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Original Contribution

ELECTROMAGNETIC SAFETY WITHIN THE SCOPE OF 6G COMMUNICATION NETWORKS

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ABSTRACT: *The transition toward sixth-generation (6G) communication networks mark a paradigm shift in wireless technology through the utilization of the terahertz (THz) spectrum, enabling data rates far beyond the capabilities of 5G. However, the move to ultra-high frequencies introduces new challenges for electromagnetic safety. This study examines the physical mechanisms of THz wave interaction with biological tissues, focusing on both thermal and potential non-thermal effects. Due to the shallow penetration depth of THz radiation (≈0.01–1.5 mm), energy absorption is confined to surface layers such as the epidermis and cornea, making localized heating and pain perception key safety determinants. The paper analyzes the main research gaps identified by the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2020) and discusses their implications for the development of 6G safety standards. Furthermore, it highlights the coordinated role of European and global organizations — including the European Commission, ETSI ISG THz, and the World Health Organization (WHO) — in harmonizing exposure guidelines, promoting dosimetric research, and integrating safety-by-design principles into next-generation network architectures. The findings underscore the necessity for precise near-field thermal modeling, real-time exposure monitoring, and dynamic beam management based on AI-driven network control to ensure compliance with future 6G electromagnetic safety regulations.*

KEY WORDS: *Terahertz (THz) spectrum, Electromagnetic safety, Biological tissue interaction, Safety standards, Dosimetry, 6G communication networks.*

1. Introduction

The development and deployment of sixth-generation (6G) wireless communication networks represent a significant transition toward the use of the terahertz (THz) spectrum. In the pursuit of extremely high data transmission capacity, the implementation of 6G will rely on THz frequency bands. This shift will necessitate both ultra-dense infrastructure and the use of highly directional (high-gain) antennas, which will inevitably result in increased electromagnetic field intensity within the near-field zone. It should be clearly noted that this refers exclusively to operations conducted in close proximity to network facilities and to prolonged exposure to the electromagnetic field.

In terms of electromagnetic safety, the absorption of THz waves leads to their penetration into biological tissues. Consequently, a recognized health risk exists, primarily manifested as localized thermal damage to surface tissues. Despite the known risks, there remain substantial gaps in knowledge regarding non-thermal effects. Experimental data indicate that resonant interactions with biological macromolecules may induce transient DNA damage within cells. The regulatory framework is further complicated by the fact that, with the transition to near-field operation, traditional dosimetric assessment methods applicable to far-field exposure become invalid, creating a major obstacle to the effective implementation of the standards of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1].

Therefore, regulatory efforts should focus on harmonizing near-field dosimetry models, funding targeted research on non-thermal effects (particularly under conditions of chronic low-level exposure), and coordinating international standards through organizations such as ETSI and the World Health Organization (WHO). The transition to 6G is driven by the urgent need for a massive increase in data transmission capacity, which necessitates the exploration of frequency bands traditionally used for optical and wired communications. This portion of the spectrum lies between microwave and infrared radiation (100 GHz – 10 THz) and, until recently, was not accessible for research or practical use due to the lack of efficient sources and detectors. The study of THz radiation has become feasible thanks to advances in other areas of physics — notably the development of lasers capable of generating stable light pulses of femtosecond duration, and progress in nonlinear optics — both of which can be utilized to generate THz radiation. In the field of communication engineering, frequency selection is practically determined by the transmission range, since THz radiation is characterized by significant atmospheric attenuation and free-space interference. Lower frequencies (100–150 GHz) are being investigated for long-distance communication over 1–10 km, mid-range frequencies up to 350 GHz are suitable for intermediate distances of 0.1–1 km, while the highest THz frequencies up to 500 GHz are more practical for indoor communications and short ranges of 10–100 m.

Propagation Characteristics of THz Signals

The physical limitations of THz signal propagation fundamentally dictate the architecture and exposure profile of 6G networks. Due to strong atmospheric attenuation and extreme propagation losses, antennas and equipment with very high gain are required. The development of such components remains limited. To overcome the severe losses and ensure ubiquitous coverage, the density of THz cellular networks must be significantly higher compared to 5G systems.

