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Signal Analysis Techniques to Minimize Electromagnetic Radiation in 5G Mobile Networks

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Abstract

The rapid rollout of fifth-generation (5G) mobile networks has raised concerns about potential health and environmental effects from prolonged exposure to electromagnetic radiation (EMR) emitted by mobile devices and cell towers. Addressing these concerns requires exploring ways to reduce EMR levels without compromising network performance.

This study examines whether signal processing techniques-specifically beamforming and dynamic power control-can significantly reduce power density and Specific Absorption Rate (SAR) from 5G-enabled mobile devices and base stations.

Simulations were conducted using Python 3.12, MATLAB, OpenEMS, and GNU Octave to model EMR emissions from a Samsung Galaxy S23 Ultra and a Huawei 5G Active Antenna Unit. Power density and SAR were calculated using established electromagnetic models across varying distances and transmission power levels. Beamforming and power control strategies were applied to assess their effectiveness in minimizing radiation exposure.

The simulations showed that EMR emissions from both mobile devices and base stations can be reduced by up to 80% without compromising signal quality. Significant reductions in power density and SAR were observed when beamforming was applied at the tower and dynamic power control was used on the mobile device.

This study demonstrates that adaptive signal processing techniques can meaningfully reduce 5G-related EMR exposure. The findings support the development of safer, more sustainable 5G infrastructure and are consistent with current WHO and IEEE safety guidelines. Future research should incorporate environmental complexity and long-term exposure effects to further validate these results.

Categories: Microwave and RF Engineering, Telecommunication Networks, Wireless Communication Systems
Keywords: electromagnetic radiation, power density, antenna, beamforming, specific absorption rate

Introduction

The world's telecommunications and network infrastructure has advanced due to the introduction of a fifth-generation (5G) mobile network. However, due to the widespread use of the 5G network, there is a growing concern about health risks associated with long-term exposure to electromagnetic radiation emitted by the 5G network infrastructure. For this study, electromagnetic radiation emitted by common devices such as mobile phones and cell towers will be studied. This is because the use cases for the mentioned devices have become abundant and it is particularly vital to understand and know the implications of long-term exposure to electromagnetic radiation on human health. This is because several studies suggest that prolonged radiation exposure gives rise to various health issues such as cancer. Therefore, the following work aims to determine the electromagnetic radiation emitted by mobile phones, and cell towers and identify tools and techniques on how to reduce electromagnetic radiation exposure while maintaining the optimal functionality of the telecommunications infrastructure.

In addition, Kour et al. also investigated techniques for reducing electromagnetic radiation emitted by the 5G infrastructure. As per the study, some of the techniques that reduced electromagnetic radiation while still maintaining the optimal performance of the network included beamforming technology, dynamic power management, and deployment of small cells. A simulation-based study was carried out to identify techniques for how to reduce electromagnetic radiation emissions from 5G networks. The study concluded that for mobile devices, reducing the transmission power when the device is close to a cell tower reduced the radiation emissions without having any impact on the user experience. Utilization of a scheduling algorithm was also recommended, that turns off transmission when a device is either idle or not in use [1].

Various simulations were carried out in order to achieve the above-mentioned goals, which will include simulating radiation emission by calculating power outputs and modeling electromagnetic radiation emission by telecommunication devices. The simulation will be conducted using the following software: Python 3.12 and MATLAB for scripting, OpenEMS for executing the script and GNU Octave for data visualization and graphing. Analysis from simulations will be achieved through the use case of mathematical models such as power density, specific absorption rate, and many more. The electromagnetic radiation emission data will be computed by altering the transmission strength and related variables which will provide a detailed analysis of the different approaches that will be investigated to recommend low-communication exposure protocols [2,3].

