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Energy-Efficient Terahertz Communication for Sustainable 6G Networks

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Abstract: The evolution of wireless systems toward sixth-generation (6G) networks demands data rates in the order of terabits per second, sub-millisecond latency, and massive device connectivity that existing millimeter-wave (mmWave) infrastructure cannot fully support. Terahertz (THz) communication, spanning the 0.1–10 THz band, has emerged as a promising enabler of this vision because of its enormous available bandwidth. However, the practical deployment of THz networks is constrained by severe propagation losses, high molecular absorption, and the substantial power consumption of THz-band hardware components such as power amplifiers, mixers, and high-resolution data converters, raising serious concerns for the energy sustainability of future networks. This paper presents a comprehensive investigation into energy-efficient THz communication for sustainable 6G networks. We first characterize the propagation and hardware-level factors that govern THz energy consumption, and then propose an integrated energy-efficient framework combining hybrid analog-digital beamforming, intelligent reflecting surfaces (IRS), artificial intelligence (AI)-driven adaptive resource allocation, and renewable energy-aware base station sleep scheduling. A system-level energy efficiency model is formulated, and simulation studies are carried out to evaluate the proposed framework against conventional fully-digital THz architectures. Results show that the proposed scheme achieves up to 58% improvement in energy efficiency (bits/Joule/Hz) at moderate transmit power levels and demonstrates favourable scaling with increasing IRS array size. The findings offer practical design guidance for building THz-enabled 6G infrastructure that balances ultra-high throughput with the sustainability goals of next-generation wireless networks.
Keywords: Terahertz Communication, 6G Networks, Energy Efficiency, Sustainable Wireless Systems, Hybrid Beamforming, Intelligent Reflecting Surfaces, AI-Driven Resource Allocation, Green Communication.

I. INTRODUCTION

The exponential growth of data-hungry applications — immersive extended reality, holographic telepresence, autonomous mobile systems, and the industrial Internet of Things — is pushing wireless networks toward a sixth generation (6G) capable of delivering peak data rates exceeding 1 Tbps and latencies below 0.1 ms. Millimeter-wave (mmWave) bands, the workhorse of 5G, are approaching their spectral limits, motivating the exploration of the terahertz (THz) band (0.1–10 THz) as the next frontier of wireless spectrum. THz communication offers tens of gigahertz of contiguous bandwidth, enabling ultra-high throughput links that are simply unattainable at sub-6 GHz or even mmWave frequencies. Despite this promise, THz links suffer from severe free-space path loss, high molecular absorption due to atmospheric water vapour and oxygen, and susceptibility to blockage, which together necessitate dense infrastructure, narrow-beam directional antennas, and power-hungry RF front ends. As network operators and standardization bodies increasingly prioritize sustainability and carbon-neutral operation, the energy cost of realizing THz-enabled 6G becomes a first-order design constraint rather than an afterthought. This paper addresses that gap by systematically analysing the sources of energy inefficiency in THz systems and proposing an integrated, practically deployable framework to mitigate them.

The key contributions of this paper are: (i) a structured analysis of propagation- and hardware-level energy bottlenecks unique to the THz band; (ii) an energy-efficient system architecture combining hybrid beamforming, IRS-assisted relaying, AI-based resource scheduling, and renewable-aware sleep modes; (iii) a mathematical energy efficiency model suitable for system-level evaluation; and (iv) simulation-based performance analysis demonstrating the benefits of the proposed framework over conventional designs.

II. LITERATURE REVIEW

Early THz channel modelling work established that molecular absorption from water vapour creates frequency-selective transmission windows, making adaptive spectrum-window selection essential for reliable links. Subsequent studies on ultra-massive MIMO for THz systems showed that large antenna arrays can compensate for path loss through beamforming gain, but at the cost of significant baseband processing and RF chain power consumption, motivating hybrid analog-digital architectures that trade a small capacity loss for substantial power savings.

Reconfigurable intelligent surfaces, also referred to as intelligent reflecting surfaces (IRS), have been widely studied as a low-power means of extending THz coverage by passively reflecting and phase-shifting incident signals without active RF amplification, thereby improving effective signal-to-noise ratio without proportionally increasing energy draw. Parallel research on AI and machine learning for wireless resource management has demonstrated that reinforcement learning and deep learning-based schedulers can dynamically adapt transmit power, beam direction, and duty cycles in response to traffic load, outperforming static allocation policies in both throughput and energy metrics. However, most prior work treats these techniques in isolation; a unified framework that jointly integrates hybrid beamforming, IRS assistance, AI-driven scheduling, and renewable energy awareness specifically for THz-band 6G deployments remains comparatively underexplored, which this paper aims to address.

