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THE IMPACT OF 5G ON SOFTWARE DEVELOPMENT

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Abstract

Fifth-generation (5G) mobile network technology is a huge change in the digital environment that will have a big impact on how software is developed, how it is deployed, and how it is structured. 5G has very low delay, a lot of data, a lot of devices that can join, and better dependability. It makes it possible to build next-generation apps that were previously limited by network issues. This includes applications that need to work in real time and with low delay, like augmented and virtual reality, self-driving cars, the Internet of Things (IoT) platforms, smart cities, healthcare, and edge computing solutions. 5G has changed more than just software development. It has also changed how applications are designed, putting more focus on distributed structures, microservices, cloud–edge interaction, and real-time data processing. It's also up to developers to deal with new problems like security, data privacy, network slicing, and scaling in a variety of settings. Also, 5G speeds up the use of DevOps, AI-driven automation, and continuous release strategies to meet the needs of apps that need to be very fast and flexible. This abstract looks at how 5G changes the way software is developed, focusing on both the chances for new ideas it opens up and the technical and business problems it brings up for developers and companies.

Keywords: 5G Technology, Software Development, Low Latency, Edge Computing, Internet of Things (IoT), Cloud Computing.

INTRODUCTION

This small project's goal is to draw attention to how telecommunications have affected the growth of digitalization and digital tools. We used IEEE and other sources, as well as articles on the web, to find useful pieces that helped us learn more about the subject. People think of telecommunication as the backbone of automation, which has changed everything about how people and computers link. As a follow up to 4G, the 5th version of cell phone technology was released by the 3Gpp (3rd version Partnership Project). Unlike 4G, 5G offers technology that is stable, highly flexible, and scalable. We will talk more about this in later parts. Additionally, it is said to send data at speeds of up to 20Gbps. In simple words, 5G can make everything we do on our phones faster and better than it was before. As a group of cellphone users grows, digitalization and digital technologies keep getting better and reaching new milestones in their use. Traditional businesses can move into the digital era with the help of new, faster, and more reliable wireless communication channels (Kortelainen et al., 2019). These channels also make it possible for new wireless data channel-based monitoring services (Eskelinen et al., 2017) and devices to talk to each other almost in real time, which makes it easier for things like GPS receivers that aren't working right on one device to share location data (Jahkola et al., 2017). Imagine robots and a bunch of drones carrying your shopping, connecting millions of devices with less than 10ms of delay, or watching an HD movie on a 500km/h train. All of these things are possible with 5G, and they can get

even better with 6G. Big steps forward and operations that have happened recently around the world have helped people talk about their thoughts on 5G and how it affects digital technologies.

Legacy technologies and Digitalization

Digitalization and progress in telecommunications go hand in hand. When there is a big step forward in telecommunications, it helps automation and digital tools move forward. Let's talk about a big picture of how it has changed over the last 40 years.

The first generation (1G) of telecommunications was put into use in 1984. It is mostly analog, like a regular radio or walkie-talkie. The user's call will reach a nearby base station instead of going all the way to the destination base station. The base station control system will then talk to either the neighboring or the destination base station before linking to the user. In addition, it was the heaviest phone. After that, around the 1990s, the second generation (2G) came out. It was the change from analog to digital sound transmission. In the telecommunications business, it was seen as the big break of the decade when everyone got a cell phone. It was also seen as the dawn of the internet age. The internet was slowly becoming more popular, and 2G offered both talk and data access (Apis, 2021). It was the start of SMS (Short Message Service), which is still widely used even though 5G is now available.