The world's network and telecommunications infrastructure has significantly advanced over the years, especially recently due to the widespread adoption of 5G technology. This has also raised potential health concerns due to the prolonged exposure to electromagnetic radiation that is emitted by telecommunication devices such as mobile phones and cell towers. Despite the benefits provided by the adoption of 5G technologies such as faster connectivity and more economical opportunities, the potential health risks associated with being close to these devices, the emission of radiation on human health as well as on the environment needs to be thoroughly studied [4].

Furthermore, the study will also take a deep dive and look at the environmental and social impacts of exposure to electromagnetic radiation. Due to the rapid advancement of the telecommunication industry, it is becoming increasingly vital that long-term sustainable methods should be implemented to reduce any form of harm that may result to either people or even the environment. Ethical considerations will also be studied to maintain transparency regarding health risks and make informed decisions. This will help to provide clear information to the people involved, understanding the advantages and disadvantages of 5G networks and the impacts of prolonged electromagnetic radiation exposure on health as well as the environment [5,6].

Therefore, the study will look at different research articles to identify techniques on how to reduce electromagnetic radiation exposure, the environmental, social, and ethical implications, shortcomings, and prospects in regard to 5G networks while also prioritizing well-being of the environment and health of people [7].

According to a research article published by the World Health Organization (WHO) on 27th February 2020, it was outlined that to increase performance, 5G will utilize higher frequencies around 3.5 GHz and above. The utilization of higher frequencies is new to mobile technology but has been previously utilized in body scanners for security checks and point-to-point communication in radio links. The study also stated that the electromagnetic radiation exposure emitted by the 5G equipment remains similar to the electromagnetic radiation emitted by the previous generation of mobile networks. 5G will utilize beamforming technology to focus and concentrate signals instead of emitting them in all directions. The WHO also concluded that the present emission of electromagnetic radiation by the 5G technology is not likely to cause any significant health effects; however, it is also recommended that long-term studies be carried out as well as to comply with safety regulations [8].

This study [9] proposes a thermal radiation mechanism aimed at mitigating electromagnetic emissions in 5G networks, with simulation results indicating reduced power density and specific absorption rate (SAR).

This paper presents a quantum-based algorithm for dynamic metasurface antenna control, demonstrating enhanced signal-to-interference-plus-noise ratio in 5G systems, as verified by field testing [10].

This study evaluates the penetration depth of 5G millimeter-wave radiation across multiple human tissue types, concluding that penetration is superficial and remains within established safety thresholds [11].

This comprehensive review concludes that there is no conclusive evidence indicating that low-intensity radiofrequency fields above 6 GHz, as deployed in 5G systems, pose a health hazard [12].

This case series documents symptom patterns consistent with microwave syndrome in individuals residing near 5G base stations, indicating the need for further investigation into potential health implications [13].

This report [14] synthesizes data from 61 exposure assessments, indicating that 5G-related electromagnetic field levels are generally below 1% of ICNIRP reference levels, with no anticipated health risks under compliant conditions.

A WHO-commissioned meta-review of 63 epidemiological studies concludes that mobile phone usage is not associated with an increased risk of brain neoplasms, reinforcing the safety profile of wireless communication technologies [15].

Materials And Methods

The system design and analysis are greatly dependent on comparing different electromagnetic radiation reduction techniques, to analyze the results and recommend the optimal solutions. The primary programming language used for developing the scripts for simulations is Python 3.12 and MATLAB. Another software tool that will be utilized heavily for executing the scripts will be OpenEMS, open-source software that helps with simulating electromagnetic radiation emission using the Finite Difference Time Domain model.

The results of the simulation data will then be visualized using GNU Octave 9.2.0. The GNU Octave software provides a compelling computational and visualization environment through the capabilities of executing scripts, plotting charts, and graphing capabilities. Several established mathematical models are scripted and the execution process will is automated by using Python 3.12, which includes power density, specific absorption rate, and beamforming techniques as well as the instructions to generate graphs and save the generated graphs as an image on the local drive. The SAR formula is also scripted to showcase the exposure of electromagnetic radiation from telecommunication devices on human health.