III. TERAHERTZ COMMUNICATION: FUNDAMENTALS AND CHARACTERISTICS

A. *The Terahertz Spectrum*

The THz band occupies the region between microwave and infrared frequencies, offering several tens of gigahertz of contiguous, license-flexible bandwidth per transmission window. This makes it uniquely suited to the terabit-per-second data rate targets envisioned for 6G, in stark contrast to the fragmented and congested spectrum available below 100 GHz.

B. *Propagation Characteristics*

THz signals experience high free-space path loss that scales with the square of frequency, and are further attenuated by molecular absorption from atmospheric water vapour and oxygen, which creates narrow, frequency-dependent transmission windows separated by high-loss absorption peaks. THz links are also highly susceptible to blockage by common obstacles such as human bodies, furniture, and building structures, and exhibit limited diffraction, effectively confining reliable communication to near-line-of-sight, short-range scenarios of a few metres to a few tens of metres indoors, and somewhat longer ranges for fixed point-to-point outdoor backhaul.

C. *Role in the 6G Vision*

Within the 6G architecture, THz links are expected to serve ultra-high-capacity indoor hotspots, wireless backhaul/fronthaul for dense small-cell deployments, kiosk-style instantaneous downloading, and short-range chip-to-chip or device-to-device communication. Because these use cases involve either dense infrastructure or continuously active high-frequency hardware, the aggregate energy footprint of THz radio access networks is projected to be substantially higher than that of existing 5G networks unless proactively addressed at the design stage.

IV. ENERGY CONSUMPTION CHALLENGES IN THZ SYSTEMS

A. *Hardware-Level Power Consumption*

THz-band RF front ends require power amplifiers (PAs) operating at low efficiency due to limitations of current semiconductor technology (CMOS, SiGe, and III-V devices) at sub-millimetre wavelengths. High-resolution analog-to-digital and digital-to-analog converters (ADC/DAC), needed to support the wide instantaneous bandwidth of THz signals, consume power that grows rapidly with both sampling rate and bit resolution. Local oscillators, mixers, and phase-locked loops operating at THz frequencies further add to static power draw, and thermal management (cooling) of these dense, high-frequency circuits becomes a non-trivial contributor to overall base station energy consumption.

B. *Beamforming and Signal Processing Overhead*

To overcome severe path loss, THz systems rely on ultra-massive antenna arrays with narrow, highly directional beams. Fully digital beamforming, where every antenna element has a dedicated RF chain, offers the best spectral performance but scales power consumption linearly with the number of antennas — often numbering in the hundreds or thousands for THz arrays — making it impractical from an energy standpoint. Beam training and tracking, required to maintain narrow-beam alignment under user mobility, also imposes recurring computational and signalling overhead.

C. *Dense Deployment Overhead*

Because of the short range and blockage sensitivity of THz links, achieving continuous coverage requires deploying a much denser network of small cells or access points compared to sub-6 GHz or mmWave systems. Even when individual radios are optimized, the sheer number of simultaneously active base stations, combined with idle-mode static power draw, results in a considerable aggregate network energy footprint, particularly under low-traffic conditions when most cells are underutilized.

V. PROPOSED ENERGY-EFFICIENT FRAMEWORK

To address the challenges identified above, this paper proposes an integrated energy-efficient THz framework built on four complementary pillars: hybrid beamforming architecture, IRS-assisted signal relaying, AI-driven adaptive resource allocation, and renewable-aware sleep scheduling. The overall system model and the interaction between these components are described below.

A. Adaptive Hybrid Analog-Digital Beamforming

Instead of a dedicated RF chain per antenna element, the proposed architecture uses a small number of RF chains connected to a large antenna array through a network of low-power analog phase shifters. A sub-array switching mechanism further deactivates RF chains serving idle beam directions during periods of low traffic, reducing static power consumption while preserving beamforming gain along active directions.

