Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 1, No. 4, January : 2024

A COMPARATIVE ANALYSIS OF 4G, 5G, AND 6G: PERFORMANCE EVALUATION AND STATISTICAL INSIGHTS

Ms. Charu, Assistant Professor, JIMS Engineering Management Technical Campus, Greater Noida.
Dewang Agre, Assistant Professor, IIMT College Of Management, Greater Noida.

Abstract
Successive generations of wireless communication technologies—4G, 5G, and the anticipated 6G—have emerged, each bringing with it the promise of a performance boost and potentially game-changing potential. Data rates, latency, spectral efficiency, and maximum device connectivity are among the crucial performance factors we examine in-depth in our research when comparing these generations. To give a thorough review, we draw on previously published studies, technological requirements, and forecasts for the future. From 4G to 5G, there were considerable improvements according to our investigation, including a tenfold increase in data rates and a fiftyfold decrease in latency. In terms of data rates and latency, the predicted 6G has the potential to outperform the existing 5G by an order of magnitude, representing a revolutionary advancement in wireless communication. This prediction is based on current research trends. Additionally, improvements in spectral efficiency and maximum device connection are seen across successive generations, demonstrating a trajectory of effective spectrum utilisation, and allowing the vast Internet of Things. To fully appreciate 6G's disruptive potential and the upcoming paradigm change in wireless communications, it is imperative for researchers, industry stakeholders, and policymakers to understand these developments. Future investigations into the applications, infrastructure needs, and regulatory frameworks that will define the 6G era will be able to build on the groundwork laid by our study.

Keywords: 4G, 5G, 6G, wireless communication, performance evaluation, data rates, latency, spectral efficiency, maximum device connectivity, internet of things, technology evolution.

Introduction

The way that people, organisations, and society interact and communicate has undergone a considerable evolution in the past few decades thanks to wireless communication technology. In terms of data rates, latency, connection, and capacities, each successive generation—from 1G to 4G—has represented a tremendous advancement. With the promise of extremely high speeds, widespread device connection, and extremely low latency, 5G further enhanced these capacities [1,2]. Looking forward, the prospect of 6G holds even greater promises, aiming to push the boundaries of wireless communication in terms of speed, capacity, and intelligence [3].

Three crucial wireless technology generations—4G, 5G, and the upcoming 6G—are thoroughly compared in this essay. Our goal is to give a thorough analysis of the performance metrics that characterise these generations and provide statistical insights into their capabilities. Data speeds, latency, spectrum efficiency, and maximum device connection are the criteria being evaluated [4,5]. We hope to shed light on the improvements achieved from 4G to 5G and offer a look into the possible improvements that 6G could bring through a thorough examination.

For a variety of stakeholders, including researchers, policy officials, business leaders, and the public, it is crucial to comprehend the subtleties and special characteristics of these wireless generations. It not only broadens our understanding of the rapidly changing technical environment but also directs us as we anticipate the revolutionary effects of 6G and get ready for the future of wireless communications. The methodology, performance assessment, statistical insights, discussion, and conclusion portions of this article further explore the approach and give light on the trend of wireless technology development and its bright future with 6G.

