5G SERVICES & USE CASES

November 2017

5G Americas Whitepaper

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1. INTRODUCTION

5G wireless mobile technology promises to enable a fully mobile and connected society by addressing a broad range of use cases and business models with disparate requirements. Therefore, 5G technology will play a significant role in empowering socio-economic transformations, enhancing productivity, sustainability, efficiency and overall well-being of communities. 5G technology is expected to bring tremendous growth in connectivity, mobile traffic capacity, and new capabilities that enhance performance by providing greater throughput, lower latency, ultra-high reliability, higher connectivity density and an expanded range of mobility. An end-to-end transformation of network architecture will equip 5G with the requisite flexibility to optimize the network usage and accommodate the wide range of current and future use cases and services.

With the advent of 5G, vertical industries will use the enhanced technical capacity and tighter integration to trigger new products and services. The expectation is that 5G will create an ecosystem for technical and business innovation that will fundamentally alter entire vertical markets such as automotive, energy, food and agriculture, city management, government, healthcare, manufacturing, transportation, and many more.

To make this a reality, there is a need for close collaboration between use case developers, vertical industries and 5G system designers to maximize the impact and ensure mutually beneficial outcomes. As an initial step towards making those connections and initiating the conversations, this paper will identify new trends in different use case categories, their technical requirements and map them to 5G capabilities. This paper will provide a methodical view of how 5G technology capabilities can meet the needs and requirements for various use cases, many of which span across several industry verticals.

As cellular technology has evolved there has been increasing interest in different use cases from enhanced Mobile Broadband (eMBB), to mission critical communication, and massive-scale connectivity for Internet of Things (IoT) devices, such as sensors, wearables, smart vehicles. Mobile network operators face deployment challenges to support these new services in a cost-efficient way. For example, mobile broadband requires a significant increase in capacity over a macro-scale coverage area. At the same time, sites along highways in close proximity are needed to support connected vehicles as the smart car becomes even smarter as part of the evolution towards fully autonomous vehicles. Drones will also require communication coverage at different heights that will support a new level of mobility. IoT devices and sensors need deeper coverage to extend reach and improved battery life. It is critical to understand how to build the mobile network of the future that will support these and a multitude of other use cases.

The mobile network of the future will also need to support the growing number of mission critical applications that have stringent communication performance and reliability requirements. For example, communications with vehicles, drones, and robots to enable safety and coordinated maneuvering applications, remote monitoring and failure handling of critical infrastructure and real-time control for industrial and process automations within a factory. These applications have high reliability (e.g. <10-5 packet drop rate), low latency (e.g. around 1ms) and in many cases, strong security requirements. 5G will incorporate advanced techniques under a unified 5G air interface framework and a flexible and scalable core network to support a wide range of services which are very diverse in terms of Key Performance Indicator (KPI) requirements.

The existing generation of mobile networks have been designed for the basic purpose of providing a general connectivity platform with no consideration for providing the differentiation needed to meet the needs of a range of use cases. There is a need for deeper understanding of the performance and coverage expectations of the expected 5G use cases and services. Particularly, features such as network topology for the core network and Radio Access Network (RAN) deployment have a significant impact in the

implementation of use cases and in supporting flexible network slices and the distribution of functionality needed to support the multitude of use cases. A primary goal of 5G networks is to provide a marked change in this approach and create a mobile connectivity platform that will meet the needs of those future use cases that we can envision today as well as those that we cannot yet imagine.

This white paper will discuss the different aspects of 5G technology and the role that it will play across multiple sectors. Part of understanding the role of 5G involves recognizing the evolution of cellular technology from 1G to 5G and the socio-economic drivers and trends that have influenced this. The market drivers and trends of today may not necessarily continue be the ones that dominate in the future. The improved connectivity from 5G networks will play a role in the transformation of vertical sectors and serve as a platform for future innovation. The evolutionary path of technology is rarely predictable, and it is likely that we are not yet able to foresee the greatest benefits that will be unlocked by 5G technology.