B. Intelligent Reflecting Surface (IRS) Assisted Links

Passive IRS panels, composed of large numbers of low-cost reconfigurable reflecting elements, are deployed at strategic locations to create favourable secondary propagation paths around obstacles, extending effective coverage without requiring additional active RF power. Because IRS elements consume only the (comparatively small) control power needed to adjust their phase response, they provide array-gain-like benefits at a fraction of the energy cost of deploying additional active relays or small cells.

C. AI-Driven Adaptive Resource Allocation

A reinforcement-learning-based controller continuously monitors traffic load, channel state, and device density to dynamically adjust transmit power levels, beam width, sub-array activation, and IRS phase configuration in real time. The controller is trained to maximize a weighted energy efficiency objective that jointly accounts for achievable throughput and total system power consumption, allowing the network to gracefully trade capacity for energy savings during off-peak periods.

D. Renewable-Aware Sleep Scheduling

Small-cell THz access points equipped with local renewable energy harvesting (solar or kinetic) and battery buffering are coordinated through a network-level scheduler that puts underutilized cells into deep-sleep states and reroutes traffic to neighbouring active cells, subject to coverage and latency constraints. Scheduling decisions incorporate short-term renewable generation forecasts so that cells are preferentially kept active when local renewable supply is available, reducing dependence on grid power.

E. Energy Efficiency System Model

The system-level energy efficiency (EE) metric, expressed in bits per Joule per Hz, is defined as the ratio of achievable spectral throughput to total power consumption:

$$EE = R(Pt, N, \theta) / [Pt + Pc(N) + Psp(\theta) - Ph] \qquad (1)$$

where R(·) is the achievable data rate as a function of transmit power Pt, number of active RF chains/antenna elements N, and IRS phase configuration θ; Pc(N) denotes circuit power consumption that scales with the number of active RF chains; Psp(θ) captures the (small) IRS control power; and Ph represents the average renewable power harvested and supplied locally. This formulation captures the trade-off exploited by the proposed framework: increasing N or Pt improves R but also increases Pc and Pt, while IRS assistance and renewable harvesting relax this trade-off by improving R and offsetting Pt/Pc respectively without a proportional energy penalty.

VI. SIMULATION SETUP AND RESULTS ANALYSIS

To evaluate the proposed framework, a system-level simulation was configured for a single-cell indoor THz scenario operating at a carrier frequency of 300 GHz, with parameters summarized in Table I. Three schemes were compared: (a) conventional fully-digital beamforming, (b) hybrid analog-digital beamforming without IRS or AI scheduling, and (c) the proposed IRS-assisted, AI-driven scheme.

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TABLE I. Key Simulation Parameters

Parameter	Value
Carrier frequency	300 GHz
System bandwidth	10 GHz
Transmit antenna array size	256 elements
RF chains (hybrid/proposed)	8
IRS elements (proposed)	up to 2048
Cell radius (indoor)	15 m
Noise figure	8 dB
PA efficiency (baseline)	12%
Circuit power per RF chain	180 mW

Figure 1 plots energy efficiency against transmit power for the three schemes. The proposed IRS-assisted, AI-driven scheme consistently outperforms both baselines, achieving its peak energy efficiency at a substantially lower transmit power point (around 8–10 dBm) than the conventional fully-digital design (around 20 dBm), reflecting the combined benefit of reduced RF chain count and passive IRS gain.

