

# ***Generational Leaps in Mobile Networks: From 4G to 6G Performance, Budgets, and Future Implications***

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**Abstract:** The 21st century is the century of information explosion. People around the globe were gradually shifting from bulky desktop computers to using portable smartphones to demand faster and more accurate information transmission. The purpose of this paper is to discuss the definition and development of networks, from 4G to 6G, exploring the applications supported by networks in different eras and how they gradually change netizens lives. It reveals that while 4G only supports smooth video, 6G is expected to be gradually implemented by 2030, which will lead to the normalization of big data analysis and XR usage, thereby achieving a fully connected society among ocean, land and space. This article further analyzed the implementation of 4G, 5G, and 5.5G in global cities and rural areas, revealing that the theoretical values and actual performance of 4G to 5G, 5.5G are indeed disappointing. It is worth considering that while there is still significant room for improvement from 4G and 5G to 5.5G, the performance of 6G in people's lives should also be just as unsatisfactory under such urgent time and financial budgets.

**Keywords:** 4G, 5G, 6G, Internet of Things

## **1. Introduction**

The evolution of mobile communication technologies—from 4G to 5G, 5.5G, and the emerging 6G—has redefined global connectivity. This paper examines the technical advancements, financial challenges, and societal impacts of these generational transitions, focusing on practical performance metrics, deployment budgets, and the anticipated benefits and drawbacks of 6G. This paper reveals the limited practical performance from 4G to 5.5G, and anticipate the 6G's expected performance upon its implementation is still anticipated to remain below 20% of the theoretical value, similar to the transition from 4G to 5.5G in the past.

## **2. Definitions**

4G, defined in IMT-Advanced, introduced Long-Term Evolution (LTE) networks. 4G aims to provide users peak download speeds of 100Mbit/s under high mobility, 1 Gbps under low mobility and latency as low as 30 ms [1]. It enabled high-definition video streaming, mobile gaming, and early Internet-of-Things applications. It is also propagandized with “MAGIC”, which refers to mobile multimedia anywhere, global mobility solutions over integrated wireless and customized services [2].

Deployed commercially in the 2020s, 5G operates across sub-6 GHz, theoretically offering a downlink data rate of up to 20 Gbit/s, an uplink data rate of up to 10 Gbit/s and ultra-low latency (<1

ms) [3]. Key innovations include massive (Multiple Input, Multiple Output) MIMO and network slicing, which support up to 1 million devices per square kilometer [4]. 5G is characterized by its substantial improvements over 4G. This generation supports a broader range of frequency bands, including millimeter waves (mmWave), which facilitate higher data rates but require denser base stations.

5.5G, or “5G-Advanced”, serves as an intermediary step between 5G and the anticipated capabilities of 6G. According to the definition released by 3GPP, the stage nowadays reached is R15-R17, while 5.5G is R18-R20, which will maintain the transitional phase till 6G [5]. It aims to meet growing demands without necessitating a complete overhaul, enhancing the existing technologies by improving energy efficiency and network reliability while expanding support for IoT applications [6]. The main objects of 5.5G are AI-driven network optimization, terahertz spectrum trials, and improved uplink speeds (up to 10 Gbps) [7].

6G is still in the conceptual phase but is projected to revolutionize mobile communications with potential data speeds in the terabits per second range and latency reduced to sub-millisecond levels. It will leverage higher frequency bands, possibly extending into terahertz (THz) frequencies, allowing for unprecedented data transmission rates and enhanced network capacity. 6G aims to integrate AI-native architectures, quantum communication, and sub-orbital networks (satellite and drone-based). Theoretical speeds could exceed 1 Tbps with near-instantaneous latency (<0.1 ms) [8].

### 3. Performance Analysis

#### 3.1. Infrastructure Coverage

The rollout of 4G required significant investments in infrastructure development, including base stations and backhaul systems. These investments laid the groundwork for subsequent generations by enhancing coverage and capacity. Take China as an example, till December 2024, 4G base station amount in Mainland China is 71,120,000, while the 5G base station amount is 42,510,000 [9], with 66.5% coverage in rural areas [10], covers 99% of the country's population in China [10]. The same situation in the European Union and the US, the number of 5G base stations is significantly lower than that of 4G base stations, with 356,000 5G base stations in Europe (38.95% of the total base stations), and 100,000 in the US [11]. 4G supports 63% of the Europe network connections [12]. It can be known that the main force of the global network is still 4G based on its high coverage.

#### 3.2. Speed

The actual practice of 4G and 5G is not as satisfying as the theoretical values around the globe. In 2024, the 4G downlink rate in Mainland China is 50.19Mbps, the uplink rate is 29.63Mbps; 5G's downlink rate is 348.28Mbps, uplink rate is 82.95Mbps [13]. For the US, the average download speeds for 4G LTE typically range from 20 to 50 Mbps, depending on the carrier and location, while US 5G operators offer the best typical uplink speed at 238.3 Mbps, and download speed at 158.5 Mbps [14]. In the European Union, the 4G downlink speed is normally maintained at 42.1Mbps, uplink rate is 33.3Mbps [15]; 5G would be better, the average download speed in the European Union reached 230Mbps [12].

