

5G Cellular (Mobile) Communication Systems

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Introduction

5G is a dramatic improvement in wireless communication technology for consumers, allowing for significantly greater applications of digital communication while previous generations of this technology were focused on simple phone calls and small amounts of data. The benefits of 5G not only allow for coverage in significantly more areas but also increased bandwidth in areas that already had preexisting coverage. This increased bandwidth gives consumers the ability to do things previously impossible. [24]

Evolution of Cellular Networks

5G stands for fifth generation, while there have been many small incremental upgrades made between all of the previous generations. The core 5 generations each denote specific major changes in how telecommunication networks operate. Starting with 1G, consumers were given the ability to make analog phone calls wirelessly over long distances. Then, with the switch to 2G, we started to use digital communication and even started experimenting with text-based digital communication and small amounts of Internet data. 3G is where Internet data started to become more mainstream, and then 4G is where we switch to a completely IP-based system that uses the Internet and IP protocols for all aspects of telecommunications. [6] The jump from 4G to 5G was especially noteworthy because the amount of data that could be transferred increased dramatically, allowing for many new applications. With 3G, you were barely able to send an extremely low-quality picture, but with 4G, you could start streaming high-resolution content or play video games that are running on a server many miles away from you. 5G takes these experiments with high-bandwidth applications and really makes them widespread and practical.

Between the increased bandwidth available and lower latency caused by new technologies, the practical experiences that LTE and 4G started to enable were made usable and reliable. [4], [24] 5G also starts to solve one of the primary issues with 4G, which was communication in dense urban areas like large cities.

5G Frequency Bands

5G is unlike previous generations because it has three distinct bands. Low band 5G is very similar to LTE and the later versions of 4G. The actual radio frequency has a significant amount of overlap, and the amount of bandwidth and latency that the end consumer experiences is very similar, however, small improvements were able to be made through changes in the technology running the back end. This version of 5G has the lowest speeds but the highest ranges. [2], [3] Mid band 5G is where the bandwidth significantly increases. However, the frequency does not increase enough to have an unusable impact on range, so this version is seen as the most optimal. [3] With the high band 5G, or millimeter wave, frequency is dramatically increased, and bandwidth is increased dramatically as a result. However, the range of millimeter wave 5G is extremely low and only practically useful in something like a sports stadium or a dense street at the center of a city. [14], [23] Because of this lack of range and penetration of the signal, it is also extremely optimal for environments with high amounts of clients.

Electromagnetic Wave Propagation

5G relies on electromagnetic waves to carry information through the air. [11] A transmitter encodes data by modulating a carrier signal, varying its amplitude, frequency, or phase, and then radiates that modulated signal outward as a radio wave. [12] A receiver will demodulate it to recover the original information. The frequency of a wave and its wavelength are inversely proportional, so 5G wavelengths are only a few millimeters in length. Antenna lengths are half to quarter wavelength, allowing them to be extremely compact, making it practical to integrate large numbers of antennas into a single device or base station. [11][17]

Before a signal can be transmitted wirelessly, information must be encoded onto an electromagnetic carrier wave through a process called modulation. [12]. The major problem of high frequency is the attenuation that occurs when the signal passes through an obstacle [22]. Walls of buildings can cause 40-80 decibels of loss, while 4G loses 3-5. [14] Weather conditions cause scattering, which is where a signal is split up into multiple directions with each direction taking part of the power, making it hard to receive the signal. [14], [23] Multipath propagation occurs when a signal reaches the receiver through multiple paths, at different times, with different phases, which can cause interference at the receiver. [22], [23] Urban design is prone to both multipath and scattering. [15], [23] The millimeter wave experiences more path loss, which is when a signal weakens as it travels from the transmitter. [14], [15], [23]

In real environments, wireless signals do not usually travel in one perfect straight path. Reflection occurs when a signal hits a surface, such as a wall or building, and bounces off in another direction, and diffraction occurs when a signal bends around the edge of an object or obstacle, allowing some energy to reach areas that are not in direct line of sight. When planned for, these effects help the signal reach a receiver. [15], [22], [23]