The outline of the paper is as follows: the evolution of cellular technology along with key market drivers, economics and trends are discussed in Section 2. Section 3 describes the transformation that is underway in vertical industries and its key dependencies on 5G technologies and features. Section 4 defines various use case categories and provides a framework for evaluating the evolution of the use cases. Section 5 outlines the 5G network architecture and the enabling technologies. Sections 6 provide an overview of the 5G network topology and unique design features, respectively. Section 7 highlights the policy implications and deployment challenges inherent in meeting the requirements of new use cases and services. Conclusions and final thoughts are provided in section 8.

2. MARKET DRIVERS, ECONOMICS, TIMELINES AND TRENDS

Over the past four decades, cellular has fundamentally changed the way people work, live and play. This section summarizes cellular technological and marketplace evolution during that time, from first generation (1G) to today's widely used 4G and the debut of 5G. For example, 2G introduced text messaging which conditioned people to view their mobile phone as a device that could be used for more than just voice calls. That technology and experience possibly laid the foundation for the smartphone revolution, where many people use their smartphone more than their personal computer.

2.1 TIMELINE AND EVOLUTION: FROM 1G TO 5G

Cellular technology has come a long way since the emergence of the first functional cellular system in 1979. This development represented a revolutionary change from the concept of the telephone that was centered on communication between two fixed locations. Suddenly the idea of communicating with a person, regardless of their location, became a possibility. The first generation of cellular technology, or "1G," modulated a voice call using a technique called Frequency Division Multiple Access (FDMA) and transmitted the analog signal between radio towers to enable "wireless" communication. In the United States, the first cellular network was launched in 1983 with limited coverage, relatively poor voice quality, and a lack of security. The initial mobile phones also left much to be desired in terms of mobility. But despite their large size and weight, their potential to solve the communication challenges inherent with fixed telephones was evident. An overview of the shifts and changes across the various generations of cellular technology is shown in Figure 1.

The deployment of the second generation of cellular technology began in 1992 in the United States and brought further improvements to help realize this potential. 2G technology used digital signals that required less power, resulting in smaller mobile phones. Better compression and multiplexing of digital signals also allowed the transmission of more voice calls per radio frequency spectrum. On top of improving efficiency

and voice quality, the digital signals also employed digital encryption that offered a level of security not previously available in 1G technology. Another big advance in 2G technology was a fledgling data service in the form of transmitting text messages via Short Message Service (SMS) between mobile phones. Since their introduction, SMS messages have increasingly influenced communication patterns, reducing the once sole dependence on voice calls.
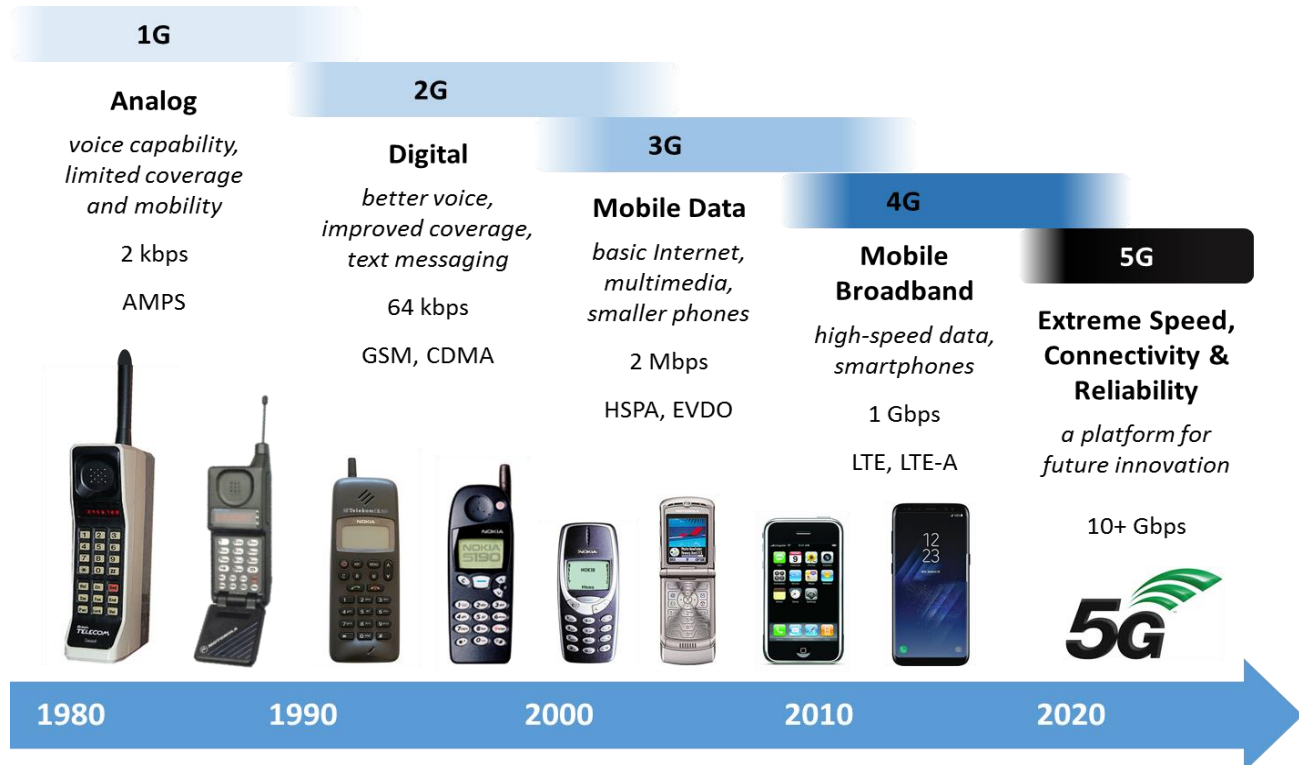

