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Next Generation Mobile Wireless Networks: 5G Cellular Infrastructure

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Mobile Networks; 5G Wireless; Internet of Things; Millimeter Waves; Beamforming; Small Cells; Wi-Fi 6

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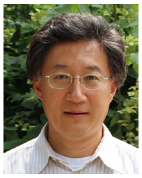
Next Generation Mobile Wireless Networks: 5G Cellular Infrastructure



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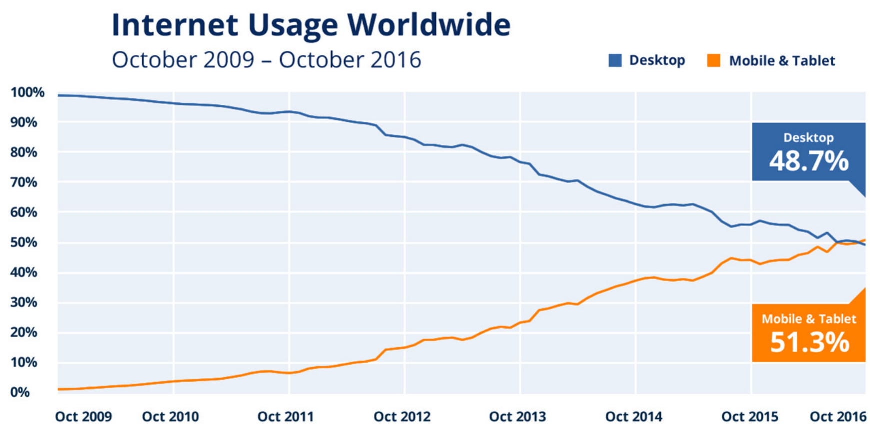
ABSTRACT

The requirement for wireless network speed and capacity is growing dramatically. A significant amount of data will be mobile and transmitted among phones and Internet of things (IoT) devices. The current 4G wireless technology provides reasonably high data rates and video streaming capabilities. However, the incremental improvements on current 4G networks will not satisfy the ever-growing demands of users and applications. The next generation of mobile telecommunication standards, 5G, promises not only ten-times the available spectrum, ten-times the download speed, but also ten-times the number of devices with a fraction of the latency. Several 5G networks have already been built for testing and early deployment. In this paper, the evolution of mobile networks from 1G to 4G is reviewed. 5G wireless and its key features are discussed. Examples of 5G applications include enhanced mobile broadband, robotic surgery, smart cars, virtual reality/augmented reality, and Internet of Things (IoT). Beamforming and small cells are the pivotal technologies that allow 5G to be implemented. Beamforming reduces signal propagation loss with antennas continuously tracking signals spatially and steering the beams in a certain direction. This along with small cells which are low-power, short-range wireless transmission systems in a geographical region, are set to catapult 5G into the 6-300GHz spectrum. We also compare 5G to Wi-Fi 6 and analyze the opportunities that new wireless technologies bring to our engineering and technology students.

INTRODUCTION

The International Data Corporation (IDC) projects that by 2025 the global datasphere will grow to 175 zettabytes, i.e., 175 trillion gigabytes (David Reinsel, 2018). A significant amount of the data will be mobile and transmitted among phones and Internet of things (IoT) devices. Mobile phones and tablets have already become the primary devices to access the Internet. In 2016, StatCounter Global Stats found that mobile and tablet devices accounted for 51.3% of Internet usage worldwide (StatCounter, 2016) (Figure 1). New American Community Survey questions revised in 2016 show a stunning increase in the reported mobile broadband usage – mobile broadband was accessed in 68 percent of households (BAUMAN, 2018).

Figure 1. Internet usage worldwide from October 2009 to October 2016 (StatCounter, 2016).



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In addition, over the next decade, billions of IoT devices will be going online. Emerging applications such as Virtual Reality/Augmented Reality (VR/AR), self-driving vehicles, live HD video streaming, and remote mobile health care require very fast and low-latency Internet access. Cisco's annual Visual Network Index (VNI) has made it clear that relying on incremental improvements on current 4G networks will not satisfy the ever-increasing demands for more speed and capacity (Cisco VNI, 2019).

The next generation of mobile telecommunication standards, 5G, promises not only ten-times the available spectrum, ten-times the download speed, but also ten-times the number of devices with a fraction of the latency (Dietz, 2017). Moreover, 5G networks are expected to have high flexibility and intelligence, advanced spectrum management schemes, and improved efficiency with lower cost. 5G will be able to support billions of IoT devices from different sources, allocate bandwidth dynamically based on user demands, integrate previous and current cellular and Wi-Fi standards, and offer broadband communication and low delay for real-time applications (Arjmandi, 2016).

Since the 1980s the telecommunication industry has been experiencing a new generation of mobile networks approximately every 10 years. At this pace, the expected deployment for 5G should get underway by 2020. Indeed, the growth of demands and the advance of technologies indicate that we are ready for this new generation of mobile networks. Several 5G networks have been built for testing and early deployment. Leading the race in deploying 5G is South Korea, the first country to launch 5G networks. SK Telecom activated 5G services on April 3, 2019 (McCurry, 2019).

This paper is organized as follows. Section II reviews the evolution of mobile networks from 1G to 4G. Section III introduces the objectives and applications of 5G mobile networks. Section IV explains the key technologies for 5G including millimeter waves, massive Multiple Input Multiple Output (MIMO), beamforming, and small cells. Section V gives a comparison of 5G and Wi-Fi 6, two parallel wireless technologies that may confuse users. Section VI discusses the need of wireless networking education including 5G and Wi-Fi 6 for technology students. Section VII presents our conclusions.