5G Architecture

5G system architecture is primarily made up of three major parts: user equipment, the radio access network, and the core network. User equipment, such as phones or connected devices, communicates wirelessly with the radio access network through base stations. These base stations are connected through backhaul links to the 5G core network, which manages routing, mobility, authentication, and connections to external networks such as the Internet. This architecture allows 5G networks to support both mobile communication and high-speed data services. [1]



Figure 1: Showcases a simplified diagram of how user equipment connects to cellular towers and the core network. [1]

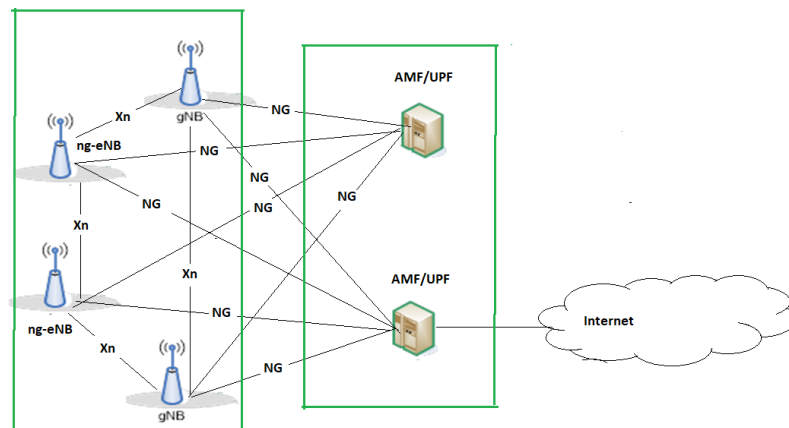


Figure 2: A more complex diagram that showcases how the new 5G network and the older LTE networks mesh together and interface with each other and user equipment. [16]

Antenna Arrays, Beamforming, and Massive MIMO

One of the most important electromagnetics-focused components of 5G is the use of antenna arrays. In older wireless systems, antennas often transmit signals more broadly, sending energy over a wide area. In 5G, especially at higher frequencies, systems can use many smaller antenna elements placed close together. By placing many antennas into a compact array, 5G systems can control how and where the signal is transmitted much more effectively. [11], [17]

These antenna arrays are important because they allow 5G networks to use beamforming. Beamforming is the process of directing signal energy toward a specific user or location instead of sending it equally in all directions. This is done by adjusting the phase and amplitude of the signals coming from each antenna element. When the signals combine, they can strengthen the signal in one

direction while reducing wasted energy in other directions. This helps improve the connection for the user and makes the network more efficient. Beamforming is especially useful for millimeter wave 5G because high frequency signals have shorter range and are more easily blocked. [18], [19]

Massive MIMO is another major technology used in 5G systems. MIMO stands for Multiple Input Multiple Output, which means that multiple antennas are used to transmit and receive signals at the same time. Massive MIMO expands this idea by using a much larger number of antenna elements. This allows the network to communicate with multiple users at once, rather than serving each user one at a time. It also improves capacity, reliability, and data rates. In crowded environments such as cities, stadiums, or campuses, Massive MIMO helps the network handle a large number of connected devices without the same level of slowdown that older networks would experience. [17], [18], [19]

Together, antenna arrays, beamforming, and Massive MIMO are some of the main reasons 5G can provide faster and more reliable service than previous generations. These technologies help compensate for some of the weaknesses of high frequency communication by focusing energy more efficiently and allowing the network to serve more users at the same time. Without these electromagnetic design improvements, the use of high frequency 5G would be much less practical. [19]

Small Cells and Network Deployment

Small cells are another important part of 5G network design because high frequency 5G signals do not travel as far as lower frequency signals. A small cell is a low-power base station that provides wireless coverage over a smaller area than a traditional cell tower. Instead of relying only on large towers that cover wide regions, 5G networks use many smaller access points placed closer to users. This is especially important in dense urban areas, where there are many users, many obstacles, and a high demand for fast data connections.