Figure 1. Evolution and Key Developments in Cellular Technology from 1G to 5G.

The limited data capabilities in the dominant 2G standards, Global System for Mobile Communications (GSM) and Code Division Multiple Access (CDMA) improved with the evolution to General Packet Radio Service (GPRS) technology with data rates up to ~100kbps and later ~300kbps with Enhanced Data Rates for GSM Evolution (EDGE). Increasing data transfer speeds helped to spur the initial mobile internet capabilities of third generation cellular technology. With 3G standards such as High-Speed Packet Access (HSPA) and Evolution-Data Optimized (EVDO), data speeds could be measured in Mbps not kbps. The capability to deliver basic mobile Internet service to consumers was further catalyzed by significant improvements in the user equipment. Better quality phone displays, more advanced chipsets, and the integration of digital cameras, all brought a new multimedia experience; a significant jump from merely voice calls and text messages. The miniaturization of digital circuitry and advances in semiconductor technology ultimately resulted in pocket-sized "smartphones" that were significantly more powerful and capable than ever before.

Fourth generation cellular technology has capitalized on smartphones and with the introduction of Long Term Evolution (LTE) and Long-Term Evolution – Advanced (LTE-A), data speeds have increased to 10's or even 100's of Mbps, with peak speeds of nearly 1 Gbps recently being tested and deployed. Another notable advance is the change from the parallel circuit-switched and packet-switched network infrastructures of 3G systems to an all Internet Protocol (IP) packet-switched 4G system. In a sense, these networks will be using similar building blocks as the Internet, enabling what is essentially a mobile broadband service. This mobile broadband service is now capable of delivering streaming video and richer