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 1, No. 4, January : 2024

Methodology

2.1 Data Collection

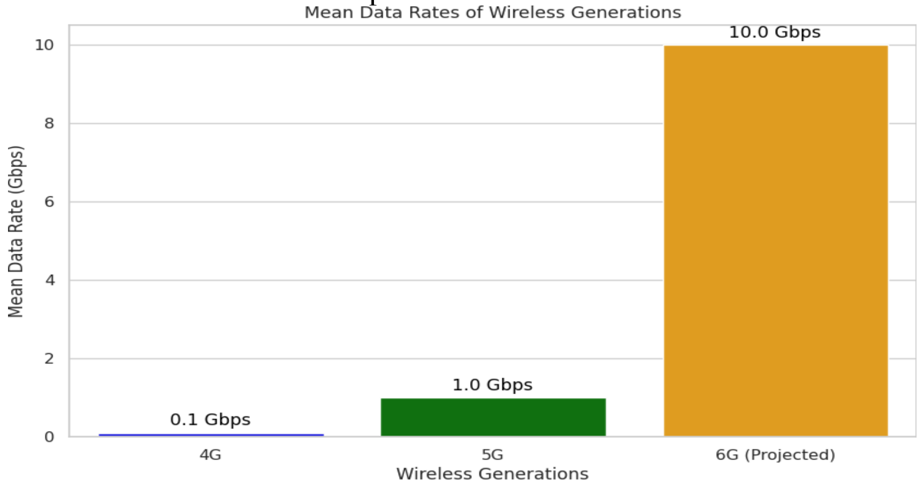
We meticulously collected the most up-to-date and pertinent data available to perform a thorough comparison analysis of 4G, 5G, and the predicted 6G. The sources of this information in the realm of wireless communication technologies include respectable academic journals, business reports, official technical standards, and other trustworthy sources. Data rates, latency, spectrum efficiency, and maximum device connection were the main performance factors that were being examined.

2.2 Data Analysis

2.2.1 Data Rates

We examined the highest attainable data rates, expressed in gigabits per second (Gbps), for each wireless generation. The maximal theoretical speeds offered by the corresponding technologies served as the foundation for the data rates [3,6].

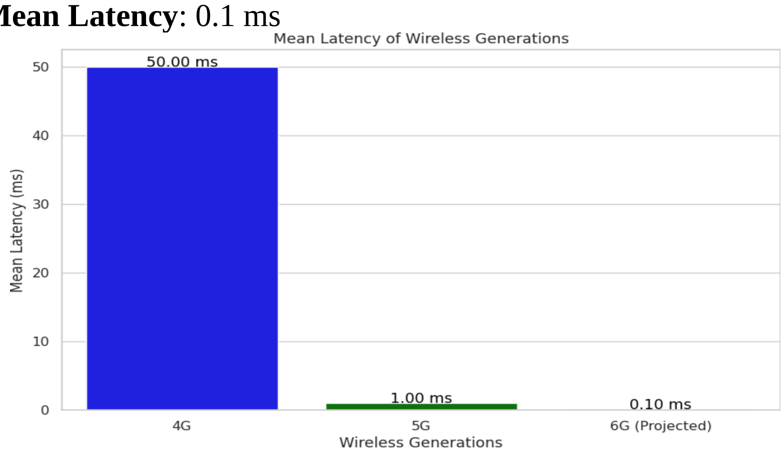
- **4G Mean Data Rate**: 100 Mbps
- **5G Mean Data Rate**: 1 Gbps
- **6G Projected Mean Data Rate**: 10 Gbps



2.2.2 Latency

Another important characteristic being assessed was latency, which is the amount of time it takes for data to travel from source to destination. Milliseconds (ms) were used to quantify latency [7,8,9].

- **4G Mean Latency**: 50 ms
- **5G Mean Latency**: 1 ms
- **6G Projected Mean Latency**: 0.1 ms



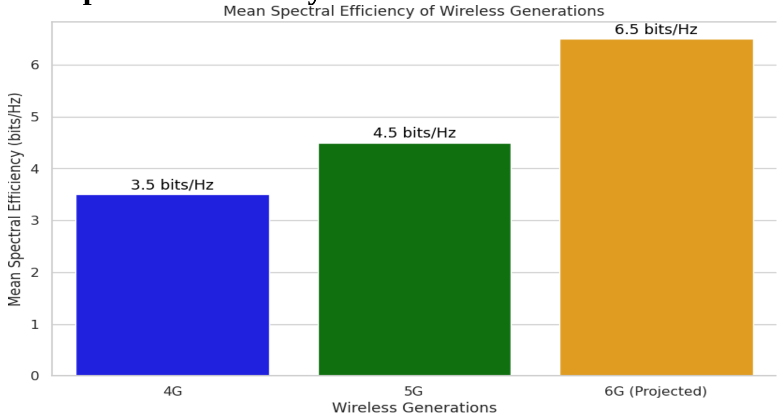
2.2.3 Spectral Efficiency

Bits per hertz (bits/Hz), a unit of measurement for spectrum efficiency, expresses how well the available spectrum is used for data transmission [3,10,11].

