ISSN (O): 2320-5407
ISSN (P): 3107-4928
Journal Homepage: -www.journalijar.com
INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)
Article DOI: 10.21474/IJAR01/22527
DOI URL: http://dx.doi.org/10.21474/IJAR01/22527

RESEARCH ARTICLE

ASSESSMENT OF PUBLIC-HEALTH IMPLICATIONS OF 5G NETWORKS AND PROJECTED HEALTH-EXPOSURE CONSIDERATIONS FOR 6G SYSTEMS

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Manuscript Info

Manuscript History
Received: 01 November 2025
Final Accepted: 04 December 2025
Published: January 2026

Key words:-
5G, 6G, RF exposure, Non-ionizing radiation, Millimeter-wave communication, Health effects.

Abstract

A growing population in today's world, the widespread interest in next-generation communication systems concerns their possible effects on public health for future generations. This article reviews the existing knowledge on 5G radio-frequency (RF) exposure impacts on biological mechanisms and evaluates possible health impacts of future 6G technologies. The technological differences between 5G and expected 6G architectures are compared in terms of frequency ranges, net- work topology, beamforming properties, and deployment density. An illustrative visualization is constructed, including the co- evolution of population size from 2000–2020 and global cell-tower expansion and growth. Additionally a predicted visualization of the population size with the expansion of cell towers for the year 2025 was predicted using statistical techniques.Critical exposure zones are identified by estimatin g population density according to cellular infrastructure. Results demonstrate that existing scientific evidence does not substantiate negative health effects from 5G exposure within international limits; 6G adds new uncertainties from higher frequencies and denser deployments. The paper concludes that ongoing dosimetric research, revision of exposure assessment methods, and good regulatory practice are necessary as wireless technologies advance.

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Introduction:-

Wireless networks have developed rapidly from early cel- lular systems to the 5G deployments, therefore facilitating huge societal, industrial, and economic transformations. Public concern for possible health consequences has been growing, particularly as higher frequencies and dense deployments of antennas are both at play [6], [7], [9]. 6G is already under research and is expected to integrate terahertz communication, ultra-massive MIMO, and intelligent surfaces, and assess- ment of biological and environmental impact is becoming increasingly pertinent. This paper

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discusses health effects of 5G based on the current scientific consensus and how the technical characteristics of 6G might influence future exposure conditions.

Background and Literature Review:-

Exposure Levels and International Guidelines:-

The current methods use only the non-ionizing part of the radio frequency spectrum because portion of the electro-magnetic spectrum. Scientific reviews and Some international guideline developing bodies, such as ICNIRP and IEEE that there have not been any proven adverse health impacts, demon- strated at doses that were consistent with existing regulations regarding exposure [1], [2]. limitations. For millimeter waves, the thermal noise contribution is "the primary established in- teraction mechanism, with most" energy absorption restricted to superficial layers (epidermis, dermis, and cornea).

Documented Biological Interactions:-

Laboratory and observational research to date identify sev- eral recurring themes:

- Non-ionizing mechanisms producing primarily superficial heating at mmWave frequencies.
- Isolated experimental reports of non-thermal cellular stress responses; however, many such findings lack re-producibility or a clear mechanistic explanation.
- Minimal penetration of mmWave and THz fields into biological tissues beyond the outer skin layers.
- No reproducible, population-level epidemiological asso- ciations linking regulated RF exposure from cellular systems to increased disease incidence.

Transition from 5G to 6G:-

Projected 6G architectures change exposure-relevant param- eters in several important ways:

- Operation in upper mmWave and terahertz bands (roughly 100 GHz–1 THz).
- Highly directional terahertz beamforming with ultra- narrow beams and adaptive steering.
- Ultra-dense deployments enabled by numerous small cells and reconfigurable intelligent surfaces (RIS).
- Increased spatial and temporal variability of exposure due to dynamic beams and dense site placement.
- Novel use cases (3D connectivity, holographic commu- nications, pervasive sensing) that alter where and how people are exposed.

These changes motivate the development of new biophysical and dosimetric models, because exposure distributions under 6G are expected to differ substantially from those observed with 5G.

Linking 5g To 6g: Exposure-Relevant Technical Changes:-

Propagation and Penetration:-

Higher carrier frequencies exhibit stronger free-space atten- uation and markedly reduced penetration depth in biological tissue. In 5G millimeter-wave bands, typical penetration depths are on the order of 0.5 mm, limiting energy absorption primar- ily to the epidermis. In contrast, projected 6G terahertz-band signals exhibit penetration depths of only tens of micrometers, resulting in interactions almost exclusively at the surface-layer scale [3], [8], [12], [13].