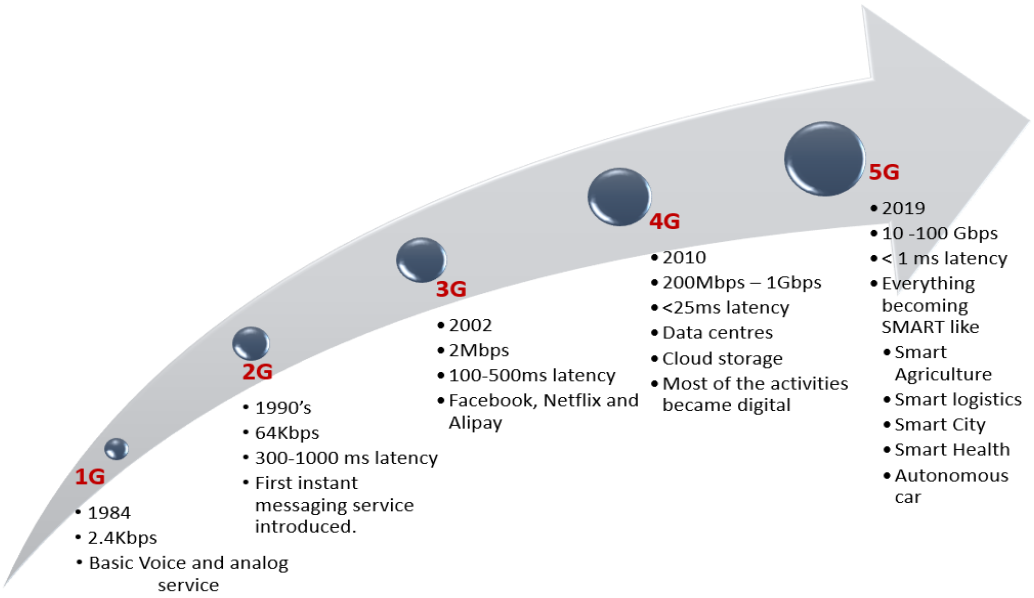


Figure 1. Evolution of cellular networks.

There were two new technologies, CDMA and UMTS, that came out around the year 2000. These were the third generation (3G) and they changed the way calls were made. Plus, it set the stage for making speech calls over IP instead of using a different line for data and voice talks. Not having a better radio link made it hard to do back then, but it led to the creation of many digital tools and apps, such as Facebook, Netflix, WhatsApp, and more. After a while, the fourth generation (4G), also called LTE (long term evolution), came out around 2009. It replaced the radio network and the core network with an IP-based service. The third generation's idea was put into action in 4G as VOIP (speak over IP). It

worked and gave me some high-speed internet, about 300 Mbps theoretically (18–36 Mbps in real life), unless I was using old technologies. It sped up the development of new technologies like live streaming services, cloud solutions, and storage that was already everywhere. Digital players put a lot of money into data centers, and a lot of software solutions were built and kept up to date in the cloud, which cut down on the huge costs of infrastructure (Apis, 2021). Finally, around 2019, the fifth generation (5G) really took off. The 3GPP's alleged specs look good, and the level of technology will be higher than the current standards. It has been split into three sections based on the different features that 5G offers. Now, let's talk about the main ways that 5G is different or better than 4G, followed by its different types.

Features of 5G

As we saw in the last part, both telecommunications and digitalization changed over time. As we move forward, let's take a better look at what makes 5G different from 4G and why it's so important. Wait time: It's the small delay that happens when we send info from one machine to another. 5G guaranteed delay of less than 1 millisecond, which is faster than a person processing images. It is very important for handling a lot of IoT devices and getting info from them right away in real time. Additionally, in the event of a treatment being done from afar or actions taking place in a different place.

Bandwidth and Speed: When people think of improvements in telecommunications, speed is usually the first thing that comes to mind. 5G is no different; it's 10 times faster than the 4th generation. It says it can give you up to 20 Gbps. It is important to have enough data when watching HD movies and material in busy places like arenas and shops. It will also be helpful for showing live sports with a delay. 5G uses both radio and millimeter band to make sure it has the range and the least amount of drop.

Capacity and Dependability: 5G is said to be able to handle 1000 times as much as 4G. If there are thousands of IoT devices linked in a small area, and the connection shouldn't drop any data, this is important. Intel (2021) also said that 5G would be reliable almost 99.99% of the time, which is important when a lot of devices are connected and sending important data. Because wireless connections lose data for a number of reasons, 5G can help reduce data loss even more. This is because the base stations and towers are so small and can be put in such a small area. This makes it more stable than generations before.

