5G Technology Fundamentals

An Online Continuing Education Course for Engineers

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5G Wireless Networks

As we launch into a new decade, another historical cycle of mobile network technologies is also beginning to emerge as its fifth-generation (5G) begins to unveil itself as a new reality. 5G is being developed with a focus not on a particular technology, as the previous generations were, but rather on what the combinations of available and new technologies will *enable* the end-user to do. 5G will therefore provide not just an incremental step from 4G but giant leaps forward for the wireless world. We will truly become what Ericcson terms a "Networked Society," expecting technological advancements and improvements in the areas of:

- Data Throughput
- Spectral Efficiency
- Power Efficiency
- Network Capacity
- Latency
- Infrastructure

A quick review of the capabilities of previous generations in Table 1 gives us a fresh appreciation of the milestones that the wireless world has accomplished thus far. Note that the time span of each generation is not necessarily clear-cut, and there is usually some overlap with each successive generation as the previous generations get phased out (or merged in):

Table 1: Evolution of Cellular Technology Generations

Generation	Capabilities added	Decade
1G	Analog voice service	1980s
2G	Digital voice service & SMS text	1990s
3G	Basic data & MMS text	2000s
4G	Mobile broadband based on Internet-Protocol (IP)	2010s
5G	Unlimited potential; technology-driven	2020s

It is believed that the exponential growth and demands for mobile data over the years will be met by this fifth generation of wireless networks, globally defined as 5G. Cisco Systems predicts that the exponential increase in the world's data usage will result in approximately tens of *billions of gigabytes every month*. Furthermore, the number of devices and point-to-point connections worldwide will reach the billions as well. Today's advancements in 5G requires many improvements on bandwidth utilization

efficiency, network capacity, multipath exploitation (to overcome attenuation), power efficiency (better battery life), and ultimately, Internet-of-Things (IoT) devices, all while synchronously allowing mobile users to be ubiquitously connected to the Internet. There will be no limit to the world of possibilities that a developed 5G technology can offer.

In this course, we will firstly gain a background on the basic elements of 5G and obtain an understanding of the relevant industry terms through the exploration of two (2) main 5G-enabling technologies that serve as fundamental principles of all the possible use cases in this exciting generation of wireless telecommunications. In fact, these two technologies are interdependent and complementary to each other in overcoming today's wireless challenges and limitations to achieve 5G standard performance. They are:

- ➢ **MILLIMETER WAVE**
- ➢ **MIMO-OFDM**

Whether you are an industry expert or an avid mobile user, we are all in unprecedented times just the same, and this course is designed to provide a fundamental understanding of the technologies behind what the billions of us data consumers hold near and dear to us every day in today's world: the cellphone device in our pocket.

Before we proceed, it would be helpful to refresh on a few terms and provide a background of the three (3) main categories driving the race toward 5G standardization. In other words, with 5G being achieved, these are the categories of use that will see the most benefit, and this is what the Information Technology & Innovation Foundation (ITIF) calls the 5G triangle (see Figure 1). Having a better understanding of the challenges of previous cellular technologies will enhance our understanding of how our two main technological advances of mmWave and MIMO-OFDM fit in.

Terms & Abbreviations

The following are terms to understand as a background for this course:

- Data - unit of digital information (coded in computer language)
  - Ex: data in your email contains the message you are conveying to the recipient
  - Ex: a voice message contains voice data
  - Ex: your internet browser contains data regarding the webpage you accessed
  - Ex: you enter your personal data when you subscribe to an online newsletter
- Capacity - the amount of data traffic that can be handled in a given network; ability to contain something (think in terms of how widening the roads/freeways affect traffic throughput)
- Spectrum - a range of frequencies
  - Ex: 5G operates within several spectrums, or ranges of frequency, including sub-6 GHz or higher ones above 24 GHz (mmWave)
- Frequency - number of recurring cycles that an electromagnetic wave makes in a given timeframe
  - Since frequency is inversely proportional to its wavelength, this is why high-frequency millimeter waves are termed that way - because their short wavelengths measure only several millimeters in length, based on the relationship between speed of light, wavelength, frequency: $c = f * \lambda$

