
# 5G Technology Fundamentals

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## 1. Introduction

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):

| 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 |

*Table 1. Evolution of Cellular Technology Generations*

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 everyday 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.

## 2. 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 - 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 - 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

## 3. 5G Triangle

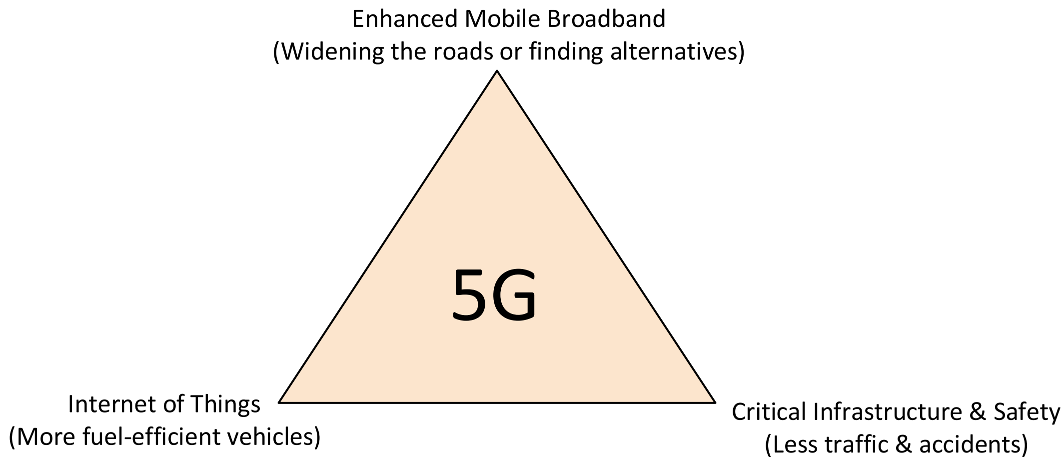



*Figure 1. The 5G Triangle*

Note: Since the word “traffic” is used both in the transportation context as well as cellular technology, the analogy of travelling 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 travelled alternative road (mmWave) or b) improving the traffic flow in a way that would yield more cars yet less 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 of:

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

### 3.1. 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 of video consumption on mobile broadband networks. The corresponding 5G benchmarks will therefore be associated with these attributes.

Up until recently, most of the bandwidth and speed adjustments and improvements that can be made have already been made and maxed out, so new frontiers must be explored to achieve the goals set by ever-increasing demands of data-hungry users. One of the foremost questions to address regarding this trend of mobile video streaming is: **"Where will the extra spectrum come from?"** As we will see more in-depth one of the breakthrough solutions being developed involves the utilization of much higher-band frequencies known as millimeter wave (mmWave) technology, analogous to finding new digital roads less travelled. Since not all spectrums are created equal (unproven mmWave spectrum gives it less economic value than mature spectrum such as 700 or 1900 MHz), it is not sufficient just to reallocate a certain spectrum; the infrastructure to utilize it must also be built.

With spectrum allocation and network infrastructure being two main priorities that greatly help streamline the deployment of new cellular technology, we could perhaps pause here to briefly discuss fun facts around the handling of new spectrum. The policy-making aspects of allocating new spectrum, much less new mmWave spectrum, often serve as a barrier of entry to deploying the new spectrum because the associated costs are usually perceived as a financial downside in the cost-factor analysis. This is due to the way that spectrum is allocated, as they are typically handled through government bid auctions often requiring an exorbitant amount of revenue on the order of billions of dollars from interested parties. Related to this are two schools of thought on how 5G should be defined. This involves how much of a hand the government should have in the standards-making process. One thought (US) is that the telecommunications industry should be free to explore and work through specific challenges to define the cellular technology standard. The other thought (Europe) is that the governing body sets a standard, while the industry works towards such technology as 5G development according to those pre-defined standards. While both methods have their respective advantages and risks, ultimately the goal is just the same: a positive global wireless ecosystem. This is not meant to preclude in any way that government - both local and national - should not get involved, as their involvement in the right avenues certainly can and have facilitated the necessary build-outs of current and previous generational frameworks. This has been accomplished, 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 new spectrum comes into play and why mmWave is an important breakthrough technology.

Because we may need to continue utilizing 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 already do have?**" The answer to this question pertains to optimizing the currently allocated (and increasingly congested) spectrum bands to increase the transmission of coded information data bits. Unfortunately, previous advancements have already approached the limits of what the laws of physics allow (generally known as the Shannon Limit), so new contributions to 5G will likely not be as much from this department as much as from the department of higher-band spectrum. Nevertheless, there are further developments of several existing technologies, one of which we will take a deeper look into in the coming sections: MIMO technologies.

The 5G performance benchmark for this first leg of the 5G triangle's enhanced mobile broadband use category therefore is: Throughput Capacity. In other words, in order to meet the standards of 5G, the throughput capacity must achieve a minimum of **100 Mbps *reliably* & more than >10 Gbps *peak***. These benchmarks are provided as improvements made relative to existing 4G technology (see Table 2). Some possible use cases and benefits in this human user category (possibly overlapping with others) include:

- 3D / 4K high-definition video gaming for enhanced user experience
- Video calling to stay connected to distant loved ones
- Information showers for instantly downloading libraries of information

## 3.2. Internet of Things (IoT) (Machine User)

The Internet of Things (IoT) (Machine User) is the second use category, and corresponds with the second leg of the 5G triangle. Whereas human users in the 1st category "gulp" down large data streams, machine users comprising the hundreds of millions if not already billions of small-form, low-power "smart" devices in this 2nd category take what the ITIF describes as small infrequent "sips" of data (think of your smart: lightbulb, doorbell, thermostat, etc).