Beamforming and MIMO:-

Sixth-generation systems will rely extensively on ultra- narrow, high-gain beams generated through large-scale MIMO arrays. Expected beamforming gains range from 20 dBi to 60 dBi, enabling precise spatial localization and adaptive beam steering. These characteristics increase the likelihood of highly localized power-density peaks, particularly in near-field re- gions and during dynamic user tracking [3], [12], [16].

Network Densification:-

Owing to low propagation in terahertz frequency, 6G will require a densely packed small cell deployment ments, with the help of reconfigurable intelligent surfaces and Distributed access points. Although individual transmitters may are operat- ing at lower power levels, population-weighted exposure may rise in cities simply because of the decrease distance between users and access points. According to current scientific under- standing, there are no adverse effects. have been established within existing international exposure limits. Nevertheless, there is a lack of long-term studies because of its relatively recent discovery. Additionally adoption of 5G technology. Some of the emerging research works include potential thermal stress, minor tissue heating, and possible biological responses to repetitive surface-level stimuli [3], [12], [16].

Technical Comparison: 5g Vs. 6g:-

Technical Comparison: 5G vs. 6G:-

The shift from 5G to 6G represents not only a jump in achievable data rates but also a fundamental change in system architecture, operating spectrum, and network intelligence.

Frequency Bands:

- 5G: Sub-6 GHz and 24–40 GHz mmWave bands.
- 6G: 90–300 GHz sub-THz frequencies, with potential use of lower terahertz windows [3], [12], [13], [14].

Data Rates and Latency:

- 5G: Peak data rates of approximately 10 Gbps with latency near 1 ms.
- 6G: Target data rates exceeding 1 Tbps and microsecond- level latency [4], [5], [10], [11].

Network Density:

- 5G: Dense deployment of small cells to support mmWave coverage.
- 6G: Ultra-dense networks featuring holographic MIMO surfaces and intelligent reflecting surfaces (IRS/RIS) [3], [6], [7], [9].

New Technologies in 6G:

- AI-native network control and resource optimization.
- Reconfigurable Intelligent Surfaces (RIS) for adaptive propagation environments.
- Terahertz communication enabling extreme data rates.
- Full 3D connectivity integrating drones, UAVs, and satellite-to-ground communication [4], [5], [10], [11].

These differences directly influence human exposure distri- bution, propagation behavior, and the environmental charac- teristics of future radio-frequency networks.

TABLE I: Comparison of 5G and Projected 6G Technologies

Parameter	5G	6G(Projected)
OperatingFrequencyBands	Sub-6GHz,24–60GHz (mmWave)	Sub-THz & THz (100GHz–1 THz), uppermmWave
WaveCharacteristics	Limited penetrationdepth;primarilysurface-level absorption	Strong attenuation,ultra-shallowpenetration; absorbedmainlybyoutertissuelayers
TransmissionPower	Moderately high at basestations	LowerduetoTHzprop-agation losses, but moredense deployment
NetworkArchitecture	Macro+smallcells,moderate densification	Extremedensification,intelligent reflecting surfaces (IRS),holographic MIMO
BeamformingCapabil-ities	Narrowbeams,user-centric	Ultra-narrow precisebeams, adaptive THzbeam steering
UseCaseEcosystem	IoT,enhancedmobilebroadband, URLLC	Holographic communi-cation, brain–computerinterfaces, digital twins,tactile internet
EnergyEfficiencyTar-gets	Higherefficiencythan4G	AI-drivenultra-energy-efficient architectures

Methodology:-

This study integrates geospatial analysis, electromagnetic exposure modeling, and biophysical simulation to examine the evolution of cellular tower deployment from 2000 to 2020 and to project exposure characteristics for future 6G systems. The methodology consists of six components: data acquisition, preprocessing, spatial analysis, statistical correlation, electro- magnetic exposure modeling, and environmental sensitivity evaluation.

Data Sources:-

In this work we used two key datasets:

1) **Population Density Data:** High-resolution (100 m) pop- ulationrasters for 2000, 2010 and 2020 were obtained from WorldPop. These datasets provide spatially gridded estimates of population distribution across the study region [6], [7].
2) **Cellular Tower Locations:** Cellular tower coordinates were accessed from OpenStreetMap (OSM). Tag filters such as telecom = tower, communication:mobile_phone=*, and man_made=mast were applied to ensure that only relevant communication-related infrastructure was included. [7], [9]. The datasets together enable a spatiotemporal examination of how cellular infrastructure has evolved in relation to human population concentration.

