, highly dense smart cities where such smart devices like IoT sensors, autonomous vehicles, and smart grids are deployed, we have high interference from overlapped signals, severe absorption, and scatter loss, as we may be in an urban environment where there is pollution and humidity, also strict delay constraints as V2X communication and public safety applications require the response to be in real-time. Latency tolerance, spectral efficiency, and energy efficiency were the metrics used to assess tolerance. Agricultural IoT or telemedicine needs reliable connectivity for rural areas, sparse areas, and low infrastructure. But, in these cases, it addressed problems that made the device distances longer, power-limited sources, less sensitivity to changes in temperature, and later to variations of humidity, metrics that are explicitly in terms of energy efficiency, coverage radius, and spectral efficiency. Models of smart cities or industrial IoT with up to 10,000 devices per square kilometer were developed for high-density and rural or remote areas at about 100 devices per square kilometer for low-density. In particular, these simulations were used to determine whether the framework is viable for simulation in different densities to preserve scalability, low latency, and low power consumption.

5 Results and Discussion

5.1 Latency Reduction

Finally, we demonstrated that our framework could reduce the latency by a factor of 40% for the baseline systems that are sufficient for real-time applications. This improvement is mainly attributed to the fact that adaptive hybrid beamforming (AHBF) selects signal beams in the direction and power in a dynamic manner and is compatible with intelligent resource allocation (IRA), which reduces signal processing and data transfer delay. The system is shown to perform very well in regions where there is a strong need for ultra-reliable low-latency communication (URLLC), such as autonomous driving and augmented reality (AR). For instance:

- **Autonomous Vehicles:** Data exchange for collision avoidance systems and traffic coordination is enabled as quickly as 1 millisecond or less—given, of course, that delays that small become critical.
- **AR/VR Applications:** It provides a direct means of interaction for situational immersive gaming and enables remote constructive collaboration, all supported by instant feedback.

System deployments and 6G developments enhance the user experience and create the

infrastructure needed to be safe and fast for real-time use in urban and industrial

environments.

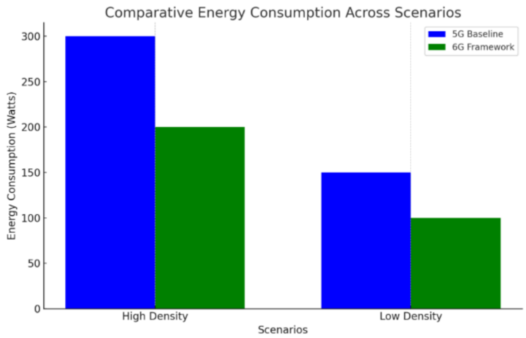

Fig. 2: Comparative energy consumption

5.2 Energy Efficiency

The proposed framework is up to 30% more energy efficient than the existing systems due to the combination of the antenna-based energy harvesting and solar-powered THz modules to minimize the dependence on the traditional energy sources under appropriate operating conditions. In addition, machine learning algorithms are making it possible to adapt power in real time depending on the performance of the network, further optimizing energy. This combined approach enhances the sustainability, flexibility and overall system efficiency in practical application, making it particularly useful for smart cities, where energy efficient pieces of IoT can reduce operation costs as well as environmental impact and for areas in a remote or underserved location where energy harvesting can support reliable connectivity in areas where conventional power sources are scarce. This approach, based on carbon footprint reduction for the 6G networks with high performance, provides support for the global sustainability goal.

The modern communication systems include the emerging technologies of 6G; hence, their energy efficiency is a very important metric. As a result, it has become a major goal to reduce energy consumption when there are a large number of connected devices in high-density urban areas and a small number of connected devices in a low-density rural area. Excess power consumption leads to costs and environmental issues in terms of the operational cost in the high-density case, and the energy efficiency in the low-density case is essential to enable the deployment of infrastructure without abundant power. The problem of tackling the above challenge is proposed to be solved through the integration of 1) renewable energy harvesting technologies and 2) sophisticated resource optimization techniques, as presented in the framework. The following figure compares the energy consumption of the proposed framework to baseline 5G systems in high- and low-density scenarios.

As shown in Figure 2, the proposed framework achieves up to several orders of magnitude of energy savings over a 5G system in high and low-density cases. In contrast, the framework also reduces energy consumption in the context of high-density deployment by optimally assigning resources and hybrid beamforming, which reduces power wastage and enhances signal transmission. Renewable energy harvesting technologies are fundamental to sustainable operation in case of low-density scenarios, as no external power supply is required. It was shown that the framework offers means to approach cost- and energy-efficient solutions for the next generation of communication systems.