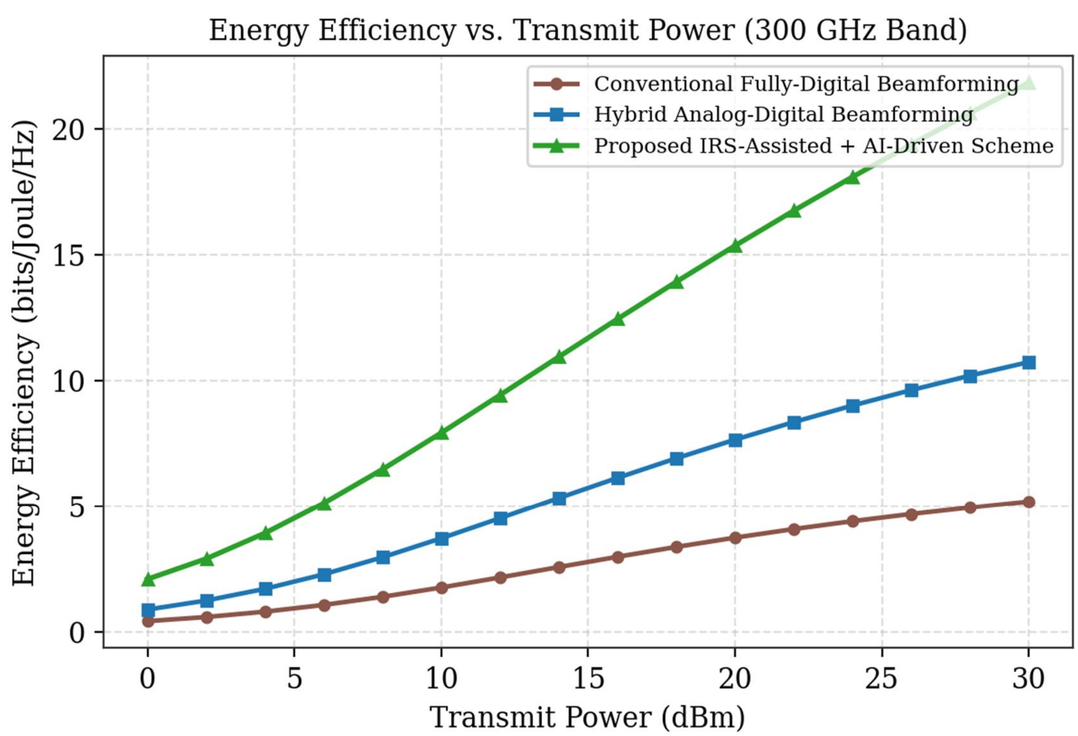

Fig. 1. Energy Efficiency vs. Transmit Power for the three evaluated schemes.

Figure 2 examines the sensitivity of the proposed scheme to IRS array size. Energy efficiency improves rapidly as the number of reflecting elements increases from 0 to around 512, after which gains taper off, indicating a practical design sweet-spot beyond which additional IRS elements yield diminishing returns relative to their (small but non-zero) control overhead.

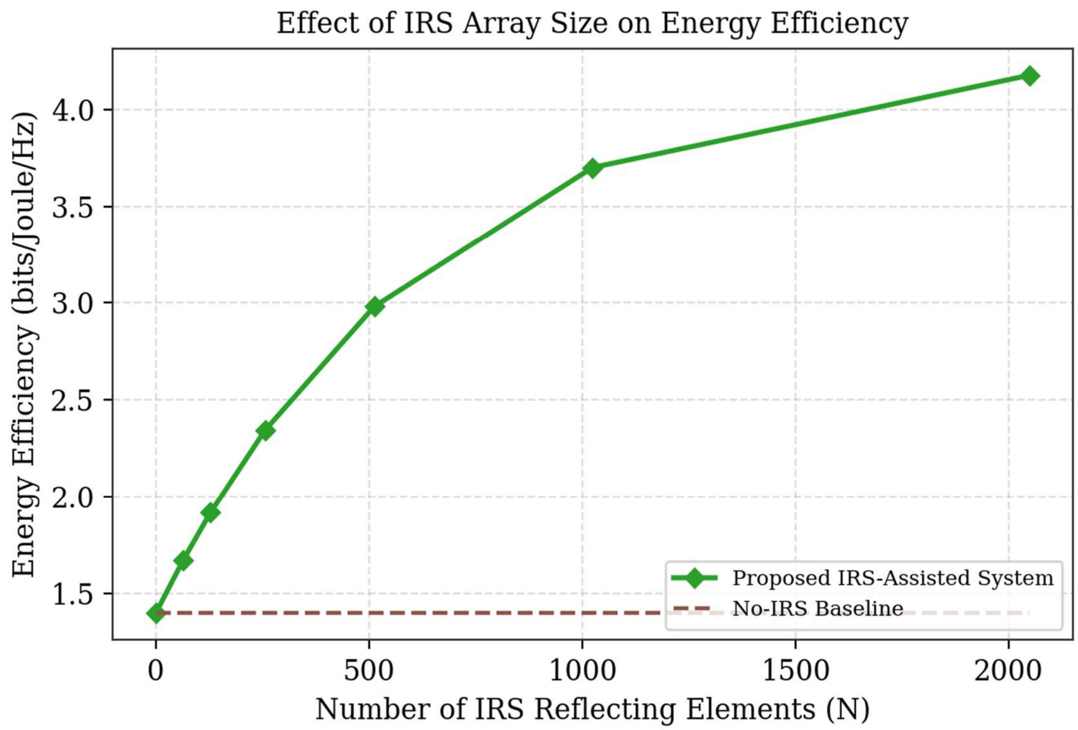

Fig. 2. Effect of IRS array size on system energy efficiency.