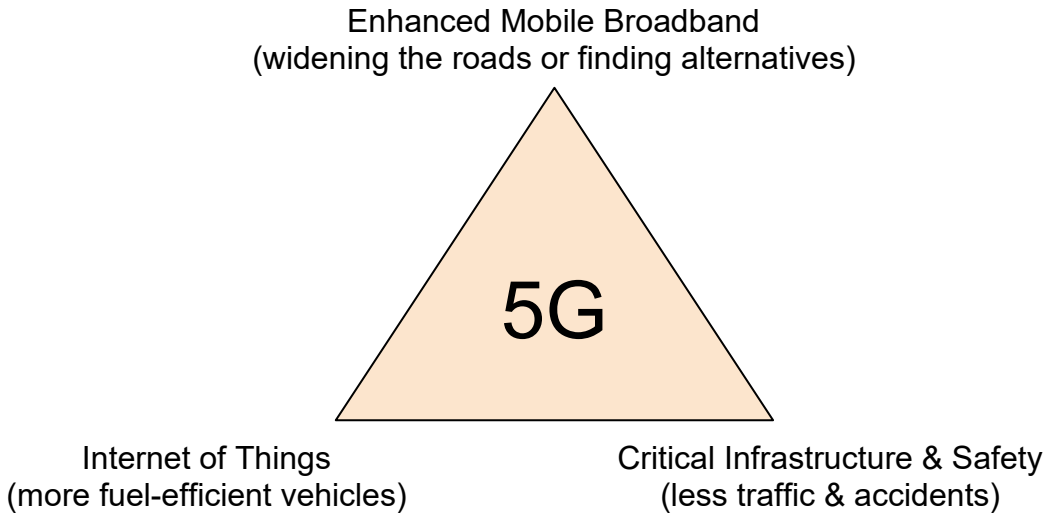
- Latency - delay in information reaching its intended destination (ideal to keep this as low as possible if "real-time" is desired)
- Speeds - the rate at which information can travel across a certain distance
- Bits - smallest unit of digital information and takes on binary form
    - When one hears of "0s and 1s", this is what is being referred to, often in the context of internet speed; you may have Gigabit internet if you have >1 Gbps
- Bytes - different from bits, as it is a group of 8 bits, and usually refers to computer storage (you may understand this in terms of megabytes (e.g., 500MB or 1TB of storage)
- Attenuate - to reduce in strength
- Massive - referring to quantity, not size, of antennas of usually 64 or more
- Multiplexing - combining multiple signals into the same transmission medium simultaneously (this medium can be the RF wave, fiber optic, etc.)

Abbreviations to be aware of without in-depth understanding:

- RF - Radio Frequency
- LOS / NLOS - Line-of-Sight / Non-Line-of-Sight
- mmWave - Millimeter Wavelength
- MIMO - Multiple In, Multiple Out
- Tx/Rx - Transmit/Receive antennas
- OFDM - Orthogonal Frequency-Division Multiplexing
- ISI - Inter-Symbol Interference
- dB - decibel, a logarithmic measure of signal gain and loss
- SNR - Signal-to-Noise Ratio
- QAM - Quadrature Amplitude Modulation, a form of signal modulation
- UE - User Equipment (such as your mobile device/cellphone)
- MUX – Multiplex

5G Triangle

Figure 1: The 5G Triangle



Note: Since the word "traffic" is used both in the transportation context as well as cellular technology, the analogy of traveling on a highway infrastructure may help simplify and relate the intricacies of cellular technology to what we may encounter in daily life. If digital information does not have sufficient "lanes" to travel on, two possible solutions would include: a) simply finding a less-traveled alternative road (mmWave) or b) improving the traffic flow in a way that would yield more cars yet fewer accidents and higher safety (MIMO-OFDM).

Now that we have defined a few relevant key terms let us continue to understand the (3) legs of the 5G triangle. (For the sake of this discussion, we will call it "legs" as opposed to "corners.") Although there are various requirements among these different use cases, there are still some much-agreed upon benchmarks that must be achieved as a minimum requirement of 5G to meet the demands of those various envisioned uses. As continuing research fine-tunes what is actually feasible - both technically and economically, these benchmarks no doubt will be adjusted accordingly. Nevertheless, each use category has its own particular emphasis on the improvements to be benchmarked, and these benchmarks correspond to each of the (3) main legs of the 5G Triangle. Each one will be mentioned briefly at the end of its respective section (along with a few use case examples), all collectively addressing the following items:

- Throughput (Speed)
- Latency
- Power Efficiency
- Scalability

Enhanced Mobile Broadband (Human User)

Enhanced mobile broadband (Human User) is the first use category, the first one-third of the 5G triangle. Today's social trends (including the recent pandemic) coupled with technological advancements such as bigger screens and longer-life batteries, along with video subscriptions, have respectively demanded and enabled large increases in the streaming of mobile video, including video gaming, even setting off a cycle of encouraging such behaviors as binge-watching (movies) or binge gaming through unlimited video streaming and gaming services. The ITIF likens this behavior to taking "large gulps" of data. This means that for this use category, larger data capacity, higher speeds, and lower latency requirements are paramount to providing a comfortable user experience on mobile broadband networks. The corresponding 5G [illegible] these attributes.

Un[illegible]s that can be made[illegible]e the goals set by th[illegible]ress regarding this tr[illegible] we will see more i[illegible]much higher-band fi[illegible]w digital roads l[illegible]ives it less econom[illegible]allocate a certain s[illegible]

[illegible]atly help streamlin[illegible]iscuss fun facts arou[illegible]ectrum, much less [illegible]m because th[illegible]ysis. This is due to th[illegible] auctions, o[illegible] interested p[illegible]volves how much [illegible]S) is that the tele[illegible]s to define the c[illegible] standard wh[illegible]e-defined stan[illegible]l is just the same [illegible] government [illegible]ement in the right avenues certainly can [illegible]current and previous generational frameworks. [illegible]ed, for example, by assisting to reduce or remove regulatory obstacles and incentivizing jurisdictional cooperation to streamline efforts toward achieving 5G. Therefore, the government plays a powerful role in advancing this new technology. This is where the new spectrum comes into play and why mmWave is an important breakthrough technology.

Because we may need to continue utilizing the existing spectrum as new "roads" are being built, another hypothetical question that arises in the context of addressing today's human user demands is: "If additional spectrum is not available, then **how can we better utilize the existing spectrum that we**