multimedia experiences to users, leading to rapid growth in global mobile data usage, which grew 63 percent in 2016 and has increased 18-fold from 2011 to 2016.[1] As Figure 2 shows, it is expected that this growth in data usage will continue in the future with video being the primary driver. To date, new technological improvements in antenna systems with the introduction of Multiple Input Multiple Output (MIMO) transmission, better multiplexing with Orthogonal FDMA (OFDMA), and improved modulation and coding schemes have combined to increase spectral efficiency allowing cellular network operators to mitigate some of the effects of the explosion in mobile data consumption.
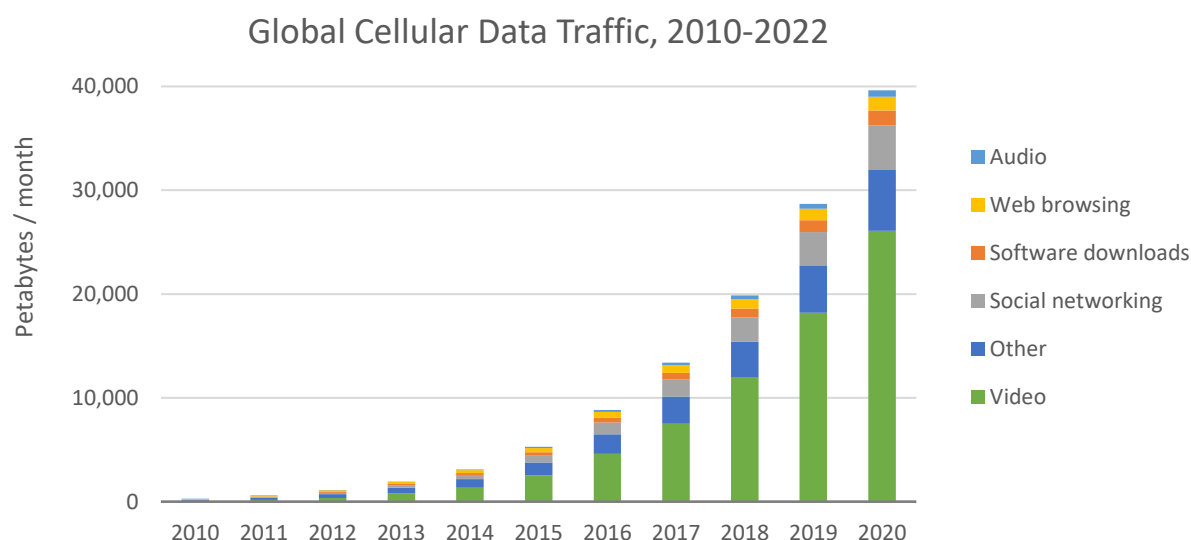
Global Cellular Data Traffic, 2010-2022

Figure 2. Global Cellular Data Traffic from 2010-2016 with Forecasts from 2017-2022, by Application Type.[2]

The evolution from 4G to 5G is still taking shape but there have already been numerous reports on the potential benefits that 5G technology will enable. Contrary to the evolution between previous generations of technology, 5G will offer advances along three fronts simultaneously: data rates, connectivity, and reliability. 5G proposes to bring multi-Gbps data rates to mobile using greater bandwidth, more flexible spectrum use with additional spectrum in higher frequency bands, such as millimeter wave (mmWave), Coordinated Multi-Point access (COMP), and enhanced spectral efficiency using massive MIMO, 3D beamforming, and other advances. Improved connectivity with reduced latency and support for networks of high-density low-bandwidth Internet of Things devices will be attained with techniques like Multi-access Edge Computing (MEC), Software Defined Networking (SDN), and others. Reliability will be improved to enable critical communication applications. The new 5G network will be flexible, configurable and scalable, with network slicing, Network Functional Virtualization (NFV), and new levels of Radio Access Network (RAN) Transport Interaction (RTI). In short, it will take concerted development across multiple areas to fully realize the potential benefits of 5G.

2.2 CELLULAR TECHNOLOGY LIFE CYCLES AND TRENDS

As we have seen, this process of development and evolution has occurred not only from one generation of technology to the next but also within each generation of technology. The advances between 1G to 2G and 3G to 4G are somewhat more pronounced and influential than some of the more incremental changes

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[1] _Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016-2021._
[2] _Ericsson Mobility Report._ June 2017.

during the 2G years such as the shift from GSM to GPRS to EDGE. There are clear parallels to technology adoption life cycles and the product life cycles that have been used to describe these cyclical trends.