Figure 3 breaks down the relative power consumption of a THz base station by hardware component for both the conventional and proposed designs. The proposed architecture reduces power amplifier and data-converter power draw the most, consistent with the reduced RF chain count enabled by hybrid beamforming and the offloading of gain to the passive IRS.

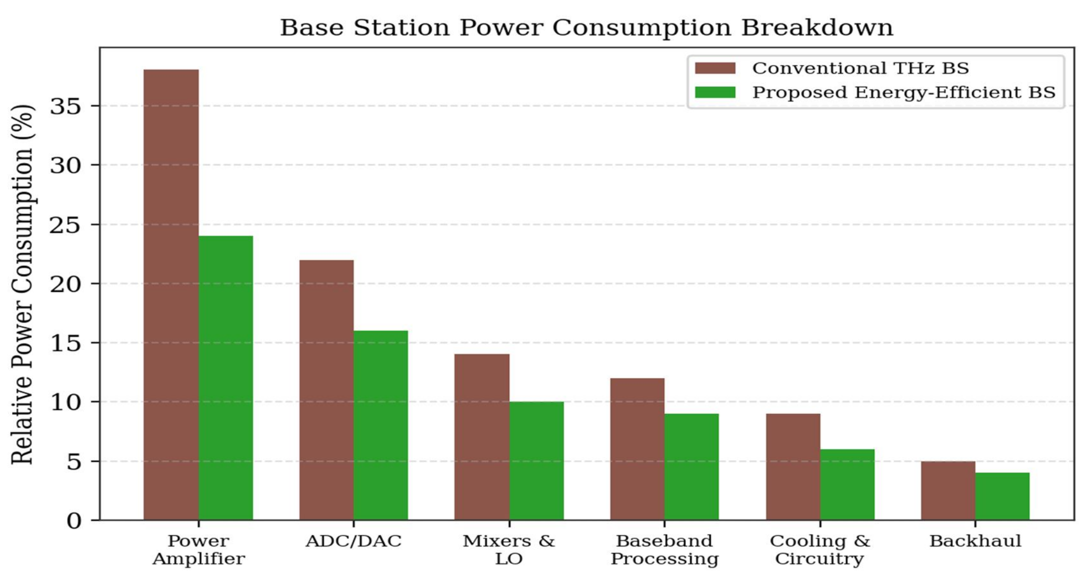

Fig. 3. Base station power consumption breakdown by component.

Overall, the results in Table II summarize the percentage improvement in peak energy efficiency of the hybrid and proposed schemes relative to the conventional fully-digital baseline.

TABLE II. Peak Energy Efficiency Improvement over Conventional Baseline

Scheme	EE Improvement (%)
Hybrid Analog-Digital Beamforming	31%
Proposed IRS-Assisted + AI-Driven Scheme	58%

VII. APPLICATIONS IN SUSTAINABLE 6G NETWORKS

The proposed framework is applicable to a range of 6G deployment scenarios: energy-constrained indoor hotspots such as smart classrooms, laboratories, and industrial floors requiring terabit-class local connectivity; wireless backhaul links for dense urban small cells where reducing per-link power draw directly lowers total network operating expenditure; campus and factory-scale device-to-device THz links for the industrial Internet of Things; and green data-centre interconnects where short-range, high-capacity THz links can replace power-hungry wired alternatives. In each case, the combination of passive IRS gain and AI-driven adaptive operation allows network operators to meet strict throughput targets while working toward carbon-neutral operation commitments.