THE EVOLUTION OF MOBILE NETWORKS

Before delving into the details of 5G technologies, this section reviews how mobile networks have evolved over the past a few decades. Starting with 1980s, mobile technologies have gone through four generations, 1G to 4G. Each generation brought a significant milestone in the development of mobile communications.

First Generation Mobile Networks (1G)

1G was an analog communication system that provided voice services. It established the foundation of mobile communication. In 1G, certain radio bands were licensed for exclusive use by mobile networks. For example, Advanced Mobile Phone System (AMPS) mostly used the 800MHz band (FCC, 2017). Operators deployed base stations to provide service for mobile subscribers. Neighboring cells operated on different frequencies to avoid interference. Through geographical separation, frequencies were reused without interference (Figure 2). Mobile networks were integrated into Public Switched Telephone Network (PSTN) or landline networks to provide integrated access (Qualcomm, 2014).

Figure 2. Frequency reuse through geographical separation (Qualcomm, 2014).

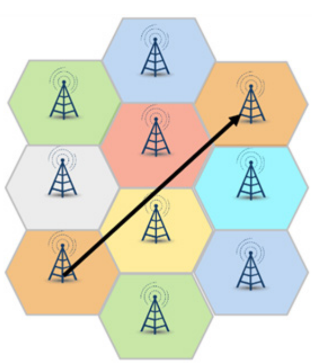

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Figure 3. Motorola DynaTAC 8000x (Wikipedia, 2019).

Second Generation Mobile Networks (2G)

The 1990s saw the emergence of 2G mobile phone systems. The most popular 2G wireless technology was the Global Systems for Mobile communications (GSM) standard. Compared to 1G, the main difference of 2G phone systems is the use of digital transmission instead of analog. 2G provided data rates of up to 64kbps. It allowed increased voice capacity and enhanced calling features such as caller ID.

In addition to vast improvement in security and reliability, 2G introduced a new variant of communication – Short Message Service (SMS) text messaging. Soon SMS became the preferred communication method for young people and continues to be so even today, with texting being the preferred way of communication for Americans younger than 50 (Newport, 2014). The usage of 2G mobile phones grew exponentially and opened the era of mass mobile communication (Linge, 2019). Figure 4 shows a revolutionary 2G cell phone, Nokia 2110 (Nokia 2110 & 2110i). It was released in 1993 and cost $850.

Figure 4. Nokia 2110 (Wikipedia, 2019).

Third Generation Mobile Networks (3G)

Instead of using circuit switching for data transmission in 2G, 3G used packet switching (Chinavasion, 2008), allowing for messages to be broken up and sent independently over optimal routes and reassembled at the destination. In the mid of 2000s, an evolution of 3G technology called High-Speed Downlink Packet Access (HSDPA), which is in the High-Speed Packet Access family (HSPA), begun to be developed and implemented. It allowed networks based on Universal Mobile Telecommunications System (UMTS) to have higher data transfer speeds and capacity (Mudit Ratana Bhalla, 2010).

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3G was optimized for mobile broadband services and enabled faster and better connectivity. With the high speed of 3G technology, up to 7.2 Mbps downloads and 2 Mbps uploads, media streaming of audio and even video content to 3G handsets became possible for the first time. Figure 5 shows one of the most popular 3G cellular phones, Moto RAZR V3, which was launched in 2004 and cost $600.

Figure 5. Moto RAZR V3 (Kravitz, 2006).

Fourth Generation Mobile Networks (4G)

4G is the current standard for high-speed wireless mobile communication. It delivers more capacity for faster and better mobile broadband experiences and expands to new frontiers. Benefits of 4G include improved mobility, dependable security, reduced latency, and improved experience for all users. 4G is also capable of supporting cloud-based applications such as live streaming, online gaming, and high-performance imaging (Mountstephens, 2017).

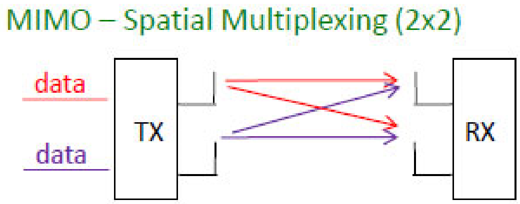
In 2009, the International Telecommunications Union-Radio communications sector (ITU-R) specified a set of requirements for 4G standards. The peak speed requirements for 4G service were set at 100 megabits per second (Mbit/s) for high mobility applications such as in automobiles and 1 gigabit per second (Gbit/s) for low mobility applications such as pedestrians (ITU, 2008).

Long Term Evolution (LTE) is a 4G wireless broadband technology developed by the 3rd Generation Partnership Project (3GPP) as the next step in the implementation of mobile Internet. 4G LTE consists of two layers. First, IP connectivity layer handles data, voice, video, and messaging traffic. Second, Evolved Packet System (EPS) layer handles the overall communication procedure.

LTE is based on Orthogonal Frequency Division Multiple Access (OFDMA) (Nohrborg, 2013). High data rates are achieved through higher order modulation (up to 64QAM, Quadrature Amplitude Modulation), large bandwidths (up to 20MHz), MIMO or spatial multiplexing on the downlink (up to 4x4) (Wannstrom, LTE-Advanced, 2013), and carrier aggregation.