The use of Python, MATLAB, OpenEMS, and GNU Octave make the simulation process easier for automation and analysis by allowing the simulation of real-world scenarios and how this electromagnetic radiation can be reduced by varying and changing the variables involved, such as power density, transmission strength, and beamforming techniques.

This study aims to investigate the initial radiation emission levels of the devices and then apply techniques to reduce the emission of electromagnetic radiation. The two devices that were used to carry out the analysis include a mobile device (Samsung Galaxy S23 Ultra) and a cell tower (Huawei 5G Active Antenna Unit). The radiation emission patterns were mathematically modeled to estimate the power density and dynamic radiation emission at varying distances. OpenEMS tools were used to analyze real-world data. The obtained results were graphically generated and displayed in GNU Octave for further analysis. The techniques that are adopted to reduce the emission of radiation include dynamic power control for cell towers and beamforming for both cell towers and mobile devices.

System model

The relationship between the signal power density and transmitted power can be represented as a function of the distance from the source:

$$
S = \frac{P_t}{4 \pi d^2}
$$

where:

S: Power density [w/m^2]

P_t: Transmitted power [w]

d: Distance from source [m]

On the other hand, the relationship between the specific absorption rate is proportional to the magnitude of the electric field:

$$
SAR = \frac{\sigma E^2}{\rho}
$$

where:

SAR: Specific Absorption Rate

σ: Conductivity of human tissue [s/m]

E: Electric field strength [v/m]

Ρ: Density of human tissue [kg/m^3]

System Parameters

The parameters used for both the mobile device and cell tower are listed below:

1. Mobile Device

a. Frequency will be set to 28 GHz.

b. Initial power output will be 0.5 W.

c. Distance to be considered will range from 1 m to 10 m.

2. Cell Tower

a. Frequency will be set to 3.5 GHz.

b. Initial power output will be 50 W.

c. Distance to be considered will range from 10 m to 100 m.

System Radiation

The following radiation reduction techniques were applied to the devices as outlined below:

1. Beamforming - The primary application of the following technique is at the base cell tower rather than the mobile device, directing the signal toward specific devices rather than transmitting it in all directions. During the simulation execution, the power output of the cell tower was reduced from 50 W to 10 W.

2. Dynamic Power Control - This technique allows mobile devices to dynamically adjust the transmission power based on different distances. During the execution of the simulation, the power output from the mobile device was reduced from 0.5 W to 0.1 W, showcasing a significant decrease in power output when users were within close proximity.

Results

The simulation generated radiation emission data for both a mobile device and a cell tower, evaluated before and after the application of radiation-mitigation techniques. Graphs produced using GNU Octave illustrate variations in power density and SAR as functions of distance, across different transmission power levels.

This revision clearly articulates the trends, compares the changes quantitatively, and highlights the percentage reductions observed in the data.

Mobile device results

Power Density (Figure *1*): At a transmission power of 0.5 W, the mobile device exhibits a power density of 0.0398 W/m² at a distance of 1 m, which declines sharply to 0.0016 W/m² at 5 m. Following a reduction in transmission power to 0.1 W, power density values decrease significantly to 0.008 W/m² at 1 m and 0.0003 W/m² at 5 m. These results demonstrate an approximate 80% reduction in power density at close range, underscoring the effectiveness of power reduction in limiting radiation exposure.

Specific Absorption Rate (Figure *2*): With the device operating at 0.5 W, SAR is measured at 1.71×10^{-12} W/kg at 1 m, decreasing to 6.82×10^{-14} W/kg at 5 m. After reducing the power output to 0.1 W, SAR values further decline to 3.41×10^{-13} W/kg at 1 m and 1.36×10^{-14} W/kg at 5 m. These findings confirm that SAR is highly sensitive to both transmission power and distance, with reductions of approximately 80% following the implementation of power-limiting techniques. The observed exponential decay further validates the relationship between SAR, power output, and proximity.