The cycle for a new technology or product, shown in Figure 3, begins in the introduction stage when it is first used by a small group of innovators or early adopters that are enticed by the novel benefits or properties that differentiate from existing solutions. This is followed by a growth stage characterized by increasing awareness and accelerating usage leading to rapid expansion. Eventually growth will slow as the technology or product has been adopted by a substantial portion of the market, marking the maturity phase. The final phase, decline, occurs when a mature technology or product loses its appeal due to increasing competition and pressure from the next wave of innovation that looks to supplant it.
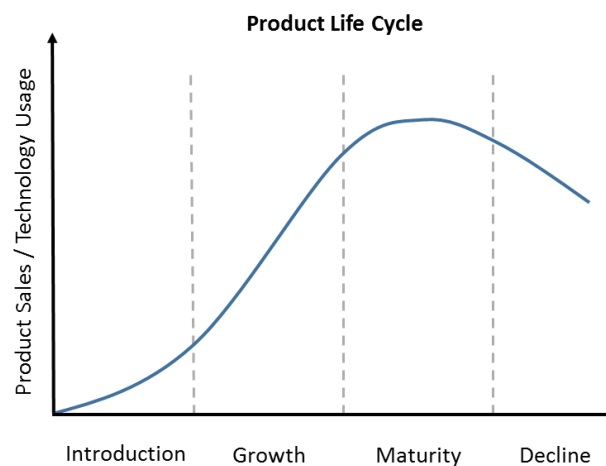

Figure 3. Representation of the Stages of a Typical Product or Technology Life Cycle.

Seen from this point of view the life cycles of cellular technologies have unfolded slightly differently. First, there has been a marked improvement in the quality and capabilities as one generation builds on the successes and achievements of the previous. This means that the decline of 3G technology has not resulted in a drop off in quality for the user but rather an improvement as it is being overtaken by faster and more efficient 4G technology.

Second, there has been significant overlap between generations of cellular technology; for example, 2G technology is still in use today even as the introduction of 5G approaches. This is partly caused by the vast array of user equipment and their disparate capabilities. Consequently, even when the next generation of cellular technology, or even a new network feature, is deployed, there may be very few devices capable of taking advantage of these improvements. Remember that the same product life cycles also apply to devices. The ever more powerful (and often more expensive) smartphones are only replaced when new devices offer a compelling value proposition, that is unless users lose or damage them. Often it might take a few years for capable devices to reach the hands of a sizeable portion of the user base. Thus, a network operator ends up supporting layers of overlapping technologies that are slowly phased out over different time scales. Furthermore, deployment of new cellular technology has not occurred simultaneously in each region of the world. This also may encourage continuing support of legacy technologies as greater economies of scale are eventually reached worldwide, prolonging the lifespan and contributing to a fragmented technology ecosystem. Figure 4 illustrates how overlapping technology and product life cycles have influenced the evolution of mobile phone subscriptions by technology type around the world, both in recent years and forecasting into the future.
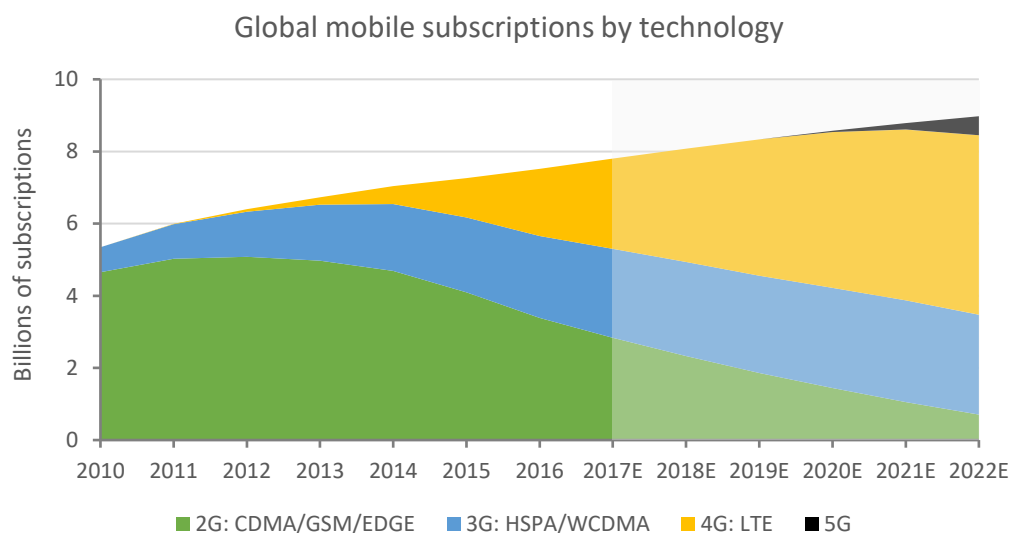
Global mobile subscriptions by technology