This massive concentration of infrastructure will have a direct impact on capital and operational costs, energy consumption, and the complexity of the supporting infrastructure. International standardization bodies such as the ETSI Industry Specification Group (ISG) THz are actively working in this field contains the definition of target scenarios and frequency bands of interest; the analysis of specific radio propagation aspects for THz communication, such as molecular absorption, effect of micro-mobility, specific considerations for scattering, reflections, and diffractions, and considerations for near-field propagation; the analysis of data from earlier measurement campaigns published in relevant literature; the performance of channel measurements for the selected scenarios and frequency bands; the development of channel models for the selected scenarios and frequency bands; the establishment of baseline for THz technology fundamentals, including antenna assumptions, simulation assumptions, and deployment strategies; the assessment of the state-of-the-art materials for THz communication e.g., electronics, photonics, plasmonics; the study of the feasibility of different channel bandwidths considering component technologies, circuits and systems; the study of the effects of RF hardware; the characterization of RF/analog impairments based on simulations measurements and obtain suitable RF impairment models in THz frequency range; the study of the low complexity large antenna array and packaging technologies; assessment of overall device complexity and cost impact; the study of the state of art for RF subsystems (transceiver, front end, antenna) in the THz frequency range; the study the energy efficiency of state-of-the-art materials and RF subsystems on transmission and/or reception.

The relationship between network density and exposure profile is complex. On one hand, the high propagation losses necessitate ultra-dense infrastructure, which increases the number of emission sources and potentially elevates the overall levels of electromagnetic fields (EMF) in the environment. On the other hand, high infrastructure density means that end-user devices transmit over much shorter distances to the nearest base station, thereby reducing the required transmission power of each individual device. This represents a complex regulatory challenge — how to balance higher environmental source density against the lower emission power of individual transmitters.

This complexity requires future regulatory focus to move beyond traditional far-field measurements from base stations and instead address the cumulative exposure profile generated by multiple short-range sources, which aligns with the data gaps identified by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1].

Furthermore, to compensate for signal loss, 6G systems employ ultra-massive multiple-input multiple-output (Ultra-Massive MIMO) antenna arrays. At THz frequencies, these antennas, while physically small, possess very high electrical power. This configuration ensures that cellular systems, WLANs, and potential base stations located in close proximity will often operate within the near-field region relative to the human body. Operation in the near-field fundamentally alters the dosimetry problem, rendering standard far-field models invalid and necessitating new protocols and limits specifically designed for localized, energy-coupled exposure [7].

Mechanisms of Interaction of THz Electromagnetic Fields

The interaction of THz radiation with biological matter differs significantly from that of lower radiofrequency (RF) bands and from high-frequency ionizing radiation. The primary physical mechanism of interaction is the strong absorption of THz fields by water molecules, which are abundant in biological tissues. This absorption is the main source of thermal effects. While at lower THz frequencies the interaction can be interpreted as a classical electromagnetic wave process (using parameters such as dielectric permittivity and conductivity), at higher frequencies molecular vibrational and rotational energy level transitions begin to play a significant role.

The rotational or vibrational energy levels of many complex biomolecules, including DNA and proteins, fall within the THz range, enabling resonant absorption. This resonant absorption forms the basis of potential non-thermal effects. The shallow penetration depth of THz radiation limits the region of biological impact to the outermost layers of the body. The penetration depth in biological tissue at 0.1 THz is on the order of 1.0 to 1.5 mm, decreasing rapidly with increasing frequency, reaching approximately 0.01 mm at higher THz frequencies. At frequencies above 100 GHz, penetration is typically below 0.4 mm. Accordingly, the primary tissues of concern are surface structures:

- Skin – The field is mainly absorbed by the epidermal layer.
- Eyes – The human cornea contains 75–80% water, making it highly absorptive. Studies have shown that the interaction of THz waves with the cornea strongly depends on its hydration level. At higher frequencies, radiation is mainly absorbed by the eyelids (epidermis) before reaching the cornea.

It is important to note that when calculating penetration depth and energy absorption, the bound water in biological tissues has a lower absorption coefficient at THz frequencies compared to free water in nature.

Table 1 summarizes the penetration depth of THz radiation and its principal modes of interaction with biological tissues.