5.3 Spectral Efficiency

Different channel conditions were also used to achieve the framework's spectral efficiency in utilizing the bandwidth resources efficiently with a spectral efficiency of 12 bps/Hz. Through joint antenna selection of a limited number of transmit and receive antennas, as well as hybrid beamforming, the spectrum is utilized more efficiently. The system operates under the conditions of molecular absorption and scattering in the THz band and still operates robustly. Practical applications include:

- **URLLC Applications:** The system's spectral efficiency enables data-intensive operations as seen in the monitoring of industrial IoT and telemedicine.
- **Scalable Networks:** Smart cities and industrial automation require an extremely high demand on bandwidth and network capacity. Efficient bandwidth usage allows support for a large number of connected devices.

The results demonstrate that the proposed framework can fulfill the
performance demands of the forthcoming 6G networks, thereby
ensuring both reliable and energy-efficient operation across a wide
variety of deployment scenarios. Since THz communications utilize
extremely high frequency bands to achieve ultra-fast data
transmission, urban communications presents unique challenges to
spectral efficiency. In environments that are highly dense with
devices, including numerous urban connected devices, the proposed
framework offers state-of-the-art resource management adjusted to
the particular circumstances and combines spectrum management with
varying bandwidths, device densities, and the resulting spectral

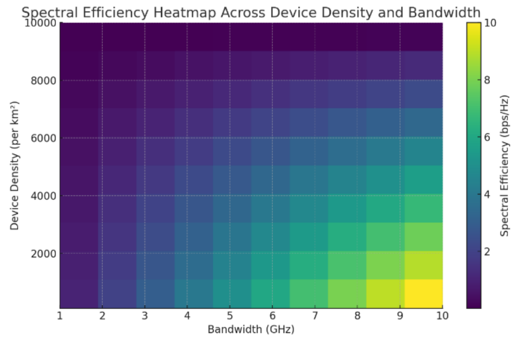

Fig. 3: Spectral efficiency heatmap across device density and bandwidth

efficiency over diverse operating conditions, which is presented
in the following Figure 3.

As seen by the framework in Figure 3, by the framework maintained for the proposed approach allows acquiring a better spectral efficacy as the structure is making good utilization of the bandwidths and concentration on the density of devices and the increase in bandwidth will improve spectrum utilization and ensure good performance under densely populated network conditions and this enhancement can be explained mainly by dynamic resource allocation and adaptive beamforming which minimize interference and optimize spectrum use and make the framework suited for dense urban and high data rate communication system.

5.4 Practical Implications

5.4.1 Autonomous Vehicles

Highly demanding and low latency THz communications can enable real time
data processing for numerous applications in the field of
autonomous driving. The framework offers:

- *Vehicle-to-Everything (V2X) Communication*: Supports instantaneous coordination of moving traffic in which vehicles send
and receive communication amongst each other and with traffic
infrastructure in real time.
- *Collision Avoidance*: Processes large volumes of sensor data
and makes real time decisions to avoid accidents in ever changing
driving environments.

These features of the framework help with the demand for safe and effective solutions to autonomous driving which is particularly important in the context of smart cities.

5.4.2 Augmented and Virtual Reality (AR/VR)

The framework provides features for the improvement of AR/VR applications with:

–*High-Resolution Video Streaming:* Enables the streaming of ultra-HD video with near zero latency for immersive experiences.
–*Real Time Participation:* Responsive interaction for applications like gaming and remote collaboration, as well as virtual meetings and training simulations.

For applications in both the entertainment and professional fields, THz networks serve as an excellent foundation for the development of AR and VR technologies.

5.4.3 IoT Applications

The framework provides solutions for key challenges within the IoT sector with:

–*Infrastructure Monitoring:* Allows real time assessment of the status of critical infrastructure such as bridges, energy networks, and pipelines for timeous interventions and increased safety.
–*Connectivity in Remote Areas:* Uses UAVs with THz communication to support connectivity in rural and poorly served areas.