Figure 6 gives a 2x2 MIMO (spatial multiplexing) illustration. Two different data streams are transmitted on two TX (Transmit) antennas and received by two RX (Receive) antennas, at the same frequency and time, separated by different reference signals (Wannstrom, LTE-Advanced, 2013).

Figure 6. 2x2 MIMO Illustration (Wannstrom, LTE-Advanced, 2013).



LTE-Advanced is provided through the aggregation of R8/R9 carriers. A carrier is a frequency block or channel. R8 means Release 8, which is the introduction of LTE and was frozen in Dec 2008. R9 means Release 9, which is an enhancement to LTE and was frozen in Dec 2009. Each aggregated carrier is referred to as a component carrier. The component carrier can have a bandwidth of 1.4, 3, 5, 10, 15, or 20 MHz. A maximum of five component carriers, i.e. 100MHz total bandwidth, can be aggregated (Wannstrom, LTE-Advanced, 2013).

Figure 7 shows one of the bests-selling 4G iPhone models of all time, iPhone 6+ (Segal, 2019). iPhone 6+ was released in 2014 and cost $750.

Figure 7. Apple iPhone 6 Plus (Gadgets360, 2019)

Table 1 shows a comparison of mobile technologies from 1G to 5G (Reshma S. Sapakal, 2013; Huawei 5G Overview, 2015). 5G will be explained in detail in the following sections but is also included here for comparison.

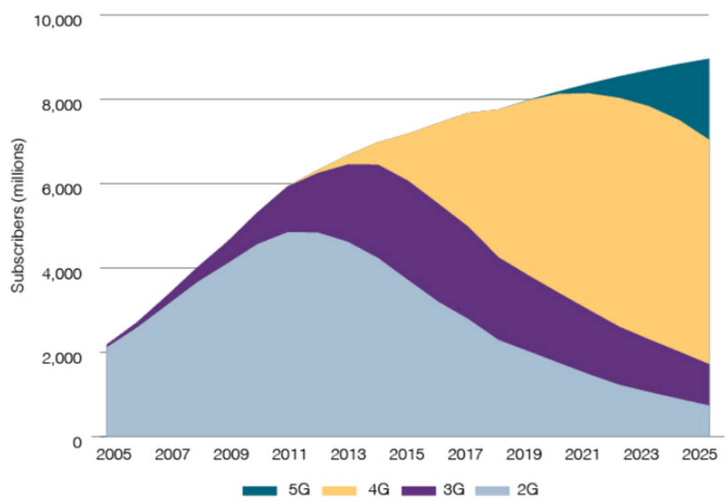
Table 1. Comparison of all generations of mobile technologies

Generation	1G	2G	3G	4G	5G
Start	1980s	1990s	2000s	2010s	2020s
Data Bandwidth	2kbps	64kbps	2Mbps	< 1 Gbps	> 1Gbps
Technology	AMPS, TACS	GSM, CDMA	WCDMA, CDMA2000, TD-SCDMA	LTE, WiMax	mmWave, Beamforming, Small Cell
Service	Analog voice	Digital voice, SMS	Mobile Broadband (MBB)	Better and faster MBB	Connected world
Multiplexing	FDMA	TDMA, CDMA	CDMA	CDMA	CDMA
Switching	Circuit	Circuit, Packet	Packet	Packet	Packet

2G services reached their peak at 4.9 billion users in 2011 and have been declining steadily since then. 2G accounts for around 30% of subscribers now and will fall below 10% by 2025. Meanwhile, 3G services topped at 2.4 billion users in 2016 and fell under 2 billion at the beginning of 2019, which was roughly 25% of the overall mobile market. By 2025, 3G is expected to shrink to about 11% of the global total (Bell, 2019) (Figure 8).

On the other hand, 4G technology continues its growth. At the end of 2018, 4G passed 3.5 billion users and 45% of the market. The forecast indicates that 4G subscriptions will flatten out at around 5.5 billion by the end of 2023. From 2024, 4G will decline and 5G take-up will accelerate. By the end of 2025, 5G is expected to have 1.93 billion users and account for 21.5% of the overall mobile market (Bell, 2019) (Figure 8).

Figure 8. Wireless Subscribers by Technology 2005-2025 (Bell, 2019)



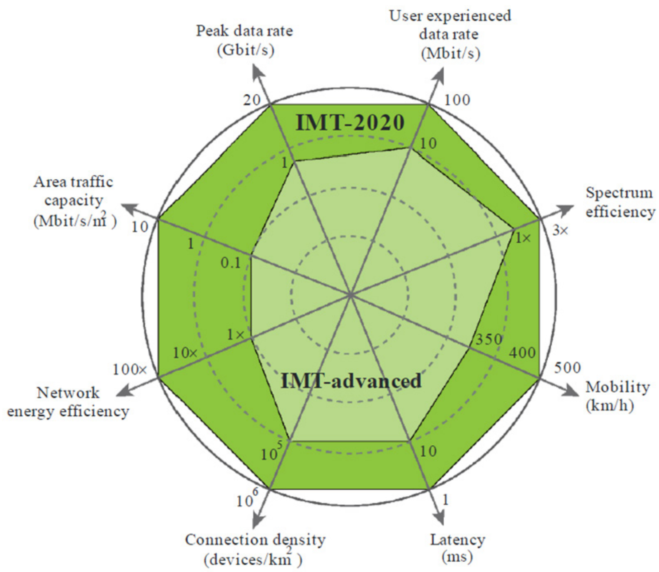
5G Mobile Networks: Objectives and Applications

5G is the fifth generation of cellular network technology. The industry association 3GPP defines systems that use "5G NR" (5G New Radio) software as "5G". This definition came into general use by late 2018. Some people and organizations may reserve the term 5G for systems that meet the requirements of the International Telecommunication Union (ITU) IMT-2020 (International Mobile Telecommunications) standard. 3GPP will submit their 5G NR to ITU.