Infrastructure is important to get the most out of 5G in terms of mobility and battery life. After it is set up, it gives you better range and is much more reliable when you are flying or moving quickly. People who use 5G say they won't lose their connection even if they're going 500 km/h. Also, because the towers are close to each other, cell phones don't have to send too much power to the base station in order to connect. It helps the batteries last longer.

Technology: 5G is built on LTE technology, which is also used by 4G. However, it works on top of a feature called MIMO, which stands for "multiple-input and multiple-output." It is just sending and getting different kinds of data over the same radio plane more than once. Massive MIMO, on the other hand, is used in 5G, which will help increase the capacity to hundreds of receivers. This makes 5G more efficient and faster. To make 5G work better with small cells, more flexible and quick methods based on software development will be used (Knieps and Bauer, 2021). Further, Network splitting is a trait

that is seen as important in 5G. It lets operators divide the network into smaller pieces so they can give only the features those customers need. This keeps the network from being overloaded (Craven, 2020).

Security: Since 5G has more access points than 4G, it makes sense that it could be more vulnerable to security risks. But because 5G has network splitting, it can be changed to send important data through a protected way instead of a regular network, which keeps private data from getting out. Because of how 4G is built, 5G can't do some things that 5G can. Overall, the current versions of mobile systems are set up in a way that means they will probably have to be kept next to each other for decades. Either all older options would be able to work with the new 5G generation, or the new tech would be so much better that we would all switch to it.

Advantages of having Edge computing

Edge computing systems, such as cloudlet, fog computing, and multi-access computing, will be helpful and offer many benefits, such as lower delay, longer battery life, and higher speed. The piece by Babou (2018) says that the current edge computing technologies will not work reliably when there is a lot of data. Because of this, the author has suggested a new three-tier system. Having a controlled system was clear to see as not being possible. Data speed will slow down as the number of users grows, which will cause delay to rise and affect user performance. The author set up a three-tier design with a central cloud, an edge server, and a home server to avoid that. Which home server will be closest to the users, and which home server can handle their requests? The core cloud and edge servers can handle the info later. The edge server doesn't have to work as hard, and the delay goes down over time. Also, there will be a lot more micro and small cells in 5G than tall buildings. This means that the home computer will be much closer. The three-tier design that is talked about in the story (Babou 2018) is shown below in a picture.

5G's many uses rely on its promised low delay. With this edge computing technology, augmented and virtual reality will become more and more possible, allowing people and virtual things to connect with each other in real time. It's also important for surgeries that are done from afar. The author used Edgelands simulation to show that low delay can be reached in a three-tier setup with a home server set up separately from the other two servers.