With this pattern comes a different 5G connectivity requirement than the first use category with human users, and therefore different technological emphases and benchmarks to design for. Rather than high data capacity and low latency (for non-video IoT devices), machine user connectivity would require a large quantity or more aptly industry-termed "massive" number of simultaneous connections and energy efficiency in the form of "decade-long" battery life (think when was the last time you had to change the batteries on your dozens of interconnected smart devices?). Hence, the 5G performance benchmarks for this category are: a **10-year battery & 10-100x more devices** simultaneously connected, and some possible use cases and benefits in this second category (possibly overlapping with others) include:

- Connected appliances to assist in housekeeping chores and improve quality of life
- Wearable technology to monitor health (also improving quality of life)

- Smart city infrastructure (streetlights, city lights, traffic cameras, parking spots, etc) to facilitate urban planning
- Vehicle-to-vehicle communication for maintaining safe vehicle distance

### 3.3. Critical Infrastructure/Public Safety (Human User)

Critical Infrastructure/Public Safety (Human User) is the third use category, and there is yet a 3rd set of requirements and parameters that must be considered for this category in order to meet 5G performance design standards. In this use category mobile networks must be able to support critical infrastructure ranging from high-precision industrial automation to public safety sector services such as connecting with first responders in emergency situations, to whom calls made are increasingly initiated from cellular phones and decreasingly from traditional public-switch telephone networks (PSTN). This in turn calls for 5G components in this category to be characterized by the following traits:

- Robust
- Resilient
- Dependable
- Low-latency
- Low error margin

Hence, with the low tolerance for errors for use cases in this category, the 5G performance benchmarks for this machine user category are: **<1 ms radio latency & 10^-9 error rate**.

Some possible use cases and benefits in this category (possibly overlapping with others) include:

- Driverless cars utilizing machine algorithms to improve reaction times over human sensory capabilities
- Military drones to gather strategic information without compromising personnel safety
- Remote surgical procedures performed by otherwise inaccessible doctors around the world

We can see that each of the three legs of the 5G triangle addresses a particular concrete and specific performance benchmark to achieve in order to attain to 5G standards, with most of these being improvements measured in relation to current 4G standards. In order to evolve toward 5G performance standards, 4G multiple access technologies allowing multiple users to access a given wireless communications channel needed to address the limited spectrum resources (by using millimeter wave spectrum, in the range of ~20 to 60 Ghz), offer higher data rates & capacity, while maintaining good spectral efficiency (enhanced multiple access schemes such as MIMO-OFDM). From the performance standards of the previous 4G generation, we can see that this evolution is more than a step, with many increases being on the order of 10x, but a significant leap in throughput, bandwidth capacity, power efficiency, latency, and error rates to collectively enable new use cases that will only continue to uncover more use cases as technology matures. Table 2 below displays how the advanced 5G benchmarks compare relative to 4G technology. In the next section we will explore the first technological advance that enables this leap from 4G to 5G which is **MILLIMETER WAVE**.

| 5G Triangle Leg | Performance Benchmark | 5G | Improvement over 4G |
|---|---|---|---|
| Mobile Broadband | Throughput (average) | 100Mbps | 10x |
| | Throughput (peak) | 10Gbps | 10x |
| IOT | Battery life | 10-yr | 90% |
| | Number of connections (per area, $km^2$) | 1M | 10-100x |
| Reliability & Safety | Latency (max) | 1ms | 50x |
| | Error rate (uptime) | 10e-9 (99.999%) | N/A |

*Table 2.5G Performance Benchmarks*

## 4. Millimeter Wave

The first 5G-enabling technology we will explore is the one that allows us to address the first question of "Where does all the extra spectrum come from?" With the ever-growing demands of increased data capacity comes the need for more contiguous bandwidth. The currently available frequency spectrums are simply insufficient and getting too congested for the speed and latency requirements of today's gigabit mobile user. Over its 40-year history, the cellular spectrum has seen but only a 3-fold increase in speeds and capacity, compared to a thousand-fold and even a million-fold increase of personal computer (PC) clock speeds and memory sizes, respectively; millimeter wave technology is believed to relieve this stagnancy in Moore's Law (which is more of a historical observation than a physical law that projects that the performance of computer-related devices should double every couple years while its associated costs decrease).

In the high-band spectrum (>24 GHz), known as millimeter wave (mmWave), there is comparatively much more available and untapped spectrum. Most of the current mobile technologies, such as the 600 MHz and 700 MHz bands, as well as the Personal Communications Systems (PCS) 1.9 GHz and Industrial, Scientific and Medical (ISM) 2.4 GHz and 5 GHz bands (e.g., Wi-Fi, Bluetooth, NFC), utilize the low-band (<1 GHz), and mid-band (1 GHz - 6GHz) spectrums. Hence, high-band spectrum utilization is a relatively new and uncrowded frontier. This is in part due to the fact that these millimeter wavelengths have characteristics that were previously viewed as disadvantages. However, due to recent trends in cellular usage patterns and wireless demands, combined with advanced antenna technologies such as MIMO, beam-forming, and beam-steering, those very disadvantages are now accepted as proven advantages. In other words, the data-hungry behavior of wireless users and the densification of devices serve as the perfect storm for mmWave's previously disadvantageous characteristics to now be valued as advantageous. Figure 2 below shows where the mmWave spectrum falls on the electromagnetic (EM) spectrum, and Table 3 below that shows a pro and con comparison of the mmWave characteristics for the 60 GHz spectrum high band:

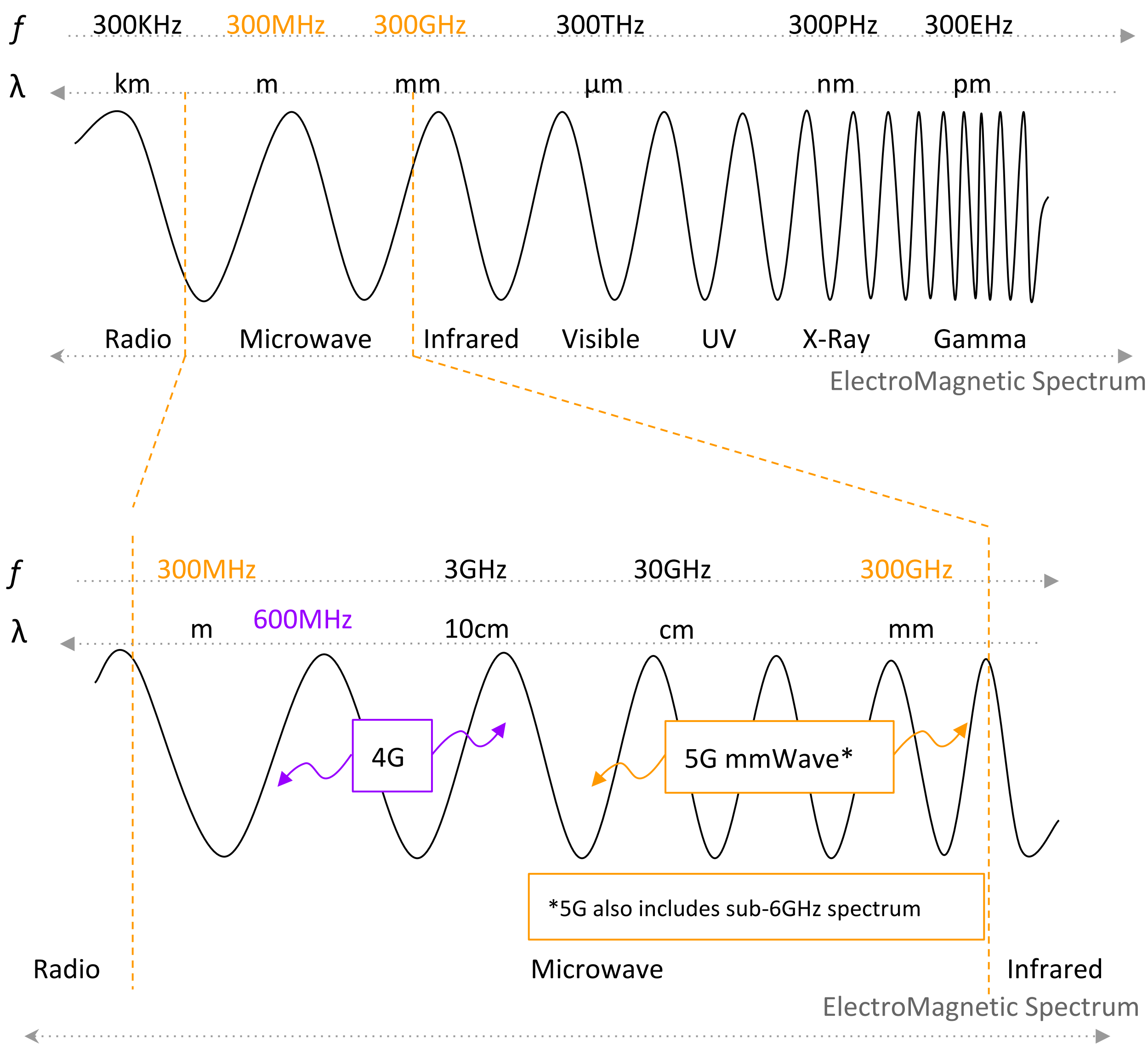



*Figure 1.mmWave on the EM Spectrum*

| Disadvantages | Advantages |
|---|---|
| ○ Atmospheric $O_2$ absorption of signal during propagation → increased free space path loss | ○ <20 dB/km attenuation is negligible w/in 100m; close-range networks<br>○ In fact, 1 km backhaul has been evident, & w/cell site densification, there'll be even less than <1 km between BTS's |
| ○ Weak signal penetration through obstacles | ○ Trend shifts from long-range to short-range communications allow frequency reuse |
| ○ Requirement of high-gain antennas result in directional communication; beamform | ○ Promotes security - as long as antenna directions can be controlled & steered flexibly |
| ○ Inter-Symbol Interference (ISI) | ○ ISI can be minimized when used w/OFDM |

*Table 3.mmWave Characteristics*

At higher frequencies (namely the upper end of mmWave 60 GHz band), the obstacles for high-band spectrum include higher attenuation rates and increased sensitivity to Non-Line-of-Sight (NLOS) obstacles. Even weather conditions such as rain - and oxygen itself - can be sources of signal absorption. Fortunately, studies have shown that attenuation under 20 dB per 1 km is negligible. This apparent disadvantage actually works out to the benefit of today's networks trending toward denser, closer-range small-cell networks, which fall well within the upper bound of the 1 km attenuation zone.

With the massive bands of mmWave spectrum available ranging from 10-100x more than currently existing spectrum, there are a myriad of possibilities for new use applications, in addition to improvements over existing applications. One potential new application is the use of mmWave to provide both wireless backhaul (LOS) and fronthaul links as well. This could save significant infrastructure construction costs for network cable trenching, boring, etc. (Recall that it is not sufficient just to find new additional spectrum, but equally important is the need to also build out the network infrastructure on which to utilize it.) In fact, almost everything within the 1 km LOS distance could eventually be not only interconnected (IoT), but also able to easily exchange enormous amounts of information among those interconnected devices by leveraging massive MIMO antenna technology. One such new use case could be information showers. Imagine arriving at a brand new place and with your phone's location services turned on, you are supplied with a "shower" of relevant information to that place such as things to explore, restaurants to eat at, or hotels to lodge at, along with the route guidance to get there.