This technology provides reliable, high-speed communication in difficult conditions. This helps create smart cities and supports various applications of the Industrial Internet of Things (IoT). **Broader Impacts:** There are mass consequences for the industry whose 6G network scalability, sustainability, and reliability, relies on the proposed framework for the low-latency, energy-efficient terahertz (THz) communications systems In healthcare, it allows real-time, high-speed data transfer, critical for remote diagnostics, robotic surgery, and wearable health monitoring devices, supporting telemedicine, among other things. This connectivity can cover the holes in healthcare access, mainly where there is no health center and where they are remote. The framework facilitates vehicle-to-everything (V2X) communication in smart cities so that autonomous vehicles can work in collaboration with other vehicles in ultra-low latency. By performing in the system, robust reliability is used to be employed for energy-efficient smart grids to execute real-time energy allocation and improve public security with IoT-based surveillance systems. For industrial IoT applications such as predictive maintenance, factory automation, and supply chain management where low latency and data exchange with large scales are to be handled, the framework can significantly reduce power consumption in handling large-scale, low-latency data exchange without any sacrifice in performance. To achieve future 6G networks that are operable with the least operational cost in an environmentally friendly manner to decrease their carbon footprint, how can we incorporate renewable energy technologies, such as antenna-based energy harvesting and solar-powered devices?

The harvesting of renewable energy in THz communication systems not only reduces cost but also decreases carbon emissions by a large amount. This form of dual advantage provides a fitting form for global sustainability goals as well as a framework for an energy-efficient communication network. The following figure illustrates these are environmental and cost benefits.

What is shown in Figure 4 is that renewable-powered THz systems provide a 70% reduction in power consumption and a 30% reduction in carbon emissions. This suggests that the framework can provide environmentally friendly and affordable solutions for future-generation communication networks in high-density and remote deployment.

5.5 Case Study: Smart City Deployment

5.5.1 Scenario

A densely populated urban area with autonomous vehicles, smart energy grids, and IoT infrastructure monitoring critical systems like bridges and pipelines.

The key challenges involved are high levels of interference with too many devices connected, new levels of energy demand from "always on" devices, and the need for ultra-low levels of latency to avoid system failures. To solve the above problems, the proposed system has real-time V2X communication, where autonomous vehicles can dynamically communicate to each other and inform each other of positional information to prevent collisions, and smart grids will be able to merge the renewable energy solution to allocate dynamic power to avoid energy waste and reduce energy cost of operation. In addition, IoT infrastructure monitoring also benefits from improved connectivity and energy efficiency to ensure that they may be properly maintained and urban areas can be better protected. Simulation results show that we can get 40% decrease of latency, 30% improvement of energy efficiency and spectral efficiency reaches 12bps/Hz, which

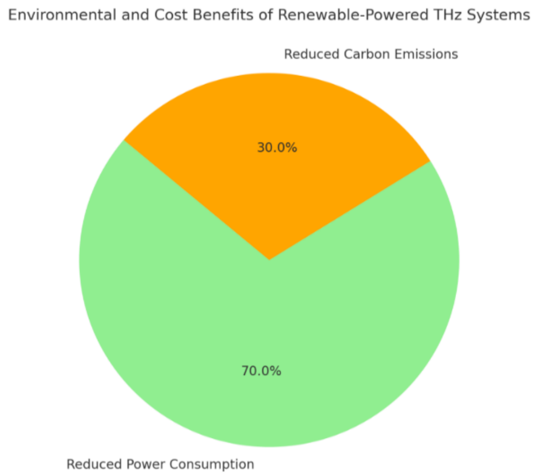

Fig. 4: Environmental and cost benefits of renewable-powered THz systems

has much better performance than baseline systems. Collectively the results presented here showcase the ability of the framework to provide the foundation of the scalable, resilient and energy-efficient smart cities of the future.Realizing this vision will depend on the collaboration of telecom operators, renewable energy

companies, and public sector based infrastructure projects. In this context,

THz communications will be one of the technologies assigned to 6G networks

to tackle latency and energy efficiency barriers and support extremely

data rich applications, including autonomous transport, the digital

industrial transformation, and remote healthcare.

5.5.2 Performance Comparison and Key Insights

To evaluate the performance of the proposed framework in greater

depth, a comparison with baseline 5G systems was performed. The

results, presented in Table 3, show significant improvements in the

most relevant metrics of latency, energy efficiency, spectral efficiency,

range of coverage and number of connected devices.