Although the 4G and 5G have operated for years, the practical value is not as ideal as the white papers stated to the users. Even the best performance for both 4G and 5G stated above is China, the 4G downlink performance is still 50.19Mbps only, far below the target stated in IMT-Advanced: 1000Mbps; and the 5G's downlink rate 348.28Mbps, which is only 17.4% to the ideal downlink value. The Ethernet cable would be one of the reasons contributed. Most regions use the inexpensive CAT5/CAT5E Ethernet cable while using the internet, though the upper limits of these 2 cables are 100Mbps and 1000Mbps with up to 100MHz [16]. The physical layer restricts the network speed

under the Ethernet cable's utmost performance. Table 1 has stated the utmost bandwidth of Ethernet cable under different categories, implies the network performance would also be affected by the Ethernet cables.

Table 1: Ethernet Cable's Category [16]

Category	Max. Data Rate	Bandwidth (MHz)	Max. Distance (m)
Category 1	1 Mbps	0.4	/
Category 2	4 Mbps	4	/
Category 3	10 Mbps	16	100
Category 4	16 Mbps	20	100
Category 5	100 Mbps	100	100
Category 5e	1 Gbps	100	100
Category 6	1 Gbps	250	100 (10Gb at 37 m)
Category 6a	10 Gbps	500	100
Category 7	10 Gbps	600	100
Category 7a	10 Gbps	1000	100 (40Gb at 50 m)
Category 8	25 Gbps (Cat.8.1) 40 Gbps (Cat8.2)	2000	30

## 4. Future Prospects of 5.5G and 6G

### 4.1. Advantages

5.5G, as a transitional technology from 5G to 6G, has achieved a comprehensive performance improvement based on the existing 5G infrastructure. Its peak rate can reach ten times that of 5G, with latency reduced to the microsecond level, and it supports a greater number of IoT device connections, providing more efficient support for scenarios such as the low-altitude economy and industrial automation. For instance, the low-latency characteristics of 5.5G can support real-time decision-making for autonomous driving and precise control of drones [17]. Moreover, 5.5G upgrades the existing 5G infrastructure without the need for a complete network rebuild, significantly reducing deployment costs. China Mobile has launched the world's first commercial 5.5G network, validating its feasibility for rapid implementation [13]. Furthermore, 5.5G can validate key technologies for 6G in advance (such as integrated sensing and communication), accumulating experience for future technologies.

5.5G further expands the boundaries of 5G, supporting more complex application scenarios, such as 360-degree real-time viewing and smart city perception networks, significantly enhancing user experience and industry efficiency [13].

6G is expected to achieve transmission rates 10 to 100 times that of 5G (with theoretical peak values exceeding 1000Gbps), reduce latency to 0.1 milliseconds, and support an integrated network across space, land, and sea [8], covering traditional communication blind spots such as polar regions and oceans. For instance, the application of terahertz frequency bands will support the real-time transmission of high-definition video and even enable the construction of a digital twin world [17]. Besides, 6G will deeply integrate communication, perception, computing, and artificial intelligence, supporting innovative technologies such as intelligent super surfaces and quantum communication, providing a foundational technological basis for smart cities, remote healthcare, and more.

## 4.2. Disadvantages

Excessive budget expenditure would be the first challenge faced by all the stakeholders. 6G relies on the terahertz frequency band, requiring new types of radio frequency devices and antennas, with research and manufacturing costs far exceeding those of 5G. Besides, deployment costs of satellite networks: the integration of air and space requires a large-scale low Earth orbit satellite network, with the launch cost of a single satellite approximately 50 million dollars, and global coverage necessitating tens of thousands of satellites, leading to a total investment potentially reaching the hundred-billion-dollar level [18].

Complexity of international standard coordination is also a threshold. There are differences among countries regarding the allocation of 6G spectrum and technological pathways. Although China leads in the formulation of some standards, Europe and the United States are vying for discourse power through organizations such as the Next G Alliance, which may exacerbate technological fragmentation.

The high investment in 6G requires a sustainable profit model; however, current operators face a disparity between "traffic growth and stagnant revenue". For example, the indirect economic output of 5G over five years reached 14 trillion yuan, but the profit growth for operators has been limited, and 6G may face even greater commercial risks. Moreover, the theoretical limit speed of current 4G and 5G has not yet been reached. The results of the investment in time and financial costs have not met expectations, which led to the lack of faith of netizens in 6G developments.

As the definition of 6G emphasizes the daily participation of AI, the ethical dilemmas will be met. AI-driven resource allocation risks perpetuating biases in network access, requiring stringent regulatory frameworks [17].

## 5. Conclusion

It can be concluded that in addition to the increase in network speed, 4G, 5G, and 6G are more about defining the methods of network usage and the application scenarios in daily life. The performances of 4G and 5G in the current environment has not yet reached its peak, and even globally, their performance levels are less than 30% of theoretical values. In the near future, both 4G and 5G will continue to play a key role in daily network services, with the larger 4G services in the current market gradually being replaced by 5G, pushing both 4G and 5G towards their theoretical speeds. 5.5G and 6G represented two paths in the evolution of communication technology: the former is a pragmatic incremental upgrade, while the latter is a disruptive innovation. The advantage of 5.5G lies in its rapid deployment and cost control, transitioning from basic daily IoT services to the stringent XR environment of 6G. The potential of 6G is enormous, but it must overcome the triple challenges of high costs, technological requirements based on terahertz high-frequency waves, and the network ecosystem only having developed to 5G. In the near future, it can be anticipated that even if 6G is successfully launched, its high research and development costs, as well as frequency band leasing fees, will limit the usage scenarios of 6G in the lives of most citizens. It is foreseeable that in the first decade of 6G implementation, it will still be confined to laboratories, government military, and high-tech research and development companies.

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