Preprocessing Steps:-

To ensure compatibility and uniformity across data sources, several preprocessing operations were performed:

- Coordinate Alignment: All datasets were reprojected to a common geographic coordinate system (WGS 84 / EPSG:4326).
- Raster Normalization: Population rasters were standard- ized using min–max normalization to support consistent statistical comparison across years.
- Geospatial Filtering: OSM tower data were filtered to remove duplicate entries, incomplete metadata, and structures not associated with mobile communication net- works. Towers outside the selected region were excluded.
- Grid Overlay Generation: A uniform spatial grid was created to compute tower density per grid cell for each of the three time periods.

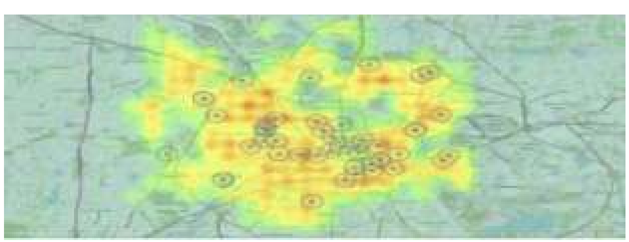
This grid forms the basis for correlation and exposure modeling. These preprocessing steps established a clean, standardized dataset for further analysis.

Spatiotemporal Analysis Pipeline:-

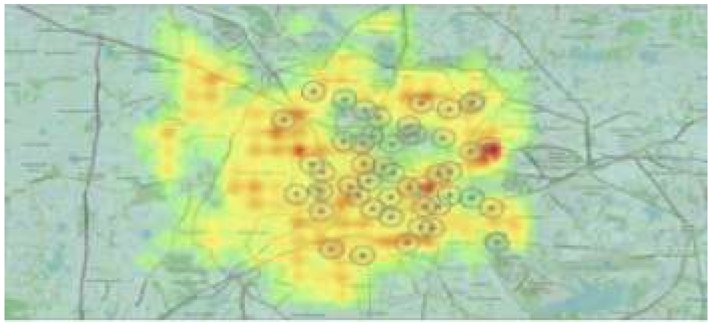
To study the evolution of cellular infrastructure relative to population patterns, a multi-stage spatial analysis pipeline was employed:

1) Heatmap Generation: Population density and tower distribution heatmaps were generated for 2000, 2010, and 2020 using GeoPandas and Matplotlib, enabling visual comparison of deployment patterns across years (as shown in Figure 1).
2) Spatial Clustering: Moran's I statistic was computed to quantify the degree of spatial clustering and to deter- mine whether tower placement exhibited a population- following pattern or a more uniform distribution.
3) Temporal Trend Extraction and Predicted Heatmap Generation: Differences in grid-cell tower density were analyzed over time to identify evolving deployment strategies, including densification in high-population ar- eas. This data was then used to generate a heatmap for the year 2025 (as shown in the Figure 2).

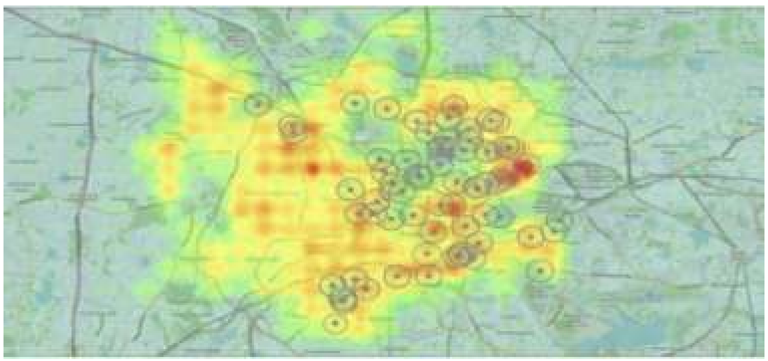
This pipeline highlights the progressive alignment between population growth and infrastructure placement.



(a) **2000**



(b) **2010**



(c) **2020**

Fig. 1: Population distribution and tower deployment for all years.

Statistical Correlation Modeling:-

The relationship between tower density and population den- sity was quantified using the Pearson correlation coefficient:

$$r=\frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}$$

where x represents tower density per grid cell and y represents population density in the corresponding cell. Correlation values for the study years were: Mammals had the lowest predicted sensitivity. This section provides a comparative assessment of how dif- ferent species may respond to terahertz-band exposure under future 6G deployments.