Recent breakthroughs in semiconductor technologies have also revolutionized the wireless world, allowing capabilities for generating mmWave RF signals. Such materials as silicon germanium (SiGe), along with technologies like complementary metal oxide semiconductor (CMOS) which also refers to a type of circuitry design used to construct integrated circuits, or chips, have the following characteristics:

- Have very low power consumption
- Are immune to signal noise
- Able to process circuitry logic at ever faster speeds

Abiding by the same Moore's law that predicts the increase of clock speeds and computer memory, the capacity and speed of the transistors that each silicon wafer can house have also increased past the billions, and are together enabling the operational processing that will be fast enough to support gigahertz speeds that mmWave technologies produce. Additionally, these advancements in chip hardware technology arrive at a time where worldwide industrial production capabilities have driven down costs to make its mass production viable and reasonably inexpensive.

With its vast bandwidth potential it was only a matter of time before mmWave attained its potential to provide the necessary spectrum to enable 5G's high data capacity and low latency requirements. Even if we consider mmWave spectrum without attenuation effects, just the available amount of bandwidth in the higher bands alone would already give mmWave a significant capacity increase. MmWave has 10-100x more spectrum availability than current bands, which makes the channel widths that much greater too. Compared to current 4G LTE channels (dozens of megahertz wide), mmWave channel bands that are *hundreds* of megahertz wide would supply more than approximately 30x wider channel bandwidths. Even factoring in attenuation losses, the wide bandwidth channels of mmWave would still allow 5G technologies to see considerable increases in capacity and data rates. Traffic congestion will be a thing of the past - at least for a very long time. However, it is not enough just to reach ultra-high data capacities and throughput - that is only half the battle. In order for mmWave to remain a feasible technology for 5G mobile broadband networks, there also needs to be improvements that boost those very high-speed mmWave signals through NLOS environments where signals otherwise "bounce" off trees, reflective buildings, and the like in order to overcome the rapid attenuation (power loss) that mmWaves would encounter.

Several years ago, Qualcomm engineers were able to demonstrate that the small antenna sizes resulting from millimeter-size waves (recall that antenna size is inversely proportional to frequency) can be leveraged to form large antenna arrays with the goal of increasing the Signal-to-Noise Ratio (SNR) needed to overcome power loss. With the help of beam-forming antennas, using a scheme called Space-Time Coding, the radio frequency signal of mmWaves were not only multiplied together using an array of small antennas, but also concentrated into a narrow directional beam that would yield higher antenna gain and maximize penetration through the NLOS obstacles that mmWaves are otherwise very sensitive to. (It is important to note here that although initially viewed as a disadvantage, the smaller millimeter-lengths actually make beamforming very feasible with the use of multiple antennas, which we will see in the discussions on MIMO technology.) The Qualcomm team was able to demonstrate mmWave feasibility in a NLOS mobile user environment maintaining a sufficiently stable SNR by also steering the beam, and thus "tracking" the mobile user. There was one interesting observational measurement in this experiment that likely served as a contributing factor: at the test frequency of ~28 GHz (within the mmWave spectrum), the reflected signals received were actually higher than the same direct signal received at a lower frequency (~2.9 GHz); the reflected NLOS signals effectively supplemented the direct LOS signals to constructively increase the SNR. Despite mmWave's susceptibility to even the slightest environmental variations or obstructions (such as the user's hand blocking the signal on the phone being held), the success of this Qualcomm experiment gives continued hope to mmWave researchers as they unceasingly investigate new ways to increase robustness of mmWave in NLOS outdoor, mobile broadband environments.

Millimeter wave technology will not only see advancements for mobile broadband networks, but is already seeing advancements in fixed wireless broadband and WLAN. IEEE 802.11ad (aka WiGig 1.2) has a lot of potential of offering very high throughput (VHT) to break the 1 Gbps barrier using 60 GHz spectrum, and will parallel cellular mmWave capabilities. One of the challenges for the WLAN standards is that they must be backward-compatible and interoperable with the previous versions. This is especially important for gigabit rate Wi-Fi, or WiGig, because due to its inherent characteristics such as high attenuation WiGig will not replace previous WiFi versions, but rather operate alongside them, switching back and forth between the best version to optimize the user experience based on environmental conditions. To take advantage of its features, a device will utilize the 60 GHz band for super fast speeds when inside of a room not subject to propagation losses characteristic of 60 GHz. Then perhaps when necessary the device will revert to slower but more interference-resistant 5 GHz and 2.4 GHz spectrums. This way, it will help the transition to gigabit wireless LAN, while also making good use of all current Wi-Fi standards available.

Some other potential applications where mmWave can effect positive change also include:

- Data centers
    - With the exponential growth of the Internet, corresponding data center buildout is analogous to that of previous generations' cell-phone tower build-out boom
    - Reduced copper-wired cable/conduit connections
    - Energy savings with better placement of cooling units
- Information showers
    - Entire information libraries and multimedia content will be capable of being instantly downloaded as people or cars pass through/underneath the "showerhead"
- Vehicular connectivity
    - Vehicular radar: self-driving cars can maintain safe driving distance
    - Vehicle-to-vehicle (V2V): vehicles can exchange live traffic information
    - Vehicle-to-infrastructure (V2I): vehicles can serve as base station signal boosters
- Aerospace
    - On-board, seat-back entertainment, including Wi-Fi services

Now that we have addressed the first question relating to spectrum resources, let us continue our discussion with the second question relating to spectral efficiency (this is the other half of the battle that overcomes mmWaves' rapid attenuation characteristic). We will see in the upcoming sections on MIMO technologies how the short, millimeter-size wavelengths enable not just very small antennas, but large "massive" arrays of them to be collectively used to multiply transmission signals that could offset any associated attenuation, thus making these very high frequency spectrums feasible for 5G mobile broadband. Eventually we will discuss the combined use of MIMO technologies with the OFDM modulation scheme and see how the combined use of these technologies can yield a powerful 5G air interface.