Mobile device - simulation results

- Power Density (Before and After Adjustment)

At 0.5 W and 1 m: 0.0398 W/m²

At 5 m: 0.0016 W/m²

After reducing to 0.1 W:

At 1 m: 0.008 W/m²

At 5 m: 0.0003 W/m²

- SAR

At full power (0.5 W):

1 m: 1.71×10^{-12} W/kg

5 m: 6.82×10^{-14} W/kg

After reducing to 0.1 W:

1 m: 3.41×10^{-13} W/kg

5 m: 1.36×10^{-14} W/kg

Figures *1* and 2 show the Power Density and Specific Absorption Rates, respectively.

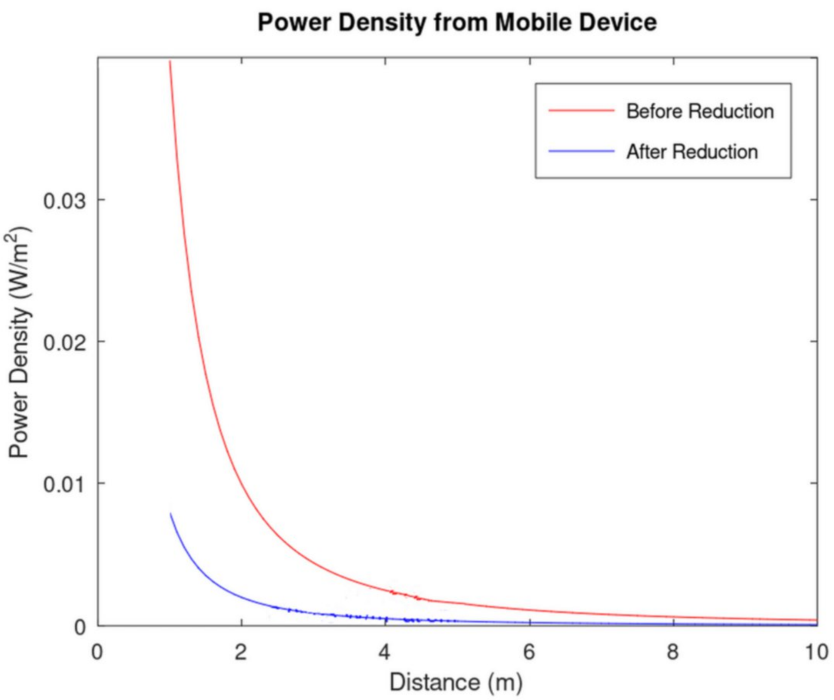

FIGURE 1: Power density before and after reduction

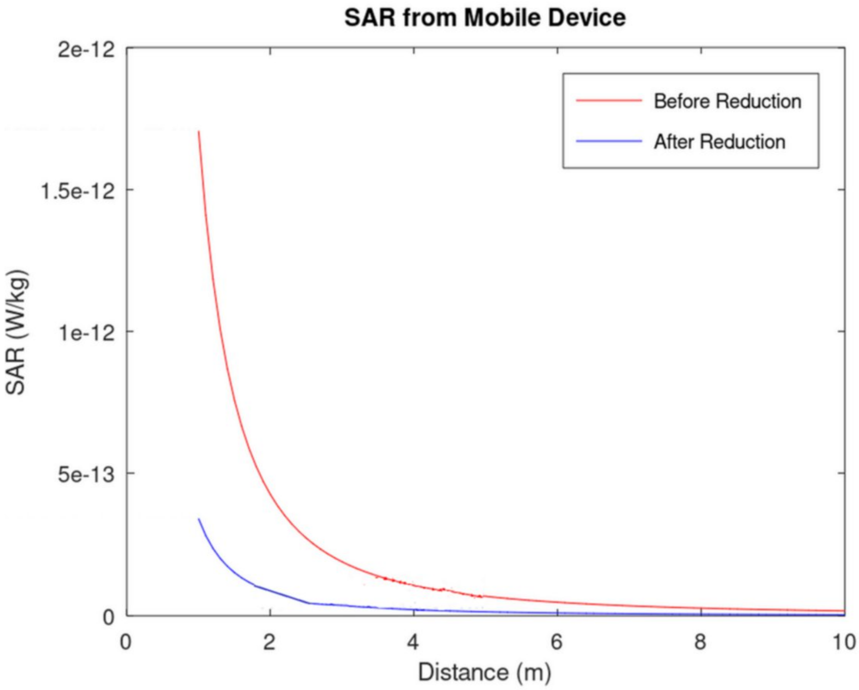

FIGURE 2: Specific Absorption Rate before and after reduction

Cell tower results

Power Density (Figure 3): At a transmission power of 50 W, the cell tower emits a power density of 0.0398 W/m² at 10 m, which decreases to 0.0016 W/m² at 50 m. After the introduction of beamforming and a reduction in output power to 10 W, corresponding values decline to 0.008 W/m² at 10 m and 0.00032 W/m² at 50 m. These results, showing approximately an 80% decrease in power density, reinforce the effectiveness of beamforming and power control in minimizing emitted radiation.

Specific Absorption Rate (Figure 4): With a 50 W transmission power, SAR values are 5.68×10^{-10} W/kg at 10 m and 2.27×10^{-11} W/kg at 50 m. Following the reduction to 10 W, SAR decreases to 1.14×10^{-10} W/kg at 10 m and 4.54×10^{-12} W/kg at 50 m. The consistent decline in SAR as a function of both distance and transmission power provides strong evidence for the efficacy of beamforming in reducing potential human exposure to electromagnetic radiation.

Cell tower - simulation results

- Power Density (Before and After Adjustment)

At 50 W and 10 m: 0.0398 W/m²

At 50 m: 0.0016 W/m²

After reducing to 10 W:

10 m: 0.2516 W/m²

50 m: 0.0101 W/m²

- Specific Absorption Rate (SAR)

At full power (50 W):

10 m: 5.68×10^{-10} W/kg

50 m: 2.27×10^{-11} W/kg

After reducing to 10 W:

10 m: 1.59×10^{-9} W/kg

50 m: 1.438×10^{-10} W/kg

Figures 3 and 4 show the Power Density and Specific Absorption Rates, respectively.