5G Objectives

The IMT-2020 is the requirements issued by the ITU Radio communication sector (ITU-R) in 2015 for 5G networks, devices, and services. The eight parameters shown in Figure 9 are the key capabilities for IMT-2020 5G (ITU, 2015).

Figure 9. Framework and overall objectives of the future development of IMT for 2020 and beyond (ITU, 2015).



1. Peak data rate: It is expected to reach 10 Gbit/s for enhanced Mobile Broadband (eMBB). Under certain conditions and scenarios, IMT-2020 can support up to 20 Gbit/s.
2. User experienced data rate: For wide area coverage cases such as in urban and sub-urban areas, 100 Mbit/s is expected. In hotspot cases, higher values (e.g. 1 Gbit/s indoor) are expected.
3. Spectrum efficiency: It is expected to be three times higher compared to IMT-Advanced (marketed as 4G or sometimes as 4.5G) for enhanced mobile broadband (ITU, 2008).
4. Traffic capacity: For example, 10 Mbit/s/m2 in hot spots can be reached.
5. Energy consumption for the Radio Access Network (RAN): It should be no greater than networks deployed today. The energy efficiency should therefore be improved by a factor at least as great as traffic capacity increase.
6. Latency: 1 ms over-the-air latency, capable of supporting real-time services with very low latency requirements.
7. Mobility: It can handle high mobility up to 500 km/h with acceptable QoS (Quality of Service). This is envisioned particularly in high speed trains.
8. Connection density: It is expected to reach up to 106/km2, in scenarios such as massive machine type communications, where one or more entities do not need human interaction.

5G Applications

5G is not only an upgrade of the previous generation of mobile networks, it is also a revolutionary technology that will create unprecedented uses, where high speed communication, low latency, and massive connectivity are required. 5G has the potential to generate fundamentally new applications, industries, and business models. The quality of life around the world could be significantly improved (Baby, 2018).

The download speed of 5G can reach 10-20 Gbps, which is comparable to a fiber optic Internet connection. Downloads through mobile wireless will be dramatically faster. Users are expected to have always on, connected, and responsive mobile broadband Internet experience. 5G networks will enable fast and secure access to cloud storage and enterprise applications that handle complicated tasks.

The entertainment industry will greatly benefit from 5G technologies. High speed streaming of 4K videos with crystal clear audio quality may only take a few seconds. Live events can be streamed via wireless networks in high definition. HD TV channels can easily be accessed on mobile devices. 5G network can support unprecedented virtual experience of Augmented Reality (AR) and Virtual Reality (VR), which require high definition video transmitted with low latency.

The IoT is another broad area that requires supercharged 5G networks. In IoT, numerous objects such as smart appliances and sensors connect to the Internet. 5G is important in IoT innovation due to its capacity, spectrum availability, and low-cost deployment. IoT can benefit from 5G networks in many applications:

- Healthcare and mission critical applications: smart medical devices, Internet of medical things, smart analytics, and high definition medical imaging.
- Smart cities: smart power grid, smart street lighting, energy management, water resource management, traffic management, crowd management, and emergency response.
- Autonomous driving: smart traffic signs, communications about surrounding objects and other vehicles on road, and collision avoidance in which high-performance and low-latency wireless network is critical.
- Security and surveillance: facility security, traffic monitoring, public safety, and emergency response.
- Smart home: smart appliances configured and accessed from remote locations and closed circuit cameras providing high quality real-time video for remote users.
- Logistics and shipping: fleet management, database management, staff scheduling, and real-time delivery tracking and reporting.

Key Technologies for 5G

In information theory, the Shannon-Hartley theorem (Shannon, 1949; Herbert Taub, 1986) describes the maximum rate at which information can be transmitted over a radio communication channel (Figure 10).

Figure 10. The Capacity of a Radio Channel (Qualcomm, 2014).

Shannon's Law

$$\underbrace{C}_{\text{Capacity}} \approx \underbrace{W}_{\text{Spectrum}} \cdot \underbrace{n}_{\text{Antennas}} \cdot \log_2(1 + \underbrace{SNR}_{\text{Signal Quality}})$$

Higher transmission speed can be achieved by using more spectrum (W), more antennas (n), and less interference (SNR).

- More Spectrum (W): The radio channel on spectrum is analogous to the highway built on land. As global demand for spectrum intensifies, regulatory strategies such as Licensed Shared Access (LSA) and Authorized Shared Access (ASA) are attracting considerable interest and investigation (GSMA, 2013). LSA and ASA allow spectrum that has been licensed for International Mobile Telecommunications (IMT) to be used by more than one entity. When the primary licensee is not using its designated frequencies, other operators can access complementary spectrum for mobile broadband (e.g., 2.3GHz band in Europe or 3.5GHz band in the United States). More channels can be aggregated to have up to 100MHz for higher data rates.
- More Antennas (n): More antennas mean more spatially separated paths, analogous to building highway overpasses. Advanced multiple antenna techniques can create spatially separated data paths. For example, 4x4 Multiple Input Multiple Output (MIMO) will achieve significant performance gains. 4×4 MIMO means that with the same resource blocks on the air interface, the base station transmits 4 different signals via 4 transmit antennas to one user equipment (UE). To receive the signals and benefit the most, the UE must be equipped with 4 antennas as well.