## 5. MIMO-OFDM

Don't be intimidated by the number of letters in the abbreviation combination; it is a simple concept to grasp. Invented in the mid-1990's by Greg Raleigh, MIMO, which stands for multiple-input multiple-output, technology is a natural progression of the advancements in mmWave technologies. As high frequencies drive down antenna sizes, more antennas can fit into the same area of the user equipment (UE) and base stations. (As we saw earlier, antenna size is inversely proportional to frequency.) MIMO leverages this attribute by employing multiple, spatially-separated, co-located transmit antennas (Tx) to send same-frequency signals to multiple receive antennas (Rx). It is being used in 4G LTE and Wi-Fi and will continue to be improved upon for 5G use. MIMO is the technology that allows mmWave technologies to capture the reflected NLOS signals caused by the multipath effects, thus overcoming small-scale multipath effects while in turn increasing bandwidth spectral efficiency. It is an established method for not only correcting, but also exploiting, the multipath propagation effects in a wireless radio channel. When coupled with the reduced receiver complexity afforded by Orthogonal Frequency-Division Multiplexing (OFDM) modulation, MIMO-OFDM is a powerful pair for the new 5G New Radio air interface ("5G NR"), and together addresses the second question of how to better utilize the existing spectrum that we already do have (spectral efficiency). See Figure 3 below for an illustration of a MIMO system combined with leveraging mmWave characteristics through a typical urban NLOS environment.

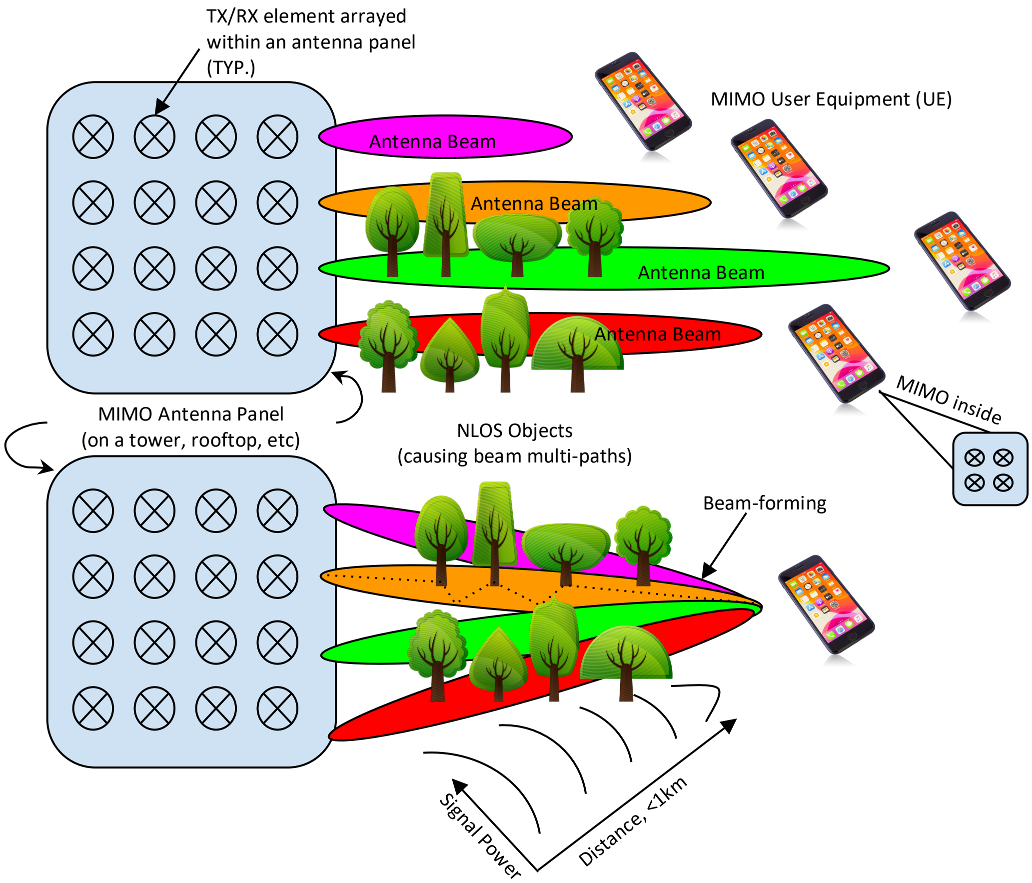



*Figure 3. MIMO System*

In a typical mobile channel, especially in today's dense, urban environments where direct Line-Of-Sight (LOS) propagation conditions are difficult to achieve, multipath effects resulting from the natural phenomena of reflections, refractions, and scatterings, are dominant in the ever hostile environment that mobile signals must propagate through. In a typical dense urban environment, there could be many reflective metal objects (in the form of tall buildings, billboards, cars, etc), reflecting and scattering the transmitted signals before those signals reach their targeted receivers, causing micro, rapid fluctuations known as small-scale fading effects. These interferences thereby distort the signals, causing multiple versions of them to arrive at different times (differing in time) and along different paths (differing in space), and at different angles of arrival. Essentially, multipaths are a series of attenuated replicas of transmitted signals that potentially arrive time-delayed, amplitude- and phase-shifted. These random phase/amplitude changes as you can imagine also cause signal strength loss and fluctuations, inducing small-scale fading effects and other distortions. Below in Table 4 is a comparison of some of the multipath phenomena and their effects on radio waves.