Figure 4. Global Mobile Phone Subscriptions by Technology Type from 2010-2016 and Estimates for 2017-2022, (numbers in billions of subscriptions).[3]

In the past, much of what has propelled these cellular technology cycles forward has been consumer demand for new features and capabilities. From 1G to 2G there was a clear need for better voice communication and mobility. The transition between 2G and 3G was driven by demand for more capable mobile data access and improvements in data service caused consumers and businesses to consider and explore the ramifications of the mobile Internet. The shift from 3G to 4G, spurred by consumer demand for faster mobile data speeds and expanded network coverage, has mostly been about consumers and businesses beginning to reap the benefits of a more connected and mobile society that has resulted from a combination of technological developments and increasing global market penetration. 5G is expected to expand on this theme of connectivity and mobility but will likely have profound economic implications but through a different set of market drivers.

2.3 MARKET DRIVERS AND ECONOMIC IMPLICATIONS FOR 5G

Over the course of the last 20 years we have witnessed a rapid expansion in the number of cellular phone subscriptions. People around the world have adopted cellular technology because it has provided dramatic improvements in communication, added flexibility, and enabled entirely new services. In 1995, there were only 33.6 million cellular phone subscriptions in the United States for the population of 266 million people. By 2015, the number of cellular phone subscriptions had grown to 382.3 million, nearly a twelve-fold increase, surpassing the total population of 321 million. At the same time the utility of cellular phones coupled with expanding coverage and enhanced reliability have all directly impacted traditional landline telephones. Landline telephone subscriptions in the United States grew steadily until peaking at 192.5 million in 2000, this peak and subsequent decline coincided with the rise of cellular phones. In other words, as cellular technology developed and evolved it began to offer consumers more utility and better value than landline telephones, a clear parallel to the technology life cycles described in the section above. Similarly, 5G will need to drive new use cases to expand its value proposition to continue to play a prominent role in people's lives. This is especially important in mature markets like the United States, which shows slowing

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[3] *Ericsson Mobility Report*. June 2017.