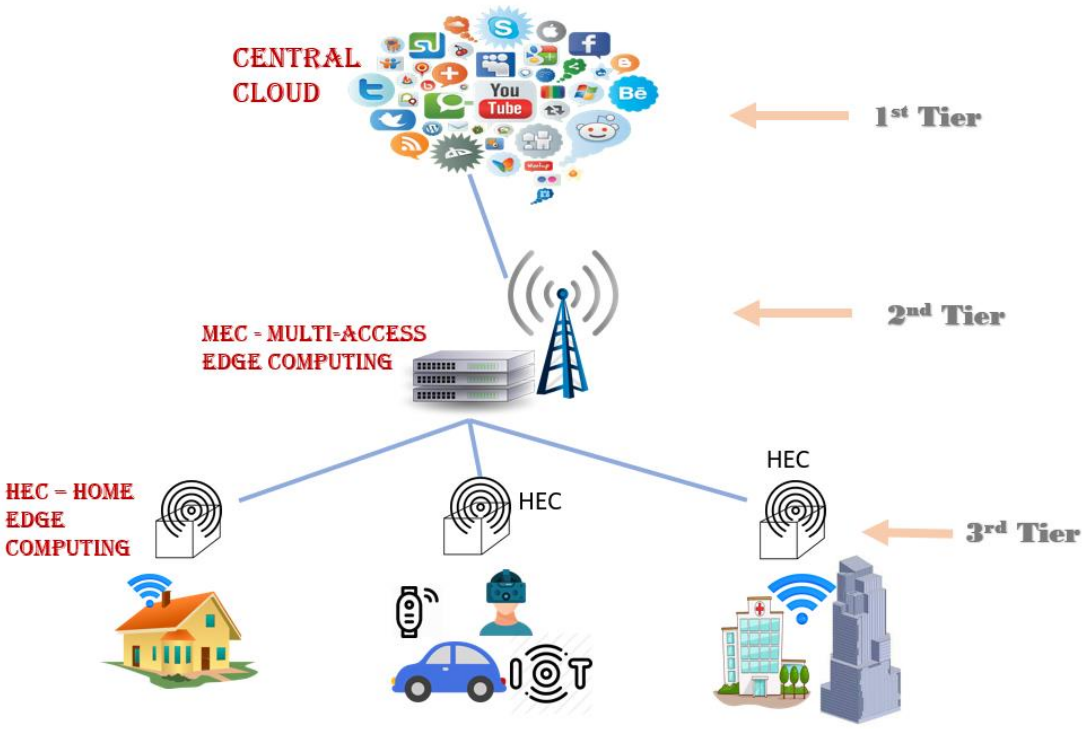


Figure 2. Proposed 3-tier computing infrastructure.

Based on this, it looks like this setup could be used in the real world in the future. However, when it does become real, there will be problems that need to be fixed.

Types of 5G based on application

Due to the fact that it offers high-speed data at approximately one gigabit per second, 5G has been divided into three distinct categories. The first division is known as ebb, which stands for enhanced mobile broadband. Applications such as high-definition video streaming, augmented reality, and virtual reality technologies will fall under the eMBB category. As a result of its ability to accommodate a large number of devices while minimizing the amount of data that is lost, it was classified as massive machine type communication (mMTC) and Ultra-reliable low latency communications (URLLC). Applications connected to the Internet of Things (IoT) that connect millions of devices, remote surgery that requires extremely low latency, and autonomous vehicles are the primary emphasis of this initiative.

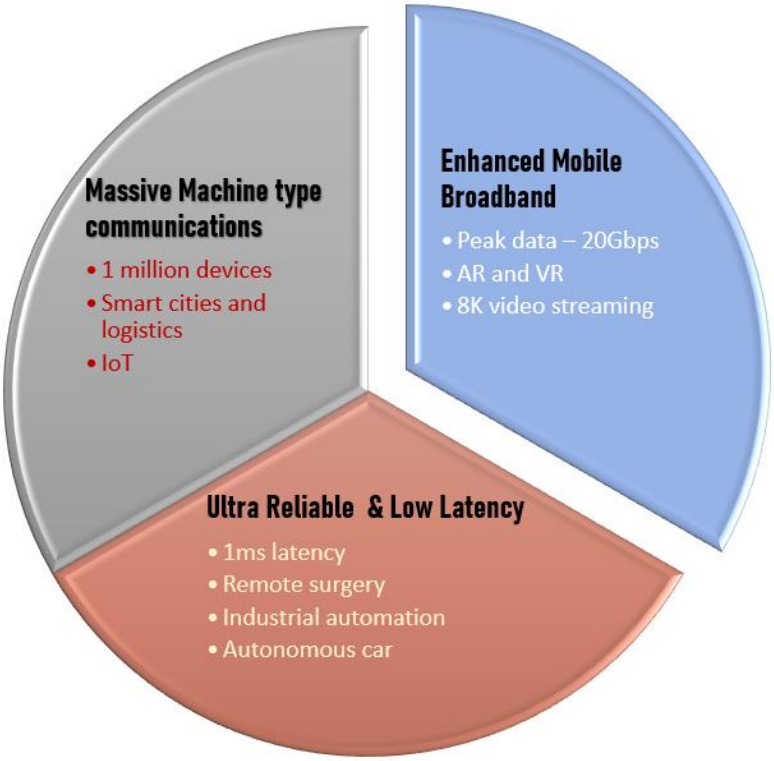


Figure 3. Focus areas of 5G networks.