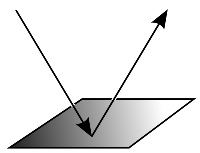
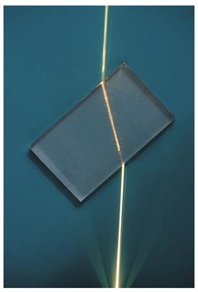
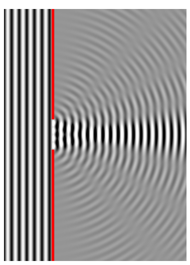
| Phenomena | | Influence on RF communication fidelity (in decreasing order of severity) |
|---|---|---|
| Reflection |  | ● Reflection deflects off a material at the same angle that it hits it (angle of incidence)<br>● With dense urban environments, with many reflective metal objects, including mirrors, the signal may reach its target at different times and/or along different paths (multipaths), making the signal impossible to calculate and predict precisely and negatively affects the fidelity of the RF signal<br>● Occurs from earth's surface and from buildings & walls |
| Refraction |  | ● The propagated radio wave may change direction due to a change in the transmission medium (directional change is accompanied by wavelength & speed change too)<br>● As it passes through different mediums, it may change direction, but more importantly, it may altogether become absorbed or weakened, depending on the medium<br>● Trees, water, glass, plastic, and humans all potentially absorb radio waves, with increased absorption occurring in proportion to increased amount of water<br>● Hence, refraction has less of an effect on the fidelity of RF signal, although it can be predicted or solved by simply avoiding objects of varying medium/densities |
| Diffraction |  | ● "Waves going around corners"<br>● The wave bends around an object and can still maintain signal behind the object (in its shadow)<br>● Huygens principle<br>● The power/energy of a diffracted wave is decreased compared to the wave front<br>● Sometimes, diffraction is useful in circumventing obstacles<br>● Most predictable in behavior, since it is a matter of what is in the signal's Line-of-Sight (LOS), and can be easily corrected to restore the fidelity of the signal |

*Table 4. Multipath Effects on Radio Waves*

The solution of utilizing multiple antennas on spatially separated (multiplexed) Tx and Rx antennas allows for a system network to capture the multiple signal paths and constructively form a better version of the signal than if the signal were only transmitted and received from just a single antenna at each end. In effect, MIMO enables the processing of the information to be multiplied, rather than self-cancelled.

Prior to the exploitation of multipath effects with MIMO, RF engineers treated these multipath effects as impediments to be mitigated. As they attempted to model real-world scenarios with multipath effects against theoretical channels without the same effects, the outcomes of their efforts were unfortunately not very successful. MIMO technology, on the other hand, instead of nullifying multipaths actually welcomes more of it. In fact it thrives in rich multipath scattering conditions. What previously was taken as a disadvantage can now be leveraged advantageously through the use of MIMO technology. Since MIMO gathers and analyzes information from multiple versions of the original signal before piecing them back together, the more signal "layers", or data sets, it can process, the better and clearer the signal that will be received, which is why MIMO depends on and operates best in these rich scattering conditions.

MIMO uses two keys to achieve high throughput gains: antenna diversity (or plurality) and spatial multiplexing. Although variations of MIMO processing techniques may exist, whether only one of the multiple Tx or Rx antennas at a given time would actually be connected to the Transmitter or Receiver for processing, or switched between the one with the best signal, the principle remains the same. Whereas Single-Input Multiple-Output (SIMO) is based on Rx diversity with multiple antennas on the receiver side of the link, MISO is based on Tx diversity. However, MIMO systems utilize antenna diversity for both Tx and Rx, but the MIMO system does not just simply incorporate multiple antennas; it actually processes multiple signals from each of those multiple antennas, resulting in what is called a "processing gain" (expressed in decibels, or dB). I like to think of MIMO like a game of telephone, except that there would be a "massive" number of ears to hear, process, and ultimately aggregate and report (Rx) what the whisperer whispers (Tx).

These processing gains behave differently at low SNR than they do at high SNR. At low SNR, MIMO's throughput gains increase linearly (faster), whereas at high SNR, gains increase logarithmically (slower). Hence, there are diminishing throughput returns at higher SNR. MIMO uses a technique called spatial multiplexing to overcome this behavior, and requires high SNR and rich scattering conditions. In spatial multiplexing, the total power at a sufficiently high SNR is divided into spatially-separated individual lower-power signals where each signal's SNR behavior can leverage the lower SNR's characteristic of linear increases. This splitting of the signal into multiple signals collectively - yet counterintuitively - provides much higher throughput gains than if using just a single channel at the same power levels. Spatial multiplexing essentially creates a signal capacity gain without the need to add extra power or bandwidth.

Although MIMO can be combined with modulation techniques such as TDMA and CDMA, and various modulation schemes are currently well-integrated into 4G technology, the high throughput and advancements of OFDM make it, together with MIMO, the most practical air interface combination for the high data rates of 5G. Orthogonal frequency-division multiplexing (OFDM), which is a specialization of FDMA, works by using Fourier Transforms to divide a single high-speed, frequency-selective fading, radio channel into a series of multiple, parallel, closely-spaced, lower-speed, flat-fading channels of smaller bandwidth, or sub-carriers, which are then individually modulated using 64-QAM. Converting a high-speed signal into many slower-speed sub-carrier signals with longer-duration symbols, in turn, makes it possible to add guard bands between consecutive data information symbols to prevent data symbols from overlapping, and thus eliminates intersymbol interference (ISI). ISI is a big interference obstacle in 4G's broadband communications and therefore makes OFDM a modulation scheme well-suited for the extremely high data speeds of 5G as it eliminates ISI. To successfully prevent ISI, the OFDM guard band, specifically called a cyclic prefix (CP) must use a time interval that is longer than the time-domain delay spread between symbols. With ISI minimized and essentially eliminated, the equalization processing required to reverse any signal distortion is also simplified. The elimination of ISI, especially at high data transmission rates, is a key factor that gives OFDM modulation its advantage over other modulation methods, while also simplifying the complexity of the receiver processor, resulting in lower costs.