growth in cellular phone subscriptions and is nearing market saturation with 95 percent of American adults owning a cellular phone, as of November 2016.[4]
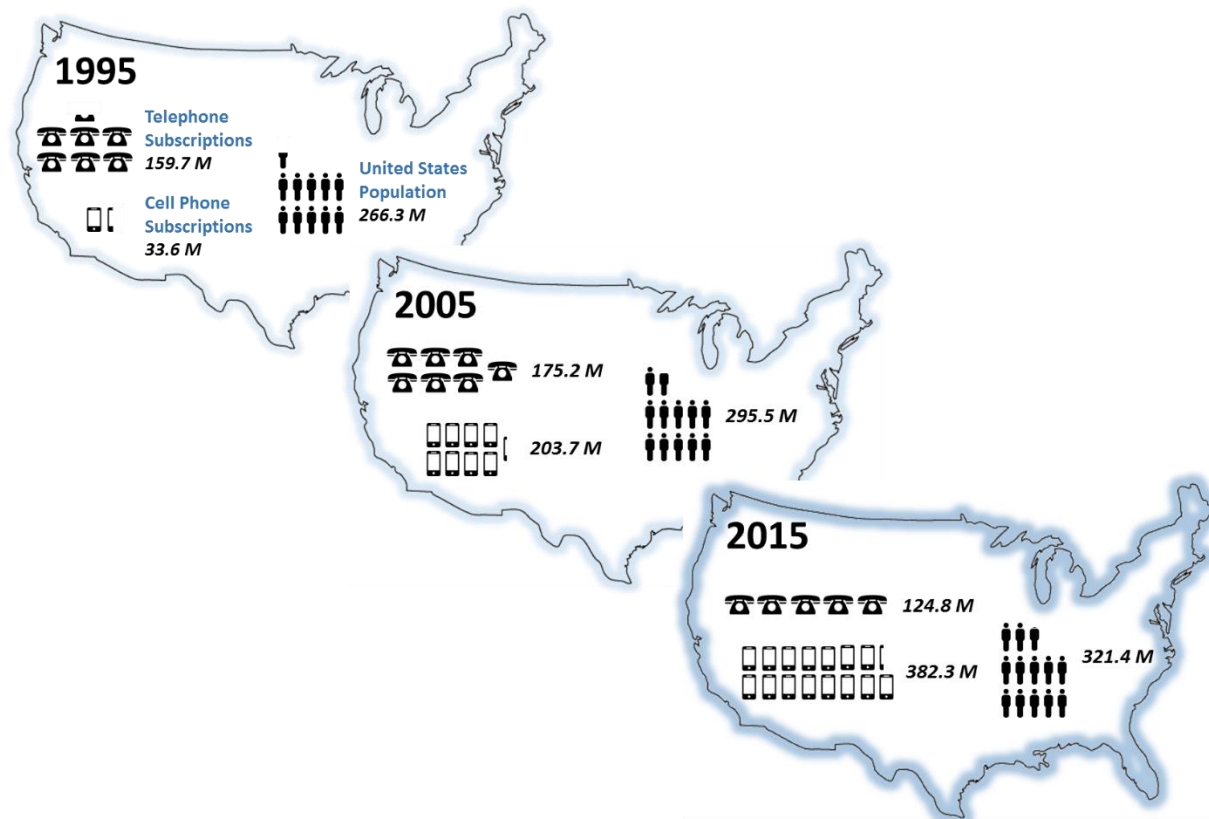
Figure 5. Evolution of Landline Telephone Subscriptions, Cellular Phone Subscriptions and Population in the United States from 1995-2015.[5]

5G has the challenging task of needing to deliver incremental value for both consumers and cellular network operators on multiple fronts. In economic terms, think of the balancing of supply and demand, with network operators providing the supply of 5G networks and consumers the demand for 5G cellular service. For cellular network operators to make the necessary upgrades on the network side they will need to be able to realize benefits from their capital investments through reducing their costs to supply the service, increasing consumer demand, or a combination of both. 5G innovations such as massive MIMO, software defined networking, mobile edge computing, network slicing, and network functional virtualization, among others, promise improved efficiencies in data delivery and more flexible and cost-effective network architectures. This alone should provide network operators a substantial incentive for 5G deployments.

On the consumer demand side, cellular phones have become an integral part of people's lives and that has led to rising expectations. It is no longer sufficient for there to be network coverage; consumers now demand high data speeds and high reliability, wherever they are and whenever they want. 5G can meet and exceed these expectations by providing gigabit speeds while retaining the high mobility that has differentiated cellular technology. Faster data speeds and lower latency will improve the consumer experience by enabling new use cases like augmented and virtual reality (VR), ultra-high-definition (UHD) video, and

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[4] *Mobile Fact Sheet*, Pew Research Center. 12 January 2017.
[5] The World Bank.

seamless video calling. More accessible high-speed mobile broadband on public transportation and in smart offices will improve mobility while mobile TV, on demand video, and broadcast improvements will create richer multimedia experiences. Faster data speeds will also allow consumers to do more on their mobile devices, boosting efficiency and productivity. Likewise, better service reliability will not only reduce frustration and improve the user experience but will be critical in delivering improvements to public safety and emergency response.