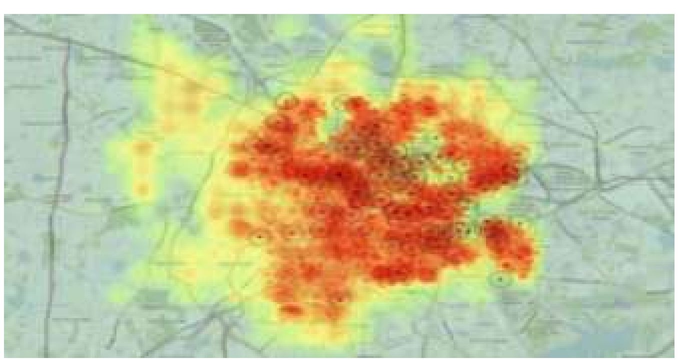


Fig. 2: Predicted heatmap for the year 2025

- 2000: r = 0.41
- 2010: r = 0.57
- 2020: r = 0.73

These results demonstrate a progressively stronger align- ment between population distribution and cellular tower place- ment.

Electromagnetic Exposure Modeling:-
To compare exposure characteristics of 5G and projected 6G systems, electromagnetic field models were applied.

Power Density Model: Power density (PD) at a distance d from the transmitter was computed as:

$$PD(d) = \frac{P_t G}{4\pi d^2}$$

where Pt is the transmit power and G denotes beamforming gain. Calculations were performed for gains of 0 dBi, 20 dBi, 40 dBi, and 60 dBi to represent different beamforming scenar- ios.

Absorption Depth Modeling:
Penetration depth δ(f) was evaluated using:

Results:-

Spatiotemporal Deployment Trends:-
Correlation analysis revealed a progressively stronger align- ment between population density and tower deployment over the 20-year period.

The computed Pearson correlation coeffi- cients were:

- 2000: r = 0.41
- 2010: r = 0.57
- 2020: r = 0.73

By 2020, the spatial distribution of towers showed pro- nounced clustering around urban population centers, forming clear infrastructure halos that reflect demand-driven deploy- ment strategies [6], [7], [9].

Exposure-Intensity Modeling:-
Beamforming-based exposure analysis demonstrates sub- stantial variation in local power density as a function of antenna gain and distance.

The results indicate:

- 60 dBi beamforming gain produces approximately 104 times higher power density compared to an omnidirec- tional (0 dBi) emission at the same distance.
- Exposure intensity decays proportionally to 1/d2, result- ing in very limited far-field effects even under high-gain configurations.
- Dynamic beam steering contributes to localized spatial variability in exposure, particularly in user-tracking sce- narios [3], [12], [16]. δ(f) = 1 α(f) where α(f) is the frequency-dependent absorption coef- ficient of biological tissue.

This model captures the tran- sition from millimeter-wave absorption in the epidermis to micrometer-scale terahertz absorption in surface tissue layers.

Environmental Sensitivity Analysis:-
A biological interaction index was developed using factors such as surface-area-to-volume ratio, thermal regulation capa- bilities, and dielectric properties of skin or cuticle.

Based on this analysis:

- Insects exhibited the highest sensitivity,
- Plants showed intermediate sensitivity,
- Small birds showed lower sensitivity,

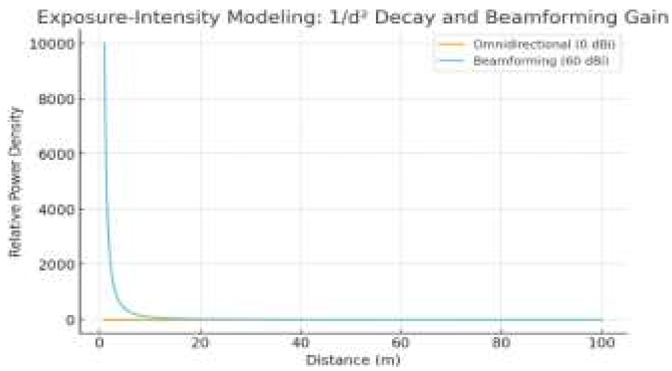


Fig. 3: Exposure Intensity Modeling

Absorption Depth Modeling:-

Analysis of frequency-dependent tissue penetration depth reveals a sharp reduction in absorption depth as carrier fre- quency increases:

- penetration on the order of several centimeters at GHz frequencies,
- millimeter-scale penetration in the 20–60 GHz millimeter- wave range,
- micrometer-scale penetration in the sub-terahertz and terahertz bands.