- Interference Mitigation (SNR): The quality of radio signal can be improved by mitigating interference with advanced receivers and antenna techniques. Heterogeneous Network (HetNet) is an effective approach to enhance network capacity (Wannstrom & Mallinson, Heterogeneous Networks in LTE, 2014). A HetNet consists of regular macro cells transmitting at high power level, overlaid with low-power small cells such as Pico cell, Femto cell, and Remote Radio Head (RRH). However, this overlaying of macro cell and small cells results Inter-Cell Interference (ICI). To mitigate the ICI in HetNets, different types of ICI coordination techniques are available based on Time-Division Multiplexing (TDM) or Frequency-Division Multiplexing (FDM) resource allocations and controlling of transmission power (Ali, 2015).

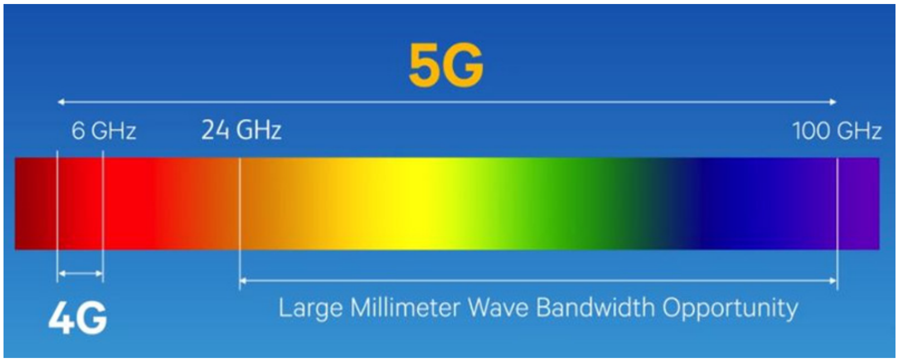
5G mainly relies on these technologies to implement performance breakthroughs: millimeter waves, massive MIMO, beamforming, and small cells. Each technology will be explained in the next subsections.

Millimeter Waves

The first and probably the most important technology is the use of millimeter waves (mmWave). mmWave and 5G are almost synonymously used. The key difference is that mmWave technology is only one part of what future 5G networks will use. From the beginning of mobile networks back in the 1980s, all devices have been operating in the frequency spectrum between 3kHz and 6GHz. With the emergence of the Internet of Things, smartwatches, virtual reality, augmented reality, self-driving cars, and many other technologies that require fast wireless connection, the traditional frequency bands are becoming increasingly congested. The number of connected devices is expected to grow exponentially to over 50 billion by 2020 (Cisco, 2016). Obviously, these devices cannot all operate within the currently established frequency spectrum.

Millimeter waves open the frequency spectrum from 6GHz to 300GHz, which allows for much more bandwidth real estate (Figure 11). One characteristic of millimeter waves is that higher frequencies are more easily absorbed by atmosphere and more easily scattered and absorbed by weather (e.g., rain and cloud) and by buildings. Therefore, they require nearly line-of-sight communication (Triggs, 2019).

Figure 11. 4G and 5G bandwidth comparison (Triggs, 2019).



Massive MIMO

The second important technology for 5G networks is massive MIMO. Currently MIMO technology is used in a smaller form with base stations that have 8 to 12 antennas to handle the traffic they transmit and receive. Massive MIMO expands this idea with the ability to equip hundreds of antennas per base station. As one example, Ericsson started to ship 64 antenna array systems, AIR 6468, in 2017 (Ericsson, 2018) as shown in Figure 12. Companies such as Huawei and ZTE have successfully demonstrated the use of 96 to 128 array systems. The number of antennas per base station will continue to increase with the advances in research and development.

Figure 12. Ericsson first 5G NR radio AIR 6468 (Ericsson, 2018).

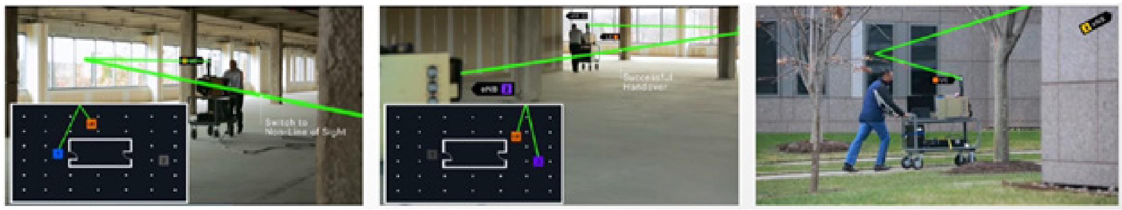
In 2020, it is expected that an average consumer will own at least 6 to 8 connected devices and will bring 3 of these wherever they go (Cisco, 2019). If we multiply these numbers with the population density of cities, we will see that massive MIMO is essential in providing connectivity for these devices. With good design and deployment, massive MIMO will be able to connect over 1 million devices per square kilometer. This capacity is enough to provide quality connection in tightly packed areas such as stadiums and city hubs, where current 4G systems often struggle and even fail. Due to the tight packing of the antennas, the main problem with massive MIMO is the interference that all the intersecting radio waves will create. The next two technologies will solve the issues that arise due to the use of millimeter waves and massive MIMO.