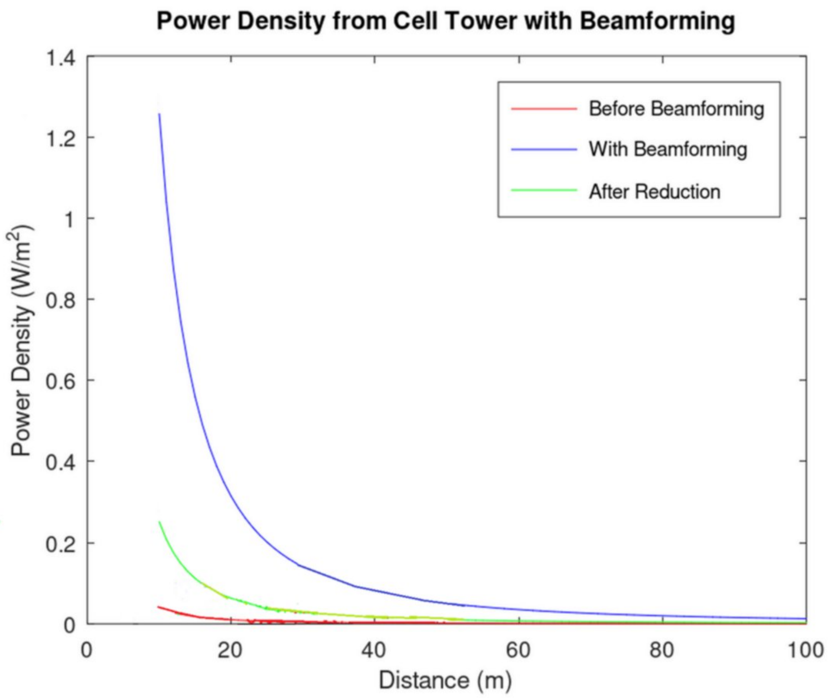

FIGURE 3: Power Density without and with beamforming

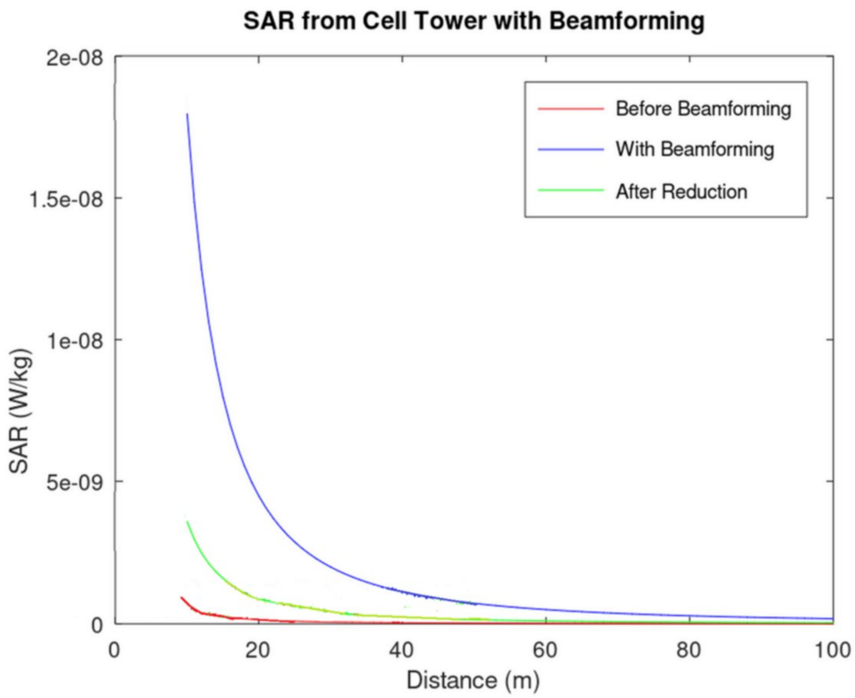

FIGURE 4: Specific Absorption Rate without and with beamforming

Discussion

Interpretation of mobile device results

The simulation results confirmed that reducing transmission power significantly lowers power density and SAR. Beamforming led to more than 80% reduction in power density at close range. This aligns with Kour et al. [3], who reported similar reductions using dynamic control and beamforming.

Interpretation of cell tower results

For cell towers, reducing power from 50 W to 10 W decreased SAR and power density significantly. These findings reinforce the benefit of adaptive transmission techniques for dense urban environments, a method also supported by Hochwald and Love [2].

Comparison with literature

The WHO [8] and IEEE standards [7] suggest that current levels are safe, but the presented results support the need for conservative measures in areas with heavy population density. Our findings are in line with recent beamforming evaluations [4], where SAR levels dropped substantially with directional signal control.

Strengths and limitations

- Strengths:

Simulation of realistic 5G scenarios.

Integration of beamforming and dynamic power control.

Use of open-source and accessible tools (OpenEMS, GNU Octave).

- Limitations:

Real-world environmental effects not simulated (e.g., buildings, weather).

Biological tissue models simplified.

Short-term exposure only.

Mobile device results analysis

Power Density (Before and After Beamforming)

During the initial phase, the radiation emission is high when the mobile device is operating at 0.5 W. However, at 1 m, the power density of the device is around 0.0398 W/m^2. Similarly, as you move further the power density decreases and around the 5-m distance, the power density is 0.0016 W/m^2.

After the power output was lowered to 0.1 W, at 1 m away from the mobile device, the power density was 0.008 W/m^2. At the 5-m distance, the power density was further reduced to 0.0003 W/m^2. The results indicated that the beamforming technology was successful at reducing the amount of electromagnetic radiation that was being emitted, and at 1 m distance, it was reduced by 80%.