The main purpose of small cells is to improve coverage, capacity, and latency. Since millimeter wave signals have short range and are easily blocked, placing small cells every few hundred meters can

help keep users connected. Small cells bring the network closer to the user, which can reduce the distance the signal has to travel and improve the strength of the connection. They also increase capacity because more users can be served by nearby access points instead of all relying on one large tower. This is useful in places like cities, stadiums, shopping centers, and college campuses where many people may be using the network at the same time. [5], [21]

However, small cells also create deployment challenges. Since many more base stations are needed, the cost of building and maintaining the network increases. Each small cell needs a location, power, and a connection back to the larger network. This can be difficult in cities because of zoning rules, permits, construction costs, and concerns about how the equipment looks in public spaces. Because of this, small cells are necessary for making high performance 5G practical, but they also make the network more expensive and complicated to build.

Small cells solve one of the biggest problems created by high frequency 5G, which is the limited range of the signal. By placing smaller base stations closer to users, the network can keep a stronger connection even in crowded areas. This allows users to experience faster speeds and lower latency in places where a normal tower may not be enough. At the same time, this also shows that 5G is not just about using faster wireless signals, but also about placing more equipment in the right locations so the network can actually support those speeds.

Social, Economic, and Environmental Impacts

Providing people with a network that covers almost every single area on the planet with high-bandwidth Internet connectivity has massive and dramatic social, economic, and environmental impacts. Socially, users have increased access to digital services and increased connectivity with others which will especially help immobile people. This increased connectivity can also support things like smart cities, telemedicine, and more connected transportation options. [9], [24]

Economically 5G provides new avenues for potential business opportunities. Utilizing this increased connectivity, it is possible now more than ever to provide end users with vast amounts of information and communication. One large area we're currently seeing this in is with AI and how users can receive vast amounts of information at a rate far quicker than before. While text-based AI alone does not require a lot of bandwidth to the end user, the low latency can impact the experience of something like voice communication dramatically. Users using 5G Internet for their home Internet have also become very popular, which allows for people to have high speed internet where the alternatives were much worse. [9], [24]

There are, however, environmental concerns. Increasing the bandwidth available to every end user requires a lot more equipment and power. There are also concerns that such excessive bandwidth will cause inefficient use of it. [10]

Also, 5G primarily focuses is on increasing bandwidth to the end consumer but makes little to no improvement in the range that cellular towers have for the low band. With the mid and high band types of 5G, there are concerns regarding signal blockage due to the lower ability for the signal to penetrate objects like the natural environment. Overall, range seems to be getting worse or stays the same, but there is little focus on improving it. 6G is currently expected to release around 2030 and is focused on faster speeds specifically focused at better upload performance and even lower latency. [25]

Future Recommendations

Some recommendations that we would have going forward are specifically regarding the low band range of 5G to ensure that reasonable connections are accessible in more rural areas. [2], [3], [5], [21] The energy efficiency of 5G is also something not much talked about, and we would like to see specific focus made to not only increase the bandwidth but also to try to use the same data speeds but in a more efficient way. [10]

Conclusion

Overall, 5G represents a major step forward in cellular communication because it greatly improves the speed, capacity, and latency of wireless networks compared to previous generations. These improvements are made possible through the use of higher-frequency spectrum, modern core network architecture, phased antenna arrays, beamforming, Massive MIMO, and small cell deployment. Together, these technologies allow 5G networks to support more users, faster data transmission, and new applications such as smart cities, telemedicine, remote work, and connected transportation. However, the same features that make 5G powerful also create practical challenges, especially with signal blockage, limited millimeter wave range, infrastructure cost, and energy consumption concerns. Because of this, the long-term success of 5G depends not only on improving performance, but also on solving the coverage, environmental, and economic issues that come with building a more complex wireless network. While 5G is not a perfect solution, it is an important foundation for the future of mobile communication and for the development of even more advanced systems such as 6G.

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