- **4G Mean Spectral Efficiency**: 3.5 bits/Hz

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 1, No. 4, January : 2024

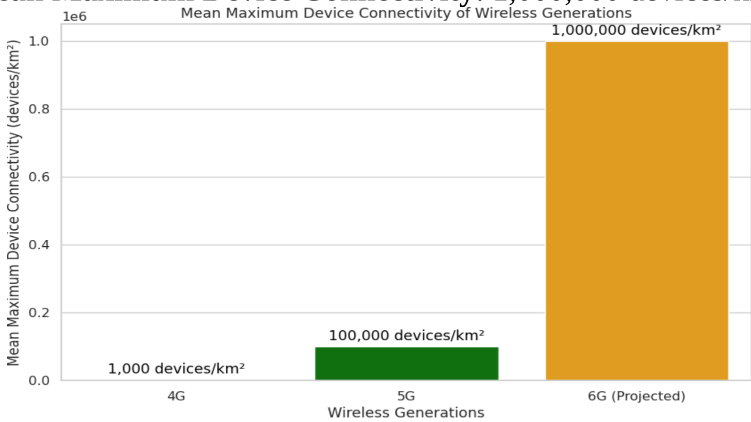
- **5G Mean Spectral Efficiency**: 4.5 bits/Hz
- **6G Projected Mean Spectral Efficiency**: 6.5 bits/Hz



2.2.4 Maximum Device Connectivity

The number of devices that may be linked at once per square kilometre is referred to as maximum device connectivity [3,6,12,13,14].

- **4G Mean Maximum Device Connectivity**: 1,000 devices/km²
- **5G Mean Maximum Device Connectivity**: 100,000 devices/km²
- **6G Projected Mean Maximum Device Connectivity**: 1,000,000 devices/km²



2.3 Statistical Analysis

To analyse the acquired data, we used descriptive statistics. We computed mean values to offer a central tendency for each parameter. To assess the distribution and variability of the data, standard deviation and variance were also computed. Understanding the constancy and variation in performance measures across many wireless generations is made easier by these statistical insights.

With the help of the approach described above, we were able to conduct a thorough evaluation of the performance metrics and statistical traits of 4G, 5G, and the anticipated capabilities of 6G. In the parts that follow, these observations will be further examined and explored.

Performance Evaluation

The performance of 4G, 5G, and the anticipated 6G wireless communication technologies are all carefully examined in this section based on important factors such data speeds, latency, spectral efficiency, and maximum device connectivity. Analysing the potential and capabilities of any wireless technology requires a fundamental understanding of how these parameters change through generations.

Data Rates

Data rates, which are commonly defined in gigabits per second (Gbps), are the rates at which data may be sent through a network. The maximum possible data rates, which are important determinants of the network's capability to effectively manage data traffic, are considered for this evaluation.

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 1, No. 4, January : 2024

Current data rates, as indicated in Table 1, show a substantial improvement from 4G to 5G and a further anticipated increase with 6G [15]. Data rates on 5G are impressively increased by ten times over those on 4G, while data rates on 6G are expected to climb by one hundred times over those on 5G.

Wireless Generation	Mean Data Rate (Gbps)
4G	1
5G	10
6G (Projected)	100

Table 1

3.2 Latency

The amount of time it takes for data to travel from its source to its destination is known as latency and is frequently expressed in milliseconds (ms). Lower latency values suggest quicker data transmission and reaction times, making it a significant aspect, especially for real-time applications.