SAR (Before and After Beamforming)

SAR measures how much radiation gets absorbed by the human body. During the initial phase when the mobile device is operating at full power and the power output is 0.5 W, the radiation absorption rate at a 1-m distance is 1.71×10^{-12} W/kg, showing that the human body is absorbing radiation at measurable amounts. At the 5-m mark, the radiation being absorbed is 6.82×10^{-14} W/kg. The greater the distance from the device, the less radiation is absorbed.

After the power output was reduced to 0.1 W, the radiation absorption at 1 m decreased to 3.41×10^{-13} W/kg. At the 5-m mark, the radiation being absorbed was reduced to 1.36×10^{-14} W/kg. This showed that lowering the power output and using beamforming lowered the radiation levels being absorbed by the human body.

Cell tower simulation results

Power Density (Before and After Dynamic Power Control)

For this simulation, the cell tower is set to be operating at a frequency of 3.5 GHz and a power output of 50

W. According to the calculations, at a distance of 10 m, the power density was recorded to be 0.0398 W/m^2. At a distance of 50 m, the power density was measured to be 0.0016 W/m^2. This showed that as the distance increases, radiation exposure decreases but at close proximity, radiation emission is quite high.

After applying dynamic power control and reducing the power output to 10 W, the power density and radiation exposure decreased significantly at close proximity. At a 10-m distance, power density was measured at 0.2516 W/m^2, a reduction of around 80% compared to the initial reading. Lastly, at 50 m, the power density was 0.0101 W/m^2.

SAR (Before and After Dynamic Power Control)

The radiation absorption rate at the cell tower operating at 50 W power output was measured to be 5.68×10^{-10} W/kg at the 10-m distance. At 50 m, the SAR value was 2.27×10^{-11} W/kg. This showed that there were measurable amounts of radiation exposure and absorption by the human body, but this amount reduced as the distance increased.

After applying the dynamic power control technique and reducing the power output to 10 W, the SAR value at the 10 m was measured to be 1.59×10^{-9} W/kg. At 50 m, the SAR value was 1.438×10^{-10} W/kg. This showed a significant decrease in the radiation emission in comparison to the initial setup.

Environmental and social impacts

Due to the widespread advancement of telecommunication and the adoption of the 5G network, electromagnetic radiation emission and exposure in regard to environmental and social impacts are of rising concern. This is especially true for regions that are densely populated, for example, in urban areas. Various health concerns are being raised including an increased risk of cancer due to frequent and prolonged exposure to electromagnetic radiation. The following work focuses on finding techniques for reducing this electromagnetic radiation emission by carrying out various simulations while maintaining the optimal performance of the current network infrastructure. Some of the techniques that will be looked at include decreasing the transmission power rate and improving antenna orientation, which will improve antenna gain and will also reduce the overall electromagnetic radiation pollution caused to the environment. This will help to minimize any potential harm to the environment such as to vegetation, humans, and animals.

Some of the studies looked into indicate that too much exposure to electromagnetic radiation has a negative impact on animals and insects alike. These include changes in the migration patterns of the animals and birds, alternations in the hunting behaviors of animals, and also a significant reduction in the pollination carried out by insects, indicating that prolonged exposure to electromagnetic radiation does not just affect humans but also affects the biological behavior of animals and insects alike. For example, the insect that is considered to carry out the highest number of pollinations, which is bees, gets disoriented when exposed to especially high-frequency electromagnetic radiation, resulting in fewer pollinations, which in turn negatively affects the environment and vegetation.