First, we will investigate each application area and the real-time use cases associated with it, and then we will discuss the constraints of 5G.

OBJECTIVES:

This study is to investigate the effects that 5G will have on digital communication and information technology systems from a technical, operational, and social perspective. Some of the most important goals are:

1. We want to examine the social impact of 5G, including its effects on customers, producers, the digital landscape, and the digital divide.

2. To understand 5G, we must analyze its deployment problems and potential, including security, privacy, infrastructure, and global access.

MATERIAL AND METHOD

The influence of 5G technology on software development is investigated via the use of a qualitative and analytical research technique in this study. Various authoritative sources, such as research publications that have been subjected to peer review, white papers from the industry, technical studies, and standards issued by telecommunications agencies, were used to obtain secondary data. The analysis focuses on key characteristics of 5G, such as ultra-high speed, reduced latency, increased bandwidth, enhanced

connectivity through network slicing, and edge computing. It then compares these characteristics to those of previous generations (3G and 4G) in order to evaluate the implications that these characteristics have for software design, development, deployment, and performance. With a special focus on Internet of Things (IoT) applications, smart cities, healthcare, agriculture, and digital media platforms, the research assesses the impact that 5G will have on information technology (IT) infrastructure, cloud and edge computing environments, data centers, and digital communication systems. The identification of developing software development paradigms, such as real-time processing, cloud-native and edge-based architectures, and scalability needs, is accomplished via the use of a thematic content analysis technique. It offers a systematic framework for understanding how 5G reshapes software development techniques and enables next-generation digital applications by synthesizing insights across technology aspects and industrial use cases. This is accomplished via the creation of the methodology.

Key Features of 5G Technology:

- Faster Speeds: The download rates of 5G are 10 to 100 times faster than those of 4G, and it enables quicker data transfer, synchronized video streaming, and the delivery of material in real time.

- Reduced Latency: As a result of 5G's ability to cut latency, which is defined as the amount of time it takes for data to transit between devices, down to milliseconds, manufacturing applications and real-time communications, such as autonomous vehicles, are made possible.

- Increased Bandwidth: As a result of the much-increased bandwidth that 5G provides, millions of devices may be linked simultaneously without any issues, which is essential for the Internet of Things and Smart Cities.

- Enhanced Connectivity: This concept of 5G is brought to life by the capabilities of network slicing, which enables 5G to address and adapt to a wide range of applications that need different kinds of network experiences. Edge computing delivers data closer to the user, allowing it to be processed closer to the user, hence reducing the amount of time that the user has wait for the data to be processed.

Comparison with Previous Generations (4G, 3G):

- Speed: The download rates of 5G are predicted to be up to 100 times faster than those of 4G, and this will apply to both uploading and streaming. 5G is much faster than both 4G and 3G services.

- Latency: In comparison to 4G, which has a latency of tens of milliseconds, and 3G, which has a larger latency, 5G has a latency of milliseconds, making it appropriate for real-time applications.

- Data Capacity: With regard to the number of devices that can be linked concurrently without any relative loss in functionality, 5G has a carrying capacity that is much higher than that of 4G and 3G. This is significant primarily because of the ever-increasing usage of Internet of Things devices.

Impact of 5G on IT Infrastructure

- The performance of the network has been improved. Here, we will discuss the ways in which 5G networks may boost data speeds. When it comes to the capacity of information technology to fuel 5G networks via the use of cloud, virtualization, and edge solutions.

- The difficulties that information technology would face in deploying 5G. The typical amount of responsibility when it comes to the planning and administration of the network setup. A discussion of the fundamentals of cloud-native architectures and virtualization in relation to the support of 5G.

- The emergence of computing at the edge of networks. Real-time analysis is made possible by the new fifth generation, also known as 5G, which speeds up edge computing. Applications of edge computing in the industrial industry, the healthcare service industry, and the autonomous vehicle industry.