Beamforming

Beamforming is one of the essential data transmission technologies required for massive MIMO. It also reduces signal propagation loss for high-frequency millimeter waves. Beamforming works like a crossing guard by transmitting signals directly to the point of use. Signals are spatially tracked and are sent exactly where and when they are needed to reach their target device. Beamforming works dynamically, like a spotlight on the stage tracking a performer. As the performer moves around, the spotlight follows the performer. Based on the arrival angle of the energy, and based on reflection in the environment, beamforming algorithms select the best communication path between User Equipment (UE) and base station. Beamforming can even be aware enough of the environment and can bounce signals off obstacles to reach the target location.

In May 2018, Qualcomm demonstrated 5G mmWave beamforming and scanning in indoor and outdoor mobility scenarios (Qualcomm, 2018). Figure 13 (A) shows non-line-of-sight (NLOS) coverage through reflection. Figure 13 (B) shows indoor mobility and eNB handover. eNB means E-UTRAN Node B or Evolved Node B, the hardware that directly and wirelessly communicates with mobile user equipment (Artiza Networks, 2019). Figure 13 (C) demonstrates outdoor mobility.

Figure 13. Qualcomm 5G mmWave beamforming demonstration (Qualcomm, 2018).



(A) (B) (C)

Beamforming can already be found in some new Wi-Fi routers, where Wi-Fi signal is focused to improve strength and range (Dietz, 2017). Currently Netgear Nighthawk X6 AC3200 and Asus AC1900 RT-AC68CU are two of the best routers that support beamforming (Beren, 2019).

Similar to massive MIMO that adds more antennas to base stations, more antennas can be added to user devices as well, ranging from 4 to 16 or more. More antennas allow for more precise spatial tracking and better beamforming performance. More antennas also allow a device to connect to the best station in its vicinity to establish a line of sight communication. Beamforming sets the right amplitude and phase for each of the antennas. Collectively the antennas steer the beam in a certain direction.

Small Cells

Small cells are low-power and short-range wireless transmission systems that cover small geographical areas or indoor applications. Small cells are established by base stations and thus still have the fundamental characteristics of a traditional base station. Small cells deliver high-speed mobile broadband efficiently and play a significant role in LTE advanced and 5G networks (Rajiv, 2018). Based on the coverage area and number of users it can support, small cells can be divided into three types: metrocell, picocell, and femtocell. The performance measures of each category are summarized in the following table.

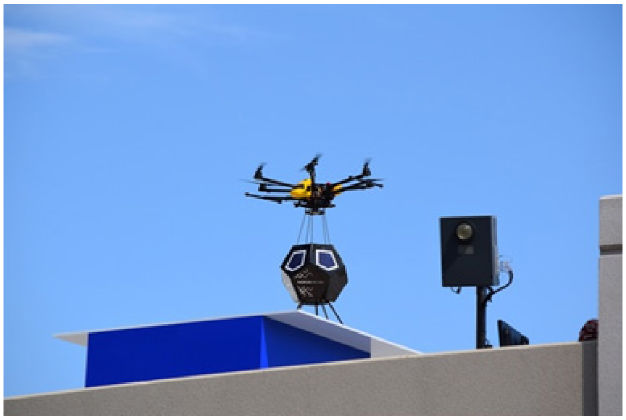
Table 2. Metrocell, picocell, and femtocell performance measures.

Type	**Power** (watts)	**Coverage Radius** (meters)	**Capacity** (users)	**Application**
Metrocell	2 to 5	500 to 2500	up to 200	Outdoor
Picocell	0.25 to 1	100 to 250	32 to 64	Indoor
Femtocell	0.1	10 to 50	8 to 16	Indoor

Small cells aren't a new technology, but they have greater use in the evolution of mobile networks. In 5G, small cells will be the key in reducing propagation loss of mmWaves and in routing beamforming signals. This technology ensures consistent high speed and low latency coverage in the network.

As an example of how important and powerful small cells can be, Nokia demonstrated small cell delivery concept in 2016 (Lawson, 2016). Based on network capacity and coverage need in an area, autonomous drones can deploy solar powered small cells (Nokia calls F-Cell) wherever they are needed (Figure 14). The F-Cells can connect to base stations and provide high-speed wireless coverage.

Figure 14. Nokia F-Cell deployed by drones (Lawson, 2016).



A Comparison to Wi-Fi 6

The wireless technology terms 5G and Wi-Fi 6 can be easily confused. The use of Wi-Fi 6 may even subtly suggest that it is one step better than 5G. These related but different wireless technologies often co-exist on mobile devices. Whereas 5G refers to cellular wireless technology, Wi-Fi 6 is simply the latest generation of Wireless Local Area Network (WLAN) technology. It uses the 5GHz Wi-Fi spectrum as one of the primary frequency ranges with separate bands in the 5.150 to 5.825 GHz spectrum. The other frequency range Wi-Fi 6 currently uses in the 2.4GHz frequency band, specifically the 2.400 to 2.4835 GHz spectrum.