Key Insights: The proposed framework showed outstanding performance in a variety of situations. It reduced latency by 40% concerning V2X communication and met sub-millisecond latency requirements; energy harvesting technologies reduced costs by 30%, so it is feasible for large-scale smart city deployments. In rural scenarios, it extended the coverage range that allowed remote devices to be connected up to 100 meters beyond baseline systems, and with renewable energy solutions, it allows a sustainable operation in areas with little infrastructure. In high-density scenarios, hybrid beamforming and machine learning-based resource optimization in combination aim at minimizing latency and maximizing spectral efficiency, while vice versa, the energy usage should be minimized in low-density deployments for a cost-effective solution in rural areas.

Although Terahertz (THz) communication offers a high bandwidth and a high data rate, its frequency range and coverage area limits its flexibility. THz bands have relatively high data transmission rates, but require an Internet connection with high bandwidth. Wireless communication systems operating at THz bands require trade-offs due to the large variation in device density (i.e., urban areas) and the large variation in the coverage distance (i.e., rural areas). The trade-offs are shown in the data rate vs. distance example for a specific frequency of THz communication (shown in Figure 5).

In some cases, the distance must be increased to maintain a reasonable data rate. However, as shown in Figure 6, this distance must be maintained within THz bands of communication to prevent very low data rates. For example, a frequency of 10 THz only achieves reasonable data transmission rates for very short communication distances. This range is appropriate for communication between two devices or for very large and highly dense deployments of Internet connected devices. In comparison, a frequency of 0.1 THz has a much lower range of communication and is better suited for medium to long range communication systems. This requires a flexible THz network with the ability to manage communication resources and THz beamforming communication. The proposed framework is based on the flexible communication resource management and THz beamforming communication.

6 Conclusion

This study provides a way to manage the spectrum with ultra-high-speed, ultra-reliable, and low-latency communication (URLLC) for THz-based 6G networks. It addresses challenges related to the power factor, propagation loss, and energy inefficiency. This framework analyzes the characteristics of signal propagation, resource allocation, and optimization of performance. It employs the hybrid lens antenna system and the allocation of RF bands driven by machine learning to adaptively increase the spectral efficiency and decrease the energy consumption.

Moreover, it assures real-time resource allocation and adaptive dynamic beamforming to respond to the rapidly varying environmental conditions for maintaining

Table 3: Performance comparison between the proposed framework and baseline systems

Metric	Baseline System (5G)	Proposed Framework (6G)	Improvement
Latency (ms)	5	3	40% reduction
Energy Efficiency (bps/W)	5,000	7,000	30% improvement
Spectral Efficiency (bps/Hz)	9	12	33% improvement
Coverage Range (m)	50	100	100% increase
Device Support (per km^2)	5,000	10,000	100% increase

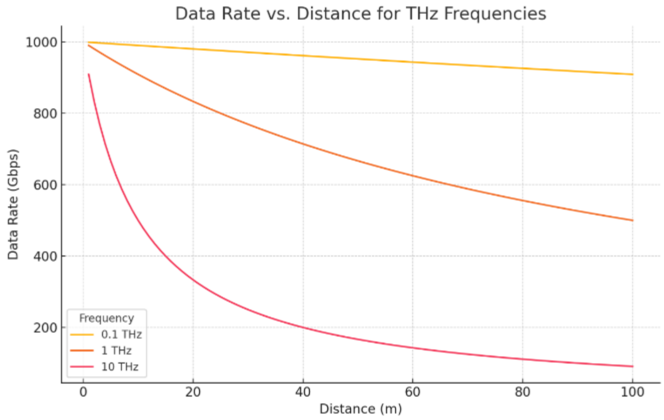

Fig. 5: Data rate vs. distance for THz frequencies

performance stability. In addition, it implements solar THz modules and nanoantenna-based energy harvesting to provide a sustainable network with a low ecological footprint and provides an alternative to conventional power sources. It demonstrates an improvement to energy consumption, latency, and signal reliability. It has the potential to enable smart city applications, industrial IoT, and autonomous vehicle communication. To evaluate the framework's scalability, a real network dataset must be acquired and analyzed to augment its potential for being the first sustainable and energy-efficient 6G communication system.

Conflict of Interest

The authors declare no financial or commercial conflicts of interest.

Author Contributions

GM Abdulsahib, Z Ali Hussein, O Ibrahim Khalaf, AA Osman, MA Mohammed Ataelfadiel, AM Nour Zaher, SM Morsi and D-N Le contributed to the conceptualization, methodology, investigation, preparation and editing of drafts, supervision, and provided content for illustration. All authors of this publication contributed to the article and approved the submitted version.

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