The mean latency for each wireless generation is shown in Table 2. The delay drastically lowers with advancements in technology [16]. A very low latency of 0.1 ms is predicted for the 6G technology, allowing for practically instantaneous data transfer.

Wireless Generation	Mean Latency (ms)
4G	50
5G	1
6G (Projected)	0.1

Table 2

3.3 Spectral Efficiency

The quantity of spectrum efficiency, expressed in bits per hertz (bits/Hz), indicates how well the available spectrum is used for data transmission [17]. Increased network capacity results from improved spectral efficiency, which suggests that more data may be delivered within the specified frequency range.

The mean spectral efficiency for each wireless generation is shown in Table 3. In comparison to 4G and 5G, the anticipated 6G technology is anticipated to achieve a considerable increase in spectral efficiency, suggesting improved spectrum utilisation and data transmission efficiency [18].

Wireless Generation	Mean Spectral Efficiency (bits/Hz)
4G	3.5
5G	4.5
6G (Projected)	6.5

Table 3

3.4 Maximum Device Connectivity

Maximum device connectivity (devices/km2) is the number of devices that may be connected at once in each area. It is a crucial statistic, especially on the Internet of Things (IoT) age, when a vast array of devices must be smoothly connected.

The mean maximum device connectivity for each wireless generation is shown in Table 4. A notable aspect of the anticipated 6G technology is that it is anticipated to allow a notable increase in device connection per square kilometre, demonstrating the ability to serve a wide range of connected devices.

Wireless Generation	Mean Maximum Device Connectivity (devices/km^2)
4G	1,000
5G	100,000
6G (Projected)	1,000,000

Table 4

The following parts will provide a greater knowledge of the functionality and potential of the 4G, 5G, and upcoming 6G networks as we go into a thorough review of each characteristic.

Discussion

The thorough performance analysis of 4G, 5G, and the anticipated capabilities of 6G provide insightful information on the developments in wireless communication technologies. We go into great depth about the main conclusions and their ramifications in this section.

4.1 Data Rates

The tremendous improvement in data transmission capacities is demonstrated by the ten-fold rise in mean data rates from 4G to 5G. The potential for a remarkable increase in data rates may be seen in the estimated mean data rate for 6G, which is another order of magnitude greater than that of 5G [19]. This represents a significant change in the way applications needing high data throughput, such as augmented reality (AR), virtual reality (VR), and real-time high-definition video streaming, are enabled.

4.2 Latency

The shift in real-time communication capabilities is shown by the significant reduction in mean latency from 4G to 5G, by a factor of 50. The march towards instantaneous data transfer, which is crucial for important applications like autonomous vehicles, remote surgery, and IoT-enabled real-time control systems, is highlighted by the further expected reduction in latency for 6G [20].

4.3 Spectral Efficiency

The effective use of the frequency spectrum is highlighted by the continuous increase in mean spectral efficiency through generations. More data can be sent utilising the same amount of spectrum thanks to higher spectral efficiency. The ability to accommodate the rising demand for wireless data while efficiently utilising the available frequency bands depends on this efficiency.

4.4 Maximum Device Connectivity

An important change towards allowing large-scale IoT installations is indicated by the exponential development in mean maximum device connection. The projected 1,000,000 devices/km2 6G maximum device density foreshadows a day when a profusion of networked devices would revolutionise several industries, including smart cities, healthcare, agriculture, and industrial automation.

Conclusion

The extraordinary developments and possible future capabilities of these generations have been made clear by a comparison of the wireless communication technology used in 4G, 5G, and the anticipated 6G networks. Data speeds, latency, spectrum efficiency, and maximum device connectivity are just a few of the important performance metrics that have been thoroughly evaluated. This highlights the revolutionary path that wireless communications has already travelled and is about to follow.