In October 2018, the Wi-Fi Alliance introduced Wi-Fi 6 – based on the IEEE 802.11ax standard – as the next generation of Wi-Fi networks, including WLANs and products. The naming approach adopted makes it easy for users to understand the specific Wi-Fi technology supported by their devices, and the wireless connection the device establishes with a WLAN. Significant advancements in Wi-Fi technologies are arranged in a numerical sequence, starting with Wi-Fi 4 and currently through Wi-Fi 6. Hence it is now in its 6th generation offering faster link speeds, increased reliability, higher efficiencies, and better overall Wi-Fi connection experiences (Burke, 2018).

Wi-Fi communication requires all devices to use a shared Wi-Fi version, which in turn specifies the radio frequencies, bandwidth, speed, and other associated factors such as security. The Wi-Fi Alliance has rebranded the IEEE 802.11n standard as Wi-Fi 4, offering up to 600 Mbps over the 2.4GHz and 5GHz bands. Wi-Fi 5, corresponding to IEEE 802.11ac, operates in 5GHz frequency and supports data rates up to 3.46Gbps.

Wi-Fi 6 introduced and updated multiple communication technologies, including Orthogonal Frequency Division Multiple Access (OFDMA), Multi-User Multi-Input/Multi-Output (MU-MIMO), the opening of 6GHz spectrum, and so on (Vigliarolo, 2020).

Wi-Fi 6 uses OFDMA (Kerravala, 2019), an improvement over Orthogonal Frequency Division Multiplexing (OFDM). The main difference between OFDM and OFDMA relates to the handling of multiple connected devices. OFDM transmits data to a single recipient at a time. When users wait their turn for sending data, they may experience a longer delay. On the other hand, OFDMA splits traffic into smaller packets to eliminate queuing and transmit data to multiple devices simultaneously.

Wi-Fi 6 improves the capabilities of MU-MIMO (Weinberg, 2018). MU-MIMO was previously available only for downstream connections and allowed one device to send data to multiple receivers at the same time. Wi-Fi 6 extends MU-MIMO capabilities to upstream connections, allowing multiple devices to transmit data in a network simultaneously.

In April 2020, the Federal Communications Commission (FCC) has unanimously agreed to open all 1,200MHz on the 6GHz band for unlicensed use (FCC, 2020). The new spectrum can accommodate up to seven 160MHz channels (or fourteen 80MHz channels), which addresses the problem of Wi-Fi running out of bandwidth in the future. The 6GHz spectrum is ideal for high speed and short distance communications needed by future Wi-Fi devices.

Both 5G and Wi-Fi 6 promise dramatically better communications for consumers, mobile operators, and organizations. They both offer gigabit speeds and low latency. They will co-exist, offer complimentary functionalities, and work better together to support different use cases. Thanks to its long-range, 5G will be ideal for outdoor mobile connections such as smartphones. It enables wireless access for connected cars, drones, smart city deployments, and large manufacturing operations. Due to Wi-Fi's low cost to deploy, maintain, and scale, it will continue to be the primary access choice for indoor home and business environments. Wi-Fi 6 provides excellent support for data-hungry devices such as PCs, tablets, smartphones, streaming devices, and TV sets.

The network management is different in the two technologies (intel, 2020). 5G uses dedicated and licensed spectrums, and the networks typically are managed by operators and require a subscription fee to access. As with LTE, 5G performance will depend on how close a user is to the base station (how many "bars" on our phone) and how many other people are using the network.

In comparison, Wi-Fi uses unlicensed spectrum, which means every user in a neighborhood can have a Wi-Fi network. If many neighbors are using Wi-Fi simultaneously and on the same channel, the Co-Channel Interference (CCI) will impact network performance. In enterprise office environments, Wi-Fi access points usually are managed to form an optimal channel reuse pattern and reduce the CCI.

The technologies for cellular and Wi-Fi wireless networking continue to evolve in parallel. At the same time, the core backbone networks for all Internet connectivity are transforming as well. The deployment of data center technologies from the cloud to the computer network continues to grow. This process is called cloudification (Dinitz, Dolev, Frenkel, Binun, & Khankin, 2019). Cloudification builds the foundation for service providers to support ever-growing volumes of data and billions of connected devices (things). High performance and capacity, in turn, enable and inspire new use cases.

Wireless Networking Education for Technology Students

5G offers tremendous bandwidth – peak data rate can reach 10 Gbit/s (ITU, 2015), which is more than 10 times faster than 4G LTE that currently supports 300Mbps. When fully implemented, 5G cellular services will operate on the mmWave 6-300 GHz spectrum, while 4G LTE typically operates on 1.7-2.6 GHz. Over the past decade, along with the increase in cellular network speed, wireless and mobile devices have been rapidly expanding the range of traditional wired Local Area Networks (LANs), creating sprawling wireless LANs (WLANs) with significant increases in bandwidth requirements. Students at Technology, Applied Engineering, and Management (ATMAE) accredited institutions in Electricity, Electronics, and Computer Technology (EECT) programs focused on computer networking need to be able to configure, monitor, secure, manage, and troubleshoot wireless networks.