- These are some of the consequences that 5G will have on cloud services and data centers: The capability of 5G wireless networks to improve the cloud storage and computing power of data centers and other remote services is referred to as 5G. There is a need for more robust support structures in the field of information technology in order to effectively handle the substantial amounts of data that have been accumulated.

The 5 G's Effect on Digital Communication

Improved Mobile Communication: The fifth-generation (5G) technology brings about improvements in mobile communication by enabling high-speed internet with minimal buffering and latency performance. The end result is greater surfing features, quicker download speeds, and increased coverage in places with high operating density, which ultimately results in the mobile internet being more dependable and effective. In addition, 5G is capable of supporting enhanced mobile video, online gaming, and apps that make use of augmented reality and virtual reality. It implies greater speeds as well as a considerable reduction in latency, which enables the user to reach high quality when it comes to video streaming (4K, 8K), gaming that is smooth and quick, and even a better-quality augmented reality and virtual reality experience, which has an impact on entertainment and interactive media.

A Look at the Function of 5G in the Internet of Things (IoT): Because of its much higher capabilities compared to those of 4G, as well as its low latency, 5G is appropriate for connecting millions of Internets of Things devices. It is necessary for data to be processed in the appropriate way in order to improve the interaction between the devices, such as between sensors, wearables, and other smart technologies. This is because this improves the connection between devices, which in turn requires the processing of data.

In industries:

- **Smart Cities:** Intelligent urban infrastructure is powered by 5G, which will improve public safety, traffic management, and energy consumption while also optimizing energy use.

- **Agriculture:** It offers assistance for precision farming by allowing real-time monitoring of crops, animals, and environmental factors, which ultimately results in an increase in agricultural production.

- **Healthcare:** Remote monitoring, telemedicine, and real-time data analysis are some of the ways that 5G expands healthcare services. These advancements improve patient care while also lowering operating costs.

5G has an influence on remote communication in a manner that directs video conversations and the speed at which data are delivered when utilizing virtual tools. This results in improved distant work and collaboration. It is possible to offer real-time collaborative working across teams via the use of the application that is hosted in the cloud. This will help firms enhance their timeliness and make working from any location more effective.

Impact on Digital Media and Entertainment: It makes video streaming, gaming, and augmented reality and virtual reality more efficient and effective with astoundingly fast speeds and low latency. It delivers 4K and 8K streaming, gaming that is both efficient and immersive, and augmented reality and virtual reality applications that are both practical and of high quality. For example, it might make it possible for content producers to produce high-definition interactive material of a higher quality. Additionally, it could assist digital media corporations in increasing audience engagement and introducing new methods of monetization.

The Challenges of Implementing 5G Technology

Infrastructure and Network Deployment: The usage of 5G necessitates additional expenditures, such as the installation of new buildings or masts, cables, and fibers, and it is rather pricey for places that are either distant or have a low population density. Connecting to the existing 4G networks and providing facilities that are tailored to the requirements of customers are two of the challenges. Due to the fact that infrastructures need to be able to support 5G networks, there are additional obstacles that arise from regulatory considerations such as permission, spectrum availability, issues on the right of way by the cities, and health concerns.

Security and Privacy Concerns: Because of the improved connection, there is a significant level of vulnerability, which includes the possibility of data being breached and being attacked. When it comes to protecting the data and identities of users, high-level encryption becomes an important need. This is particularly true for telecommunications companies and governments, which should establish high-security standards.

Digital Divide and Accessibility: It implies quicker 5G rollout in urban areas and likely slower in rural parts because of cost difficulties and low maturity levels that less demand and need for greater speed of 5G. A further possibility is that the development of 5G would exacerbate the digital gap that exists between wealthy countries and underdeveloped countries. This is because of disparities in the financial ability to construct and maintain the network and devices.

Opportunities and Future Trends with 5G:

- **The Future of Autonomous Vehicles:** Therefore, 5G is a key feature that has the potential to maintain the development of autonomous vehicles. Real-time communication between automobiles, traffic infrastructures, and cloud services is made possible by 5G technology, which has low latency and fast data transfer speeds. This technology helps to enhance safety and route guidance. The achievement of these goals will contribute to the enhancement of road safety, the implementation of efficient transportation and distribution practices, and the general improvement of the sustainability of urban travel.