<u>Notice</u> how the peak of the green sub-carrier coincides with and is orthogonal to the null of the yellow adjacent sub-carrier

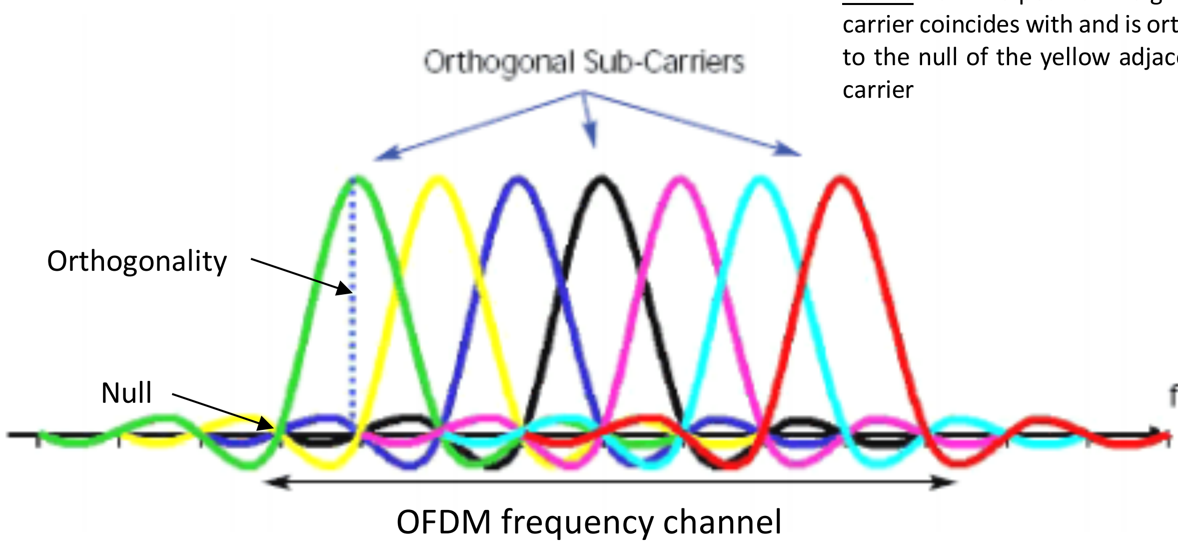



*Figure 4. OFDM Orthogonality*

OFDM's orthogonality characteristic that prevents ISI cross-talk allows it to further achieve a high spectral efficiency that utilizes nearly the entire frequency band. To be orthogonal simply means for the adjacent sub-carrier channels to overlap in the frequency domain in a manner that the zero-amplitude or null component of a sub-carrier coincides with the peak component of its adjacent sub-carrier, as shown in Figure 4. In 4G FDMA each of the above colored sub-carriers would be spaced one guard band apart from each other, occupying more precious bandwidth "real estate" and inversely reducing the amount of signals within the same frequency channel. Hence, without needing to be spaced separately with added guard bands as with FDMA modulation, OFDM allows for the sub-carriers to not only remove that guard band separation and close the gap, but additionally to even overlap with one another, being able to squeeze that many more sub-carriers into a given frequency bandwidth channel. This method improves the spectral efficiency by removing ISI as well as using its orthogonal sub-carriers to eliminate the need for inter-carrier guard bands, thus optimizing bandwidth efficiency and therefore utilizing *almost* the entire available band; "almost" because due to other environmental effects 100% efficiency is usually impossible to achieve.

To support MIMO's main objective of arriving at the highest throughput & connectivity possible by exploiting the signal environment's multipath potential, three important factors must be optimized. The first two involve maximizing multipath conditions at the transmitting end (base station) and receiving end (end user equipment), respectively. At the base station, the base station's antenna configuration must be optimized, including spatial placement, angle of tilt, and specific antenna equipment selection. For the user equipment, its antenna configurations must also be optimized, as well as ensuring the sufficiency of its processing power to leverage MIMO. The third factor that must be optimized is the selection of the best MIMO algorithms for processing at the base station. This involves using high-powered scanning receivers to measure the signal quality and power - at both the base stations and the user equipments. Some of those parameters that must be measured in each multipath signal includes (but not limited to) the following:

- Reference Signal Received Power (**RSRP**) - total power
- **RSRQ**uality - direct SNR measurement
- Delay spread - difference between 1st & last multipath signals

MIMO technology is currently being implemented in 4G LTE deployment, and since 5G MIMO will be a further development, it would be helpful to gain an understanding of the four various modes of 4G LTE MIMO.

The 4G base station, which is called an eNodeB, can operate interchangeably between a closed-loop or an open-loop mode, depending on the amount of channel condition information the user equipment (UE) can feed back to the eNodeB. We will examine how the mode selection is made, within the open- and closed-loop modes, while understanding their respective advantages and disadvantages.

The eNodeB base station will select an open-loop mode based on the quality of the UE's feedback information, which is affected by two main factors, both related to the optimization of a MIMO system. The first factor is the speed at which the UE is moving; when it is too high, the ability to provide sufficient channel state condition details back to the eNodeB decreases. The second factor depends on the UE data-processing capabilities; the slower the processing speed, the more likely the eNodeB will resort to open-loop mode. In open-loop mode, there is less information that the eNodeB receives from the UE, compared to closed-loop mode. The information received includes: (i) the quantity of layers that the current channel conditions can support, which is called a Rank Indicator (RI), and (ii) a summary of current channel conditions, called a Channel Quality Indicator (CQI), which correlates to SNR levels.