Table 1

Frequency Range (GHz / THz)	Approximate Penetration Depth (mm)	Primary Affected Tissue Layer
~100 GHz (0.1 THz)	1.0 – 1.5 mm	Dermis / Subcutaneous (Superficial)
> 100 GHz (> 0.1 THz)	< 0.4 mm	Epidermis / Eyelids
High THz (> 0.5 THz)	≈ 0.01 mm	Stratum Corneum (Extremely superficial)

While the radiation is predominantly absorbed at the surface, experimental modeling suggests that localized temperature increases may cause irreversible thermal damage. This effect can be quantified using the **Arrhenius equation**, which expresses the dependence of the reaction rate constant on absolute temperature, the frequency factor, and other reaction-specific constants.

$$k = Ae^{\frac{-Ea}{RT}} \tag{1}$$

where:

k – the rate constant;

T – the absolute temperature;

A – the pre-exponential factor or Arrhenius factor or frequency factor. Arrhenius originally considered A to be a temperature-independent constant for each chemical reaction;

Ea – activation energy of the reaction;

R – universal gas constant.

To accurately simulate this phenomenon, specialized models using specific phantom materials (e.g., glycerin-based) are required to replicate the dielectric properties and precisely assess the temperature rise in ocular tissues within the 0.1–0.6 THz range. The urgency of this issue is underscored by the fact that the ICNIRP has explicitly identified data gaps concerning ocular exposure. This calls for immediate investment in specialized biophysical and numerical dosimetric models to ensure that safety limits adequately protect the eye, particularly under pulsed, high-intensity near-field conditions [6].

Thermal interaction remains the cornerstone of existing safety guidelines, which are based on the principle of limiting temperature rise. The established mechanism involves the conversion of absorbed electromagnetic energy into heat, resulting in localized heating. Localized thermal risks are significant, as the strong surface absorption of THz radiation can concentrate energy within a confined region. Studies have shown that irradiation from multiple sources—even when each remains within ICNIRP-defined exposure limits—or exposure of tissues already under thermal stress can elevate skin temperature beyond the damage threshold of 45°C. The degree of tissue damage is a function of both temperature and exposure duration. To prevent collagen denaturation, the heating duration must be restricted, for example, $t < 720\ s$ at a power density of $Pd = 0.6\ W/cm^2$.

A major unexplored area in electromagnetic safety at THz frequencies concerns the existence and biological relevance of non-thermal effects, which arise primarily from resonance phenomena. The non-thermal mechanism is thought to result from nonlinear resonant coupling of THz radiation with biological macromolecules in neurons. This resonant interaction may induce new conformational states in biomolecules or destabilize the double-stranded DNA structure.

Experimental studies have reported a range of potential non-thermal phenomena, including acute inflammatory skin responses, conformational alterations in proteins, disruption or leakage of plasma membranes, and changes in neural function such as modified membrane permeability in nerve cells and structural changes in axons. These interactions may also affect the stability of secondary protein structures involved in neurological processes. Although reports on THz radiation as a biological modulator remain inconsistent, some findings indicate that it may trigger distinct transcriptomic profiles unrelated to microthermal responses—suggesting a genuinely non-thermal pathway.

Specific experimental results using intense pulsed THz radiation have demonstrated direct, albeit transient, cellular responses. Exposure to intense THz pulses (in the picosecond range) for short durations (e.g., ten minutes) has been shown to induce significant phosphorylation of H2AX in artificial human skin models, indicative of double-strand breaks (DSBs) in DNA. Importantly, this effect is accompanied by activation of DNA damage repair mechanisms, strongly suggesting that the damage is efficiently reparable and that the cellular response to THz pulses differs substantially from that induced by UV radiation.

The most concerning biological data are associated with intense pulsed THz radiation capable of inducing DNA damage. Since 6G communication systems employ highly directional Massive MIMO beamforming, user exposure will not consist of continuous-wave (CW) uniform radiation, but rather highly localized, directional, and pulsed energy, depending on dynamic traffic management. If safety standards are modeled solely on averaged CW exposure, they may overlook peak intensities and specific molecular resonance effects triggered by pulsed, nonlinear energy deposition [5].

This discrepancy underscores the urgent need for further research into the effects of modulated, high-peak-power pulsed THz radiation, which more accurately reflects future 6G traffic characteristics. Additionally, the transient nature of DNA damage necessitates long-term studies to assess cumulative biological effects under conditions of chronic low-level exposure and stress.

Challenges in Establishing Safety Standards for 6G Technology

The existing international safety standards established by the ICNIRP and adopted by the European Union are based on preventing adverse effects confirmed by reliable scientific evidence.

For the general public, the exposure limit is set at levels many times lower than those that international scientific data suggest could have any effect on health. Regulations define reference levels for power density (for frequencies above 30 MHz) and specific absorption rate (SAR). For whole-body exposure in mobile communication frequency ranges, the limit corresponds to 10 W/m^2.