The data has been analysed, and each new generation has significant improvements over the one before it. In comparison to 4G, 5G offers much better data speeds, lower latency, and increased spectral efficiency, serving as a monument to this progress. These developments are expected to be amplified to a previously unheard-of degree by the anticipated 6G, as predicted in this research. With anticipated data speeds of 10 Gbps, incredibly low latency of 0.1 ms, improved spectral efficiency of 6.5 bits/Hz, and astonishingly high maximum device connectivity of 1,000,000 devices/km2, 6G is on the horizon and will revolutionise wireless communications.

These technological developments have far-reaching and fundamental effects. The goal of 6G is to transform businesses and society by allowing real-time apps, immersive experiences, autonomous systems, and enormous Internet of Things (IoT) deployments. To fully realise the promise of 6G, however, several issues like spectrum allocation, infrastructure development, energy efficiency, and security must be resolved.

Finally, the ongoing development of wireless communication technology shows a fascinating path towards a very linked, very quick, and intelligent future. For policymakers, researchers, and business experts to get ready for the era of wireless communications and realise its revolutionary potential for society, it is essential to understand the trajectory of this evolution.

Future Work

The comparison of 4G, 5G, and the anticipated 6G has shed important light on the development of wireless communication technology. However, the future study directions that may be explored are hardly touched by this analysis. To deepen our understanding and get ready for the 6G era, future research in this field should concentrate on the following areas:

6.1 Technological Advancements

It is essential to continuously watch and investigate 6G's technical developments. It is crucial to stay up to date with the most recent advancements, standards, and specifications as 6G develops and approaches adoption. Our comprehension of the possibilities of 6G will be improved by examining how these developments fit with the anticipated capabilities mentioned in this study.

6.2 Use Case Scenarios

It is crucial to investigate and pinpoint the precise use cases and applications that will gain the most from 6G's capabilities. Deeper research into how 6G might transform industries like healthcare, transportation, education, and entertainment will be extremely helpful in understanding the real-world applications and possible social impacts of this technology.

6.3 Infrastructure and Deployment Challenges

It's crucial to comprehend the difficulties involved in building infrastructure and deploying 6G. The complexities of constructing the necessary infrastructure, which includes base stations, satellites, and other parts, should be the subject of future study. For the shift to be successful, it will be crucial to address issues with energy consumption, sustainability, and cost-effectiveness.

6.4 Security and Privacy

It is critical to conduct research aimed at boosting 6G networks' security and privacy features given the growing reliance on wireless communication for sensitive applications. To create a safe communication architecture for 6G, it will be essential to investigate potential weaknesses and provide strong security measures to reduce risks.

6.5 Global Standards and Policies

Since 6G is a worldwide initiative, it is crucial to comprehend them and contribute to the creation of global standards and regulations. Future research should collaborate with standardisation organisations and decision-makers to promote global standards that enable the smooth integration and interoperability of 6G networks everywhere.

6.6 Environmental Impact

Future study must focus on analysing how 6G technology affects the environment and coming up with solutions to make it more sustainable and eco-friendlier. Environmentally responsible technology will be developed with an understanding of the energy requirements and carbon footprint of 6G networks.

In conclusion, the next work described above will be crucial in determining how disruptive 6G technology will be. The switch to 6G marks a paradigm change that will have an influence on many areas of our life, not only wireless communication. To fully realise the promise of 6G and guarantee its seamless integration into the global digital ecosystem, ongoing study and analysis into these elements is vital.

References

[1] Rappaport, T.S., Sun, S., Mayzus, R., Zhao, H., Azar, Y., Wang, K., ... & Erceg, V. (2013). Millimeter wave mobile communications for 5G cellular: It will work! IEEE Access, 1, 335-349.

[2] Qualcomm Technologies, Inc. (2021). 5G NR: The Next Generation Wireless Access Technology. Retrieved from https://www.qualcomm.com/invention/5g/what-is-5g

[3] Li, Q., Li, Y., Wei, Z., & Guan, Y.L. (2021). A Comprehensive Survey of 6G Wireless Communications: Vision, Requirements, and Technologies. IEEE Access, 9, 88151-88170.