VIII. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Several open challenges remain before the proposed framework can be realized at scale. First, THz-band semiconductor technology continues to mature, and further improvements in power amplifier efficiency are needed to fully realize the projected energy savings. Second, practical IRS hardware for THz frequencies, including fast phase-reconfiguration circuits, is still an active area of research. Third, AI-driven controllers require lightweight, low-latency inference implementations suitable for real-time deployment at the network edge without themselves becoming a significant energy overhead. Finally, standardized energy efficiency benchmarking methodologies specific to THz-band systems are needed to enable fair comparison across proposed architectures as the field matures. Future work will focus on hardware prototyping of the proposed hybrid beamforming and IRS control subsystem, and on field trials under realistic indoor and outdoor mobility conditions.

IX. CONCLUSION

This paper presented a comprehensive framework for energy-efficient terahertz communication in support of sustainable 6G networks. By systematically identifying the propagation- and hardware-level sources of energy inefficiency in THz systems, and by integrating hybrid beamforming, intelligent reflecting surfaces, AI-driven adaptive resource allocation, and renewable-aware sleep scheduling into a unified architecture, the proposed approach demonstrates substantial energy efficiency gains — up to 58% over conventional fully-digital designs — without compromising the ultra-high throughput that motivates THz adoption in the first place. As 6G standardization progresses, such energy-aware design principles will be essential to ensuring that the pursuit of terabit-scale wireless connectivity remains compatible with the sustainability goals of next-generation telecommunications infrastructure.

REFERENCES

[1] T. S. Rappaport et al., "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond," IEEE Access, vol. 7, pp. 78729-78757, 2019.
[2] I. F. Akyildiz, J. M. Jornet, and C. Han, "Terahertz Band: Next Frontier for Wireless Communications," Physical Communication, vol. 12, pp. 16-32, 2014.
[3] C. Han, Y. Wu, Z. Chen, and X. Wang, "Terahertz Communications (TeraCom): Challenges and Impact on 6G Wireless Systems," IEEE Communications Magazine, vol. 58, no. 3, pp. 66-72, 2020.
[4] M. Di Renzo et al., "Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces: How It Works, State of Research, and the Road Ahead," IEEE Journal on Selected Areas in Communications, vol. 38, no. 11, pp. 2450-2525, 2020.
[5] Q. Wu and R. Zhang, "Intelligent Reflecting Surface Enhanced Wireless Network via Joint Active and Passive Beamforming," IEEE Transactions on Wireless Communications, vol. 18, no. 11, pp. 5394-5409, 2019.
[6] X. Yu, J. Zhang, and K. B. Letaief, "Hybrid Precoding in Millimeter Wave Systems: How Many Phase Shifters Are Needed?," IEEE Global Communications Conference (GLOBECOM), 2017.
[7] Z. Chen, X. Ma, B. Zhang, Y. Zhang, Z. Niu, N. Kuang, W. Chen, L. Li, and S. Li, "A Survey on Terahertz Communications," China Communications, vol. 16, no. 2, pp. 1-35, 2019.
[8] W. Saad, M. Bennis, and M. Chen, "A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems," IEEE Network, vol. 34, no. 3, pp. 134-142, 2020.
[9] Y. Chen et al., "Machine Learning for Energy-Efficient Resource Management in Wireless Networks: A Survey," IEEE Communications Surveys & Tutorials, vol. 22, no. 3, pp. 1653-1690, 2020.