In closed-loop modes, the UE provides the RI and CQI information as well, plus an additional Precoding Matrix Indicator (PMI), which selects the best precoding matrix given current channel conditions. Precoding helps to maximize the receiver output, thereby reducing receiver errors, and works by differently weighting each of the multiple data streams in such a way to constructively recombine the signals at the receiver and improve the quality of the information received. Unlike open-loop CQI, which is based on the eNodeB's current operation mode, closed-loop CQI is based on the RI and PMI information, and allows the eNodeB to flexibly adjust and adapt to the current channel conditions and improve the overall quality of the signal propagation. Table 5 on the following page provides a comparison between open-loop and closed-loop modes.

Furthermore, the one of two optional open-loop modes that is selected by the eNodeB depends on the SNR level and multipath conditions. For low-SNR, and poor multipath conditions, the Transmit Diversity mode is selected in order to help boost the low SNR levels. Transmit Diversity uses multiple Tx to send the same signal and leverages the antenna diversity in an attempt to reduce the likelihood that data losses due to low SNR would result from the same antenna. In other words, it increases the chances that a signal would survive hostile multipath propagation conditions. On the other hand, when SNR levels are high, and multipath conditions are rich in scattering, the Open-Loop Spatial Multiplexing mode is selected. As we have previously discussed, spatial multiplexing allows for high-gain throughput, as well as bandwidth efficiency.

Regardless of whether the propagation condition has low or high SNR, the two closed-loop modes, due to its additional precoding matrix information, can provide more detailed CQI feedback to the eNodeB than their respective open-loop counterparts. This in turn allows for the eNodeB to more accurately process data to model actual channel conditions, maximizing the throughput potential and SNR gains of a channel. Nonetheless, it is the optimal combination of antenna equipment, high-SNR, and rich multipath scattering conditions (the latter two of which are important for spatial multiplexing) where MIMO offers the greatest throughput gains. For low-SNR, the closed-loop mode that would be selected is the Closed-Loop Rank-1 Spatial Multiplexing mode. For high-SNR, the closed-loop mode that would be selected is the Closed-Loop Spatial Multiplexing mode. As we have seen thus far, conditions that allow for Closed-Loop Spatial Multiplexing would yield the optimal results, provided the equipment and channel conditions align accordingly as optimized.

| **Open-Loop** | **Closed-Loop** |
|---|---|
| When UE moves too fast to provide detailed channel conditions feedback to eNb in time for eNb to select a precoding matrix | Feedback is possible, and important for spatial multiplexing, where MIMO offers greatest throughput gains |
| eNb gets <u>minimal</u> info from UE, including:<br>➢ Rank Indicator (**RI**)<br>➢ Qty of layers<br>➢ Modulation/Coding Scheme<br>➢ Channel Quality Indicator (**CQI**) - <u>based on current operation mode</u><br>➢ But no feedback from UE | eNb gets <u>maximum</u> info from UE, including:<br>➢ **RI**<br>➢ Precoding Matrix Indicator (**PMI**) - unique to closed loop mode<br>➢ **CQI** - <u>based on RI & PMI</u><br>➢ Which allows eNb to adapt Tx to channel conditions |
| a. Transmit Diversity | b. Closed-Loop Rank-1 Spatial MUX |
| → Both modes selected in low-SNR / poor multipath conditions ← | |
| c. Open-Loop Spatial MUX | d. Closed-Loop Spatial MUX* |
| → Both modes selected in high SNR / rich multipath scattering conditions ←<br>*desired mode for optimal results | |

*Table 5.Closed-Loop vs Open-Loop MIMO Modes*

Suffice it here in the context of this course to state that with the base station and user equipment capabilities optimized, the advantages that MIMO bring are increased data throughput and SNR boost without the need for additional spectrum or base stations, especially in closed-loop systems with the additional data sets to process. Nonetheless, equipment costs are decreasing and with MIMO being fine-tuned for 4G and 5G systems, the benefits will deem MIMO systems to be very effective - at least a big step forward from Single-In Single-Out (SISO) systems.

Researchers are continually exploring and pushing limits on the different ways to achieve the fullest meaning of MIMO, including the use of a massive number of MIMO antennas; using not only multiple antennas, but a very large number of them. With multipath effects, the more antennas that can capture the “multi” signals, the clearer the signal would be. It then would be reasonable to postulate that the quality of a signal is directly proportional to the quantity of antennas that are used to pick up the additional reflected paths. MIMO technology is currently able to put into practice the use of hundreds, even thousands (thanks to the millimeter-size wavelengths of high-frequencies) of antennas co-operating together in one massive MIMO system. The question to ask oneself here (and perhaps the barrier to break) then is: “What, if any, is the limit to the number of antennas that can collaboratively capture the multipath signals?”

With so many advancements of 5G-related technologies, there will be more facets to this next generation of mobile broadband technology than we may currently be able to fathom. Although there is still uncertainty in this arena, surely there will be many winners in this race, including all of mankind as participants of the world’s wireless ecosystem. We get to realize a myriad of use cases and wireless capabilities, such as the Internet of Things (IoT) and convergence of device connectivity (mobile ubiquity), Personal Area Network (PAN), and wearable technologies; all of which affect our daily life. A thorough understanding of the technologies that would enable 5G can help us to not only improve quality of life, but also to consider the endless possibilities beyond the 5G vision. With the exponential growth of mobile data usage, current wireless technologies are striving to keep up, and spectrum capacity is becoming a rare resource being squeezed out. It is then at these crucial times that we especially appreciate the advancements of wireless telecommunications technologies such as mmWave and MIMO-OFDM as they take us ever closer to reaching the Shannon Limit. With the recent attainment of 5G, it is the further development of these very fundamental technologies that will bring the wireless world to the cusp of the most life-changing and life-enhancing wireless revolution in human history, enabling an endless world of possible use cases only recently imagined, with no end in sight.

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