- **5G and Artificial Intelligence (AI):** The capabilities of artificial intelligence are enhanced by 5G because it provides a resource that is both high-speed and low-latency, which makes it possible to manipulate massive data volumes. Because of this, it is now feasible to carry out machine learning and analytics at a more rapid pace, as well as to arrive at the appropriate judgments at the appropriate moment. Additionally, artificial intelligence has the ability to enhance 5G networks, anticipate traffic spikes, and provide individualized service experiences.

- **Smart Cities and Smart Homes:** The primary purpose of 5G in smart cities is to improve the connection of devices that contribute to the efficient operation of urban settings by efficiently controlling traffic, managing trash, and reducing energy consumption. The capacity of equipment, such as thermostats, security systems, and appliances, to communicate with one another in real time and improve the ease of use and efficiency of operation is another way in which it enables the automation of smart homes.

- **Healthcare and Telemedicine Advancements:** Through the ability to do operations from a distance, perform continual patient checks, and provide certain telemedicine services that demand a large bandwidth of data with low latency, 5G has the potential to transform the healthcare industry. A more quick flow of information implies that practitioners in the field of medical science are able to readily access and evaluate such data, which allows them to diagnose and treat their patients more efficiently.

- **Physical Hardware:** As well as the Network Infrastructure. a discussion of the financial implications and the practicability of putting in place 5G networks all over the globe. The challenges that are brought about by city planning include the pressures that are involved with getting the necessary regulatory approvals, frequency bandwidth licensing, and permitting concerns.

There is a problem with security and privacy. Currently, there have been negative features linked with potential security risks, such as hacking and unauthorized access to private data in 5G networks. These dangers have been encountered in recent times. The criteria for encryption and the protection of cyberspace have been further increased.

It is important to consider both the digital divide and accessibility when it comes to information technology. What are some ways that the playing field for 5G networks may be leveled so that access to 5G networks in rural regions is made comparable to that in metropolitan areas? This is the manner in which 5G has the potential to significantly exacerbate existing technology disparities on a global scale.

The Economic and Social Impacts of 5G

- The expansion of the economy and the creation of new jobs. It is possible that 5G will be a driving force behind innovation and will result in the creation of new employment possibilities in the fields of technology, media, and healthcare. Increasing productivity across a variety of businesses via the use of 5G technology.

- Social Impacts and Consumer Behavior. How consumers' expectations about speed, connection, and access to services will be altered as a result of the introduction of 5G. The societal repercussions of broad deployment of 5G, ranging from the use of digital media to educational institutions.

CONCLUSION

Convenience, high speed, less latency, and greater connectivity were some of the potential benefits that 5G technology brought to the field of information technology and digital communication. Big data has made it possible to analyze data in real time; it has also improved communication, especially distant communication; it has led to the exponential expansion of the internet of things; and it has enabled technologies such as autonomous vehicles and smart cities. On the other hand, the adoption of 5G in a more broad manner presents a number of problems, including high infrastructure costs, regulatory constraints, security concerns, and the disparity in connection that exists between urban and rural regions. Only with the participation of governments, businesspeople, and suppliers of telecom services will it be possible to overcome these obstacles. On the other hand, the potential advantages are quite diverse, ranging from fostering innovation in a variety of sectors to providing new job opportunities and enhancing customer happiness. When it comes to defining the future of business-to-consumer communication, technology has played a significant role and has had an odd midterm impact ever since the introduction of 5G. The potential exists for it to redefine the very ways in which we engage with one another, communicate with one another, do business, and even live, all while ushering in a global society that is more connected, efficient, and digital. This is provided that the challenges that are given by their receptiveness are effectively controlled.

REFERENCES

1. ResearchGate, 2023. The Impact of 5G Technology on Communication Infrastructure. https://www.researchgate.net/publication/377858983_The_Impact_of_5G_Technology_on_Communication_Infrastructure?utm_source=chatgpt.com.