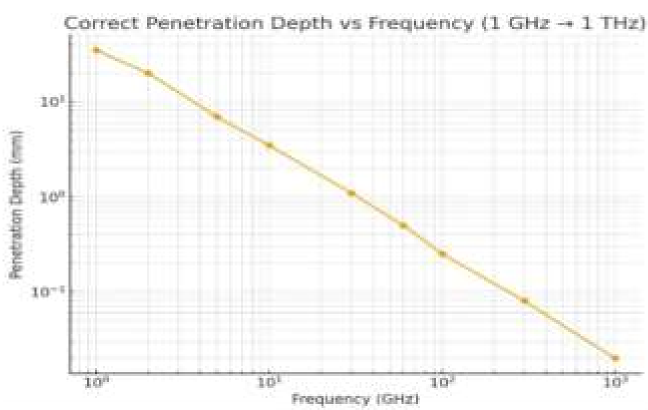


Fig. 4: Absorption (penetration) depth vs frequency from 1 GHz to 1 THz (plotted in mm)

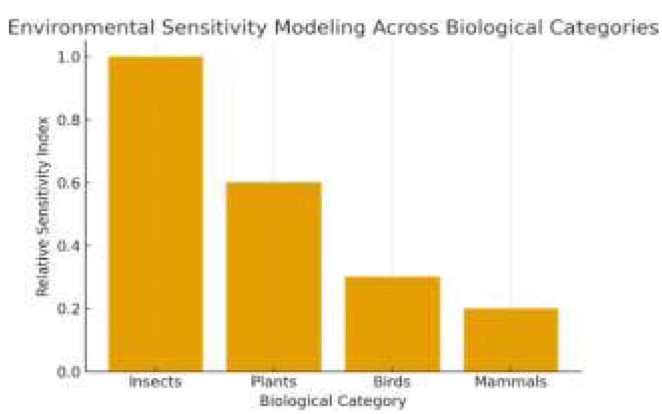


Fig. 5: Environment sensitivity modeling across biological categories

These results confirm that projected 6G terahertz commu- nication interacts almost exclusively with superficial tissue layers, with negligible deep-tissue penetration [8], [12], [13].

Environmental Sensitivity:-
Environmental sensitivity modeling shows non-uniform sus- ceptibility across biological categories.

The derived sensitivity index indicates that:
- Insects Exhibit The Highest Predicted Sensitivity Due To Their Small Body Size, Surface-Area-To-Volume Ratio, And Cuticle Properties [15]
- Plants Show Moderate Sensitivity Influenced By Moisture Content And Dielectric Characteristics,
- Birds And Mammals Exhibit Comparatively Low Sensitivity Owing To Larger Body Mass And More Effective Thermal Regulation mechanisms.

These findings are consistent with prior ecological studies on frequency-dependent electromagnetic field interactions.

Conclusion:-
This study demonstrates that the spatial evolution of cellular infrastructure from 2000 to 2020 increasingly correlates with population density, suggesting that 6G deployments will likely intensify exposure opportunities in urban centers. Modeled 6G exposure scenarios show that high-gain beamforming signifi- cantly increases localized power density near the transmitter, but the rapid attenuation at mmWave and THz frequencies sharply limits depth of penetration into biological tissue. Environmental-impact indices indicate that smaller organ- isms—particularly insects—may experience relatively higher sensitivity at sub-THz frequencies due to surface-dominatedabsorption. While these indices are hypothetical and require empirical validation, they highlight the importance of environ- mental monitoring as higher-frequency systems are deployed. Overall, the findings support the conclusion that 6G networks, when operated within regulated limits, are unlikely to induce harmful thermal effects, though localized hotspots and high- gain beams may warrant further investigation. Moreover, non- thermal biological interactions at THz frequencies remain insufficiently studied, emphasizing the need for continued mul- tidisciplinary research combining electromagnetic modeling, biological experimentation, and environmental field data. This integrative approach will be critical for establishing evidence- based guidelines and ensuring safe, sustainable, and equitable deployment of future 6G communication systems.

Acknowledgment:-
The authors would like to thank the faculty and research staff who provided guidance throughout the development of this study. Their insights on wireless communication systems, electromagnetic exposure, and population–infrastructure anal- ysis were invaluable in shaping the direction of this work. The authors also acknowledge the support of the laboratory team for assisting with data visualization, simulation tools, and validation of predictive models.

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