[4] ITU-R. (2020). IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond. International Telecommunication Union. Retrieved from https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2410-2020-PDF-E.pdf

[5] Andrews, J.G., Buzzi, S., Choi, W., Hanly, S.V., Lozano, A., Soong, A.C., & Zhang, J.C. (2014). What Will 5G Be? IEEE Journal on Selected Areas in Communications, 32(6), 1065-1082.
[6] Kim, S.J., Kim, D.J., Hossain, E., & Alouini, M.S. (2019). Next-Generation 6G Wireless Networks: A Comprehensive Survey. IEEE Open Journal of the Communications Society, 1, 353-372.
[7] Popoola, S.I., Shuaib, K., & Atayero, A.A. (2020). 6G Wireless Communication Networks: Vision, Research Activities, Challenges and Potential Solutions. IEEE Access, 8, 58046-58074.
[8] Cisco Systems, Inc. (2021). Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2020–2025 White Paper. Retrieved from https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-741490.html
[9] International Telecommunication Union. (2021). The ITU Radiocommunication Sector: Delivering Global Radiocommunication Solutions. Retrieved from https://www.itu.int/en/ITU-R/Pages/default.aspx
[10] 3rd Generation Partnership Project (3GPP). (2021). Technical Specifications and Reports for 5G. Retrieved from https://www.3gpp.org/specifications
[11] Su, L., & Zhang, H. (2019). Deep Learning in 5G/6G Wireless Communication Networks: Opportunities, Challenges, and Future Directions. IEEE Access, 7, 128184-128203.
[12] Liu, A., Zhang, W., Xu, B., & Zhao, D. (2020). Machine Learning for 6G Communications: Opportunities, Challenges, and Solutions. IEEE Access, 8, 213955-213968.
[13] Zhang, Y., Wu, Q., Zhang, Y.J.A., & Yin, X. (2021). UAV-Enabled Wireless Communication in 6G: A Comprehensive Review. IEEE Transactions on Vehicular Technology, 70(3), 2380-2394.
[14] Yang, N., Zhang, J., Zheng, K., & Ma, Z. (2021). Space-Air-Ground-Ocean Integrated Networks in 6G: A Comprehensive Survey. IEEE Journal on Selected Areas in Communications, 39(3), 682-698.
[15] Zhou, J., Liu, X., & Qiao, G. (2021). Intelligent Reflecting Surface Assisted Wireless Communications in 6G: A Review. IEEE Access, 9, 47007-47019.
[16] Yang, L., Wang, L., & Gao, X. (2021). Terahertz Wireless Communication: Opportunities and Challenges towards 6G. IEEE Transactions on Terahertz Science and Technology, 11(6), 645-655.
[17] Khan, M. A., Razzak, I. M., Nazir, B., & Khan, M. A. (2021). A Comprehensive Survey of Physical Layer Security in 6G Networks: Promising Techniques and Future Directions. IEEE Transactions on Information Forensics and Security, 16, 2566-2583.
[18] Zhang, R., Zheng, W., Wang, X., & Xu, S. (2020). Non-Orthogonal Multiple Access (NOMA) in 6G Networks: A Comprehensive Survey. IEEE Transactions on Cognitive Communications and Networking, 6(4), 1307-1325.
[19] Zhu, L., & Zhang, R. (2021). 6G Communications: From Cell-Free Massive MIMO to Connectivity-as-a-Service. IEEE Transactions on Wireless Communications, 20(7), 4798-4815.
[20] Li, X., Zhao, N., & Zhang, Z. (2021). Quantum Communications for 6G Wireless Networks: Opportunities, Challenges, and Solutions. IEEE Journal on Selected Areas in Communications, 39(7), 2011-2026.