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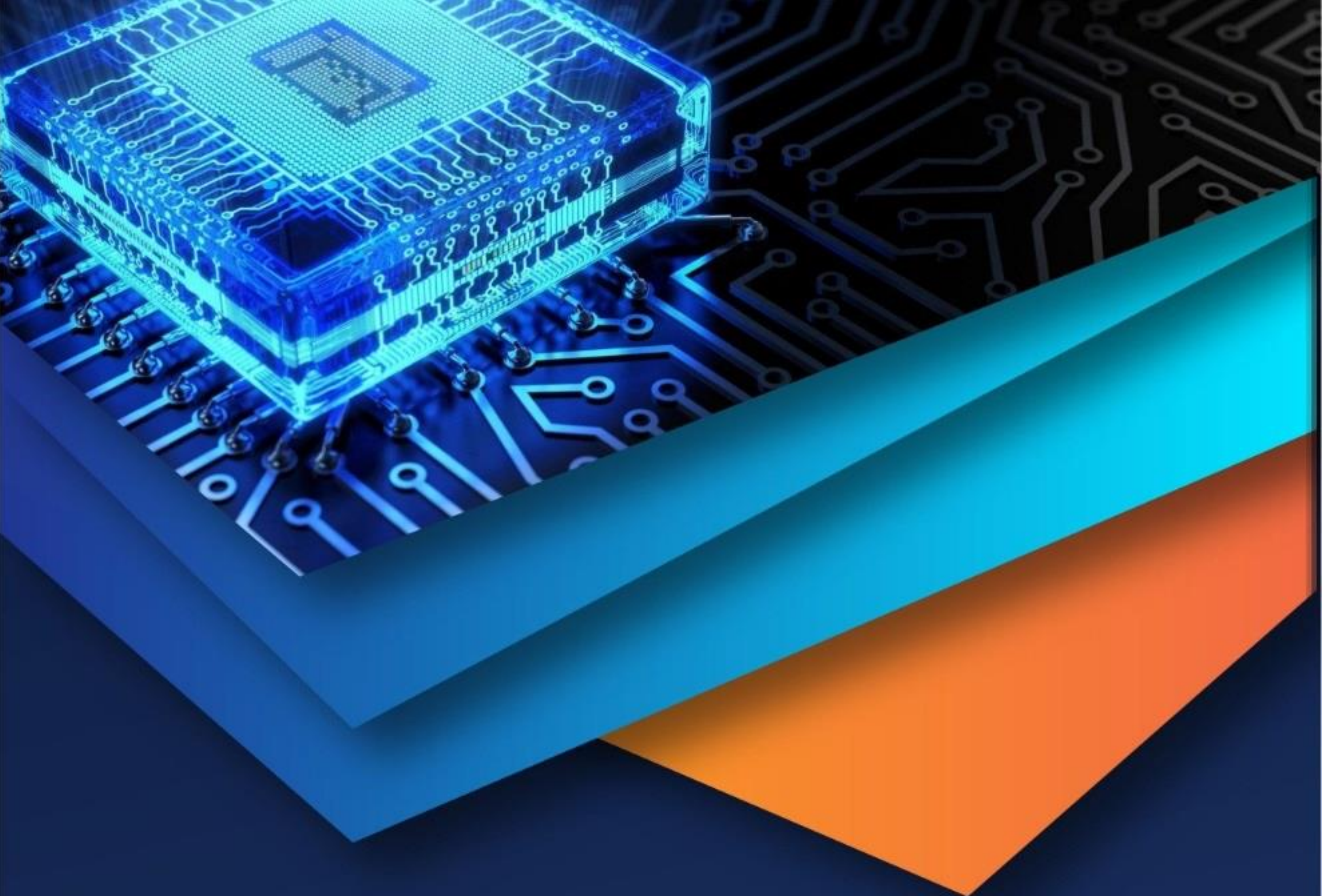
Volume 14 Issue VII July 2026- Available at www.ijraset.com

[10] M. Feng, S. Mao, and T. Jiang, "Base Station ON-OFF Switching in 5G Wireless Networks: Approaches and Challenges," IEEE Wireless Communications, vol. 24, no. 4, pp. 46-54, 2017.
[11] H. Elayan, O. Amin, R. M. Shubair, and M. S. Alouini, "Terahertz Communication: The Opportunities of Wireless Technology beyond 5G," International Conference on Advanced Communication Technologies and Networking (CommNet), 2018.
[12] S. Buzzi, C. L. I, T. E. Klein, H. V. Poor, C. Yang, and A. Zappone, "A Survey of Energy-Efficient Techniques for 5G Networks and Challenges Ahead," IEEE Journal on Selected Areas in Communications, vol. 34, no. 4, pp. 697-709, 2016.
[13] K. Tekbıyık, A. R. Ekti, G. K. Kurt, and A. Görçin, "Terahertz Band Communication Systems: Challenges, Novelties and Standardization Efforts," Physical Communication, vol. 35, 100700, 2019.
[14] P. Yang, Y. Xiao, M. Xiao, and S. Li, "6G Wireless Communications: Vision and Potential Techniques," IEEE Network, vol. 33, no. 4, pp. 70-75, 2019.
[15] Y. Liu et al., "Reconfigurable Intelligent Surfaces: Principles and Opportunities," IEEE Communications Surveys & Tutorials, vol. 23, no. 3, pp. 1546-1577, 2021.



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