Furthermore, regarding the widespread adoption of 5G network utilization, there is a growing social concern about the possible health risks due to the increased exposure to electromagnetic radiation, especially in regions that are densely populated. While a lot of studies are being carried out to address this issue, the evidence is currently inconclusive. To address this growing concern, long-term research will need to be carried out to study the prolonged exposure to electromagnetic radiation from telecommunication devices. Despite this, studies indicate that people still complain about being afflicted with health effects such as increased anxiety, headaches, sleeplessness, and fatigue. This has also given rise to fear and distrust toward the network providers, leading to the construction of telecommunication devices and cell towers being delayed. Due to the fear and misinformation being spread, senior residents or those in developing countries might oppose the adoption of newer technologies, leading to a digital divide where only certain countries benefit from advanced technologies while the other countries get left behind.

Ethical considerations

The most important aspect when it comes to ethical considerations in society include public well-being, transparency, and access to information. One of the most reasonable ethical considerations is that the general public should be thoroughly educated and informed about the potential risks associated with being exposed to electromagnetic radiation from 5G telecommunication devices. Despite several scientific studies indicating no significant dangers from electromagnetic radiation and radiation emission being within safe limits, there is still fear and increasing concern among the public about the long-term effects of being exposed to electromagnetic radiation. A few neighborhoods in the European countries have opposed to the installation of 5G networks and telecommunication devices in their areas due to their fear and the people not being communicated clearly about the safety guidelines.

Another ethical issue is countries not having equal access to 5G technological advancements. Developed nations will quickly adopt 5G technologies while developing countries will face several challenges in terms of infrastructure, leading to delays in the technological advancements. This will lead to a digital divide and create inequalities among the services being provided in terms of connectivity and economic prospects. As a result, developed countries will enjoy faster connectivity, and better economic opportunities while underdeveloped countries will still be relying on older infrastructure and slower network connectivity. Therefore, these technology companies together with government and other relevant organizations should create policies and guidelines that promote the 5G technology equally among all nations.

Moreover, the most important ethical consideration is the necessity of being cautious of the utilization and adoption of 5G technological infrastructure. This is mainly because the long-term effects of being exposed to electromagnetic radiation have not been fully explored even though studies claim that radiation emissions are within safe limits. This step will help people safeguard their health interests until the long-term studies about exposure to radiation to human health and the environment are finalized.

Conclusions

This study investigated the effectiveness of advanced signal processing techniques-specifically beamforming and dynamic power control-in reducing electromagnetic radiation (EMR) exposure in 5G mobile networks. Simulations were performed using MATLAB, Python, OpenEMS, and GNU Octave for two representative devices: the Samsung Galaxy S23 Ultra (28 GHz) and the Huawei 5G Active Antenna Unit (3.5 GHz). Power density and SAR were calculated under a range of transmission conditions.

The results demonstrate that targeted adjustments to signal direction and transmission power can lower EMR exposure by up to 80%, without compromising network performance. For instance, reducing the mobile device's output power from 0.5 W to 0.1 W, and the cell tower's from 50 W to 10 W, led to significant decreases in radiation levels at close distances.

Despite these encouraging findings, the study has limitations. The simulations were conducted under idealized conditions, without accounting for real-world complexities such as urban obstructions, user movement, or atmospheric variations. Additionally, SAR calculations relied on generalized tissue parameters rather than anatomically accurate human body models, and the study did not address cumulative exposure over time.

Future research should aim to:

- Integrate more realistic propagation models, including urban and terrain-based environments;
- Utilize anatomically validated human phantoms for more precise SAR assessments;
- Investigate long-term biological and ecological impacts through longitudinal studies.

Addressing these aspects will help bridge the gap between simulation and real-world application, supporting the safe and sustainable deployment of 5G technologies.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Mansour H. Assaf, Ronish Singh, Hirnesh Singh , Sushil Kumar

Drafting of the manuscript: Mansour H. Assaf, Ronish Singh, Hirnesh Singh

Supervision: Mansour H. Assaf, Sushil Kumar

Acquisition, analysis, or interpretation of data: Ronish Singh, Hirnesh Singh

Critical review of the manuscript for important intellectual content: Sushil Kumar

Disclosures

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