2. ResearchGate, 2023. Advancements in 5G Technology: Enhancing Connectivity and Performance in Communication Engineering.

3. https://www.researchgate.net/publication/381919739_Advancements_in_5G_Technology_Enhancing_Connectivity_and_Performance_in_Communication_Engineering?utm_source=chatgpt.com.

4. PubMed Central, 2022. The Evolving Roles and Impacts of 5G-Enabled Technologies in Healthcare. https://pmc.ncbi.nlm.nih.gov/articles/PMC9085442/?utm_source=chatgpt.com.

5. Frontiers in Business, 2023. The Transformative Impact of 5G Technology on Business Operations. https://frontiersrj.com/journals/ijfetr/sites/default/files/IJFETR-2024-0039.pdf?utm_source=chatgpt.com.

6. IEEE Future Networks, 2023. Charting an Integrated Future: IoT and 5G Research Papers. https://futurenetworks.ieee.org/topics/charting-an-integrated-future-iot-and-5g-research papers?utm_source=chatgpt.com.

7. PubMed Central, 2022. Leveraging 5G Network for Digital Innovation in Small and Medium Enterprises.https://pmc.ncbi.nlm.nih.gov/articles/PMC9135386/?utm_source=chatgpt.com

8. Journal of Economic Structures, 2024. Development of National Specialization in 5G Technologies within the European Union.

9. Catalan Economy (29 October 2019) '5 reasons why Barcelona is one of the world's leading smart cities', Catalonia Trade and Investment, accessed on 23 October 2021.

10. Craven, C (September 2020) 'What Is 5G Network Slicing?', SDxCentral Studios, accessed on 22 October 2021.

11. Eskelinen, T., Räsänen, T., Santti, U., Happonen, A., Kajanus, M. (2017). Designing a Business Model for Environmental Monitoring Services Using Fast MCDS Innovation Support Tools, Technology Innovation Management Review, Vol. 7, Iss. 11, pp. 36-46, doi: 10.22215/timreview/1119

12. EVSpecifications, 2020. GAC New Energy unveils the all-electric Aion V SUV in China [WWW Document]. EVSpecifications. URL https://www.evspecifications.com/en/news/929c2f8 (accessed 10.28.21).

13. Hartwig, M., 2021. Self-driving and cooperative cars. Bayrische Motoren Werke AG, Munich.

14. Intel (2021) 'Understanding the Advantages of 5G', Intel, accessed on 22 October 2021.

15. Jahkola, O, Happonen, A., Knutas, A., Ikonen, J. (2017), What should application developers understand about mobile phone position data, In CompSysTech'17, ACM, pp. 171-178, doi: 10.1145/3134302.3134346

16. Kavanagh, S (24 June 2021) '5G vs 4G: No Contest', 5G.co.uk, accessed on 25 October 2021.

17. Kivimäki, P. & Sormunen, E., 2021. Nopea 5G-mobiiliverkko jää osassa Suomea vain haaveeksi – tukiasemia ei saa rakentaa, koska ne häiritsevät venäläisten yhteyksiä [WWW Document]. Yle Uutiset. URL https://yle.fi/uutiset/3-11744186 (accessed 10.28.21).

18. Knieps, G. and Bauer, J.M. (2021) "Internet of things and the economics of 5G-based local industrial networks," Telecommunications Policy, p. 102261. doi:10.1016/j.telpol.2021.102261.

19. Kortelainen, H., Happonen, A., Hanski, J. (2019), From Asset Provider to Knowledge Company—Transformation in the Digital Era, In Lecture Notes in Mechanical Engineering, pp. 333-341, doi: 10.1007/978-3-319-95711-1_33

20. Liu, L., Guo, X. and Lee, C. (2021) "Promoting smart cities into the 5G era with multi-field Internet of Things (IoT) applications powered with advanced mechanical energy harvesters," Nano Energy. Elsevier Ltd. doi: 10.1016/j.nanoen.2021.106304.