Existing Wi-Fi standards are keeping pace with mobile broadband speeds. Wi-Fi 4 (802.11n) supports High Throughput (HT) speeds of up to 600 Mbps. Wi-Fi 5 (802.11ac) provides Very High Throughput (VHT) speeds of up to 3.5 Gbps. The most recent standard Wi-Fi 6 (802.11ax) uses High-Efficiency Wireless, and is four times faster than Wi-Fi 5, allowing bidirectional access with multi-user multiple input multiple output (MU-MIMO) technology. Additionally, Wi-Fi 6 reduces power consumption and thus increases the runtime of batteries. Wi-Fi 6 makes it suitable for IoT devices rather than relying on personal area network technologies such as Bluetooth technologies (Browne, 2019; Links, 2018).

It is interesting to note that the terms 5G cellular and 5GHz Wi-Fi may be confused. Whereas 5G refers to the generation of mobile wireless technology, the 5GHz spectrum is one of the primary frequency ranges used in WLANs. It includes four separate bands in the 5.150 to 5.825 GHz spectrum. The other frequency range is the 2.4GHz band, in the 2.400 to 2.4835 GHz spectrum.

Regardless of the wireless technology used in the workplace, support for Wi-Fi will be needed alongside 5G services over the next decade. EECT students need better conceptual understanding, applied hands-on laboratory, and project-based activities to enhance their learning of wireless networks. It requires setting up wireless clients that connect to Access Points (APs). The APs, in turn, may be managed by a Wireless LAN Controller (WLC), along with setting up authentication servers, typically Remote Authentication Dial-In User Service (RADIUS) servers for authenticating remote users who attempt to access the network. Creative use of open-source ecosystems such as Linux-based software and Raspberry Pi based hardware are likely to be needed for providing students with suitable learning experiences. It helps ease the limitation placed by ever-shrinking program budgets that many technology programs are facing.

Computer networking coursework includes devices such as routers, servers, and security appliances that are often housed at the core of the network with switches and APs at the edge to provide users with network access. Users, both wireless and wired, initiate data requests that are transported to the core enterprise devices and then, as needed, out to the Internet. It creates latency in this process. The delays associated with long data path may not be viable for real-time applications unless very high speed WAN connections are available. This requires significant capital expenditure. When realized, 5G network connections with less than 1ms latency can effectively and quickly secure cloud-based services located at the edge. Realizing the limitations of existing Wi-Fi technologies can inform better decision-making regarding capital expenditure regarding the networking devices within an organization. Other considerations, beyond responsiveness and security, include the range of communication, which for Wi-Fi is typically 300 feet indoors, possibly up to a half-mile outdoors using specialized configurations. In contrast, for 5G, the outdoor range is 10-15 miles (Minoli & Occhiogrosso, 2019). The coverage of 5G signals requires considerable infrastructure investment on the part of cellular carriers, and this may not be available in certain areas.

Computer Networking focused EECT programs may consider including special topics or advanced networking coursework that include content from certifications related to wireless technologies. These include the Certified Wireless Specialist (CWS) related to wireless sales and support for Wi-Fi networks, or the Certified Wireless Technician (CWT) related to the installation, configuration, securing, testing, and troubleshooting APs in WLANs (CWNP, 2020).

Students should be well versed in computational thinking for leveraging the computational challenges likely to be present at the very edge of the network. Familiarity with scripting, app development, and deploying web-based systems will be tremendously helpful for performing urgent tasks within the client application itself rather than sending to a remote server for processing. In contrast, certain computationally intensive tasks can be offloaded to devices at the core of the network. Through structural opportunities for applying computational thinking, EECT students can gain a better appreciation for systematically expressing solutions to technical problems. Senior projects that use open-source software and hardware to control appliances over the Internet, setup interactive streaming services, and so on, give students the opportunity to apply computational thinking for developing technological solutions. In many applications, cellular and Wi-Fi networks can be seamlessly integrated for wireless-based communication and control. The combination of 5G and Wi-Fi 6 technology offers exciting opportunities for EECT students to explore deploying and managing end-to-end network connectivity in real-time applications.

Jovanović, Mas, Mesquida, & Lalić (2017) presented an "inadequate to agile transition" model developed from the study of a large Information & Technology (IT) company during its transition period. In this paper, the authors showed the context and causes that lead to inefficient or inadequate transitions in a traditional organization for the creation of self-managed teams, presenting the main consequences. It can be said that the model is complementary to the model presented by Gandomani & Nafchi, (2015) because the critical success factors cited by Gandomani & Nafchi, (2015)are the main points where errors occurred in the transitions in the model of Jovanovic et al. (2017). (Gandomani & Nafchi, 2015; Jovanović et al., 2017).

Summary

5G networks will revolutionize the wireless market through a combination of improved technologies to meet the requirements for establishing a high-speed mobile network. The core infrastructure provides higher capacity, better quality of service, and greener technology. To design 5G with such capability, a denser network with small cells is the key. In order for the wireless industry to maximize available wireless capacity, the future of radio spectrum should operate within a larger matrix of sharing arrangements, although exclusive rights on frequencies still exist in some contexts (Kevin Werbach, 2014).

GSM Association or Global System for Mobile Communications (GSMA) predicts that by 2023, mobile economic contribution will reach $4.8 trillion (4.8% of GDP). Over the next 15 years, 5G technologies are expected to contribute $2.2 trillion to global economy (GSMA, 2019). The combination of 5G and Wi-Fi 6 technology offers exciting opportunities for EECT students to explore and manage end-to-end network connectivity in real-time applications. Introducing mobile communication and wireless technologies to engineering and technology students will help them learn cutting edge technology trends and will prepare them better for a revolutionizing wireless industry.

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