The European Commission notes that 5G (and future 6G) networks, which use much smaller antennas, generally result in lower exposure levels compared to 2G, 3G, and 4G networks. However, the combination of high frequencies and high-gain antennas introduces fundamental difficulties in both measurement and enforcement of safety limits. Due to the high antenna power relative to the wavelength (λ), 6G networks frequently operate under near-field conditions, where far-field models and standard power density calculations are no longer valid.

Consequently, dosimetry must shift its focus toward measuring specific energy absorption (SAR) or temperature rise in extremely shallow tissue layers. Although beamforming techniques can optimize signal strength and manage exposure, and preliminary assessments indicate that even the highest extrapolated exposure levels represent only a small fraction of the ICNIRP reference level (e.g., 0.5–0.6% at 3.6 GHz), these estimates apply to 5G systems.

The new challenges posed by THz radiation require adapting beam management and exposure control solutions. The ICNIRP has explicitly identified key data gaps concerning high-frequency and multi-source exposure, which must be addressed in future safety guidelines for 6G.

The main data gaps identified by ICNIRP in relation to 6G (THz) exposure are summarized in table 2.

Table 2

Identified research gap in ICNIRP studies (after the 2020 guidelines)	**Specific relevance for 6G (THz) exposure**
Issues concerning the relationship between RF-EMF exposure and heat-induced pain	Critical, as the shallow absorption of THz waves concentrates energy in surface nerves, potentially reaching localized pain thresholds before deep tissue damage thresholds are exceeded.
Clarification of how RF exposure affects the eye (ocular irradiation)	Extremely important; the cornea is a primary site of absorption, requiring precise thermal modeling and localized dosimetry, especially under short, high-intensity exposures
How and when body temperature increases during exposure to multiple EMF sources	Essential given the massive network density required for 6G, which results in simultaneous exposure to multiple 6G and legacy sources
Additional dosimetric studies to improve the application of exposure limits	Directly related to the need for THz near-field dosimetric protocols for consumer devices and high-gain base stations

5. Conclusion

Since the penetration depth of THz radiation is negligible (≈0.01–1.5 mm)[4], the biological target of protection shifts from whole-body averaged SAR to highly localized metrics such as skin temperature rise (ΔT) and the thermal dose delivered to surface layers (epidermis, cornea). ICNIRP explicitly mentions heat-induced pain, implying that the perception of pain may become the primary regulatory limit long before deeper tissue damage occurs. Therefore, compliance with future 6G safety standards must include precise thermal modeling of thin surface layers under realistic, non-homogeneous near-field exposure conditions [8].

Acknowledgments

The European Union is actively preparing for 6G with the goal of ensuring technological sovereignty and deployment aligned with social values. The introduction of 6G is expected around 2030, with standardization efforts beginning now, in 2025. The European Commission supports the development of 6G through the Smart Networks and Services Joint Undertaking (SNS JU). The SNS JU Work Programme emphasizes security, sustainability, and social impact, indicating a clear intent to integrate European values — including safety — into the design and operation of 6G networks [3].

From a technical standpoint, the ETSI ISG THz group coordinates pre-standardization research, focusing on defining THz use cases (e.g., holographic telepresence, extended reality) and analyzing propagation aspects such as molecular absorption and the need for near-field channel measurements. Global organizations are working to harmonize safety regulations and manage public risk perception. The World Health Organization (WHO), through its International EMF Project, is investigating health effects from exposure in the 0–300 GHz range, which explicitly includes the THz spectrum of 6G. WHO encourages further research into potential long-term health effects and promotes dialogue between scientists and the public [2].

Maintaining an international dialogue among regulators, scientists, and industry on EMF science development, WHO assessments, and risk communication strategies related to next-generation technologies is crucial, as public concerns about 5G and upcoming 6G exposure remain widespread — some of which are categorized as misinformation.

The EU's strategic focus on 6G applications such as medicine, autonomous systems, and AI demonstrates that 6G safety is becoming an integral component of overall system reliability. Since 6G networks will be AI-native and will incorporate integrated sensing capabilities, there is potential to leverage these technologies for real-time dynamic beam power management. This would enable continuous optimization of transmission power and precoding weights (resource allocation, RA) to ensure that exposure remains below localized safety

thresholds. Thus, regulation shifts from static control of base station output to dynamic safety management embedded within the network architecture itself.

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