5G will also enable a range of Internet of Things (IoT) applications that will capitalize on improvements in data speeds, latency, reliability, and massive scale communication. Many of these IoT use cases will affect consumers on the individual level by providing better efficiencies and simplifying daily tasks such as in smart homes and smart cities. Industrial automation and tactile Internet also offer potential for improvements that will benefit consumers and producers alike.

The concept of benefits being realized beyond the individual level and having an impact at the community and even national levels is important when looking at the value that 5G technology might unlock. As an example, vehicle-to-vehicle (V2V) connectivity with 5G technology has the potential to relieve traffic congestion and reduce fuel consumption, benefitting consumers at the individual level. V2V connectivity would also reduce accidents, saving lives and decreasing medical costs at the community level.

At the national level, improving individual productivity by reducing commuting times and lowering medical costs collectively have significant economic and health impacts. Similar effects on the individual, community, and national levels can be envisioned in many other areas, from wearables and health monitoring devices to industrial automation.

In Section 3, the effects that 5G technology will have on industry verticals and the transformations that will occur in automated factories, media and entertainment, healthcare, the automotive industry, and the energy industry are reviewed. The broad range of 5G use cases and services that are undoubtedly part of what will make 5G impactful will be described in further detail in Section 4. Use cases such as remote healthcare, connected vehicles, industrial automation, and mobile broadband everywhere will provide tangible benefits and additional value on multiple fronts, which will drive adoption and integration of 5G technology in our daily lives.

With its wide-ranging capabilities and impacts, 5G technology may be viewed as an innovation platform. The improvements in mobile connectivity that it will provide allow new use cases to be developed and even the creation of new ecosystems, above and beyond what can be conceived today. The rise of cellular phone apps and the digital economy, as they evolved during the transition from 3G to 4G networks, and the central role they currently play would have been difficult to predict and they have evoked such a dramatic change. The technological change from 4G to 5G promises to be more revolutionary and have a profound impact, from unexpected use cases to transforming entire industries, to possibly even creating new ones.

3. VERTICAL INDUSTRIES TRANSFORMATION BY 5G TECHNOLOGY

Vertical Industries are going through a new wave of generational transformation driven by multiple factors including societal changes, economic challenges and aging of populations. In the next decade, many industries are evolving towards distributed production, connected goods, low energy processes, increasing automation, collaborative robots, integrated manufacturing and logistics.[6]

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[6] *5G Empowering Vertical Industries*, 5G-PPP. 5g-ppp.eu, April 2016.

The major incentives abetting this transformation are the potential to reap cost advantages and improve efficiencies by leveraging and integrating the latest advancements in the cellular, electronic, computing and manufacturing industries. For example, by 2020, autonomous and cooperative vehicles with enhanced safety and security standards are expected to be adopted in the U.S., Japan and Europe.

The development of renewables for new means for energy production, the evolution of traditional power grids into more flexible and robust smart grids that will support the distributed generation and storage of power; and the dynamic routing of electricity flows using smart meters at homes, will require the advancements in wireless technologies that can be provided by 5G. Entertainment and digital media sectors are experiencing a shift in focus towards content creation both from new commercial entrants and increased demand for user generated content, ultra-high definition media and the confluence of broadcast and cable TV and digital media.

There is a major push in the healthcare sector to provide individualized healthcare that better utilizes connected technology and a transition towards distributed patient-centered models of providing specialized care both in person and remotely via the latest innovations in cellular technologies.

In this section, the most significant vertical industries that are awaiting transformation by 5G technologies are examined as well as how 5G will be a principal driver of that change. The key developments in these vertical industries are considered in terms of incorporating new and enhanced technical capacities to meet the new demands for new products and services. The latest trends and the high-level requirements needed from a 5G network to meet the key dependencies of these vertical industries are explained.[7]

3.1 AUTOMATED FACTORIES

There is a major transformation underway in manufacturing and industrial processes known as Industry 4.0 that seeks to bring in new cost efficiencies with smart factories. Transformation in industrial automation is enabled by advances in mass connectivity, cloud computing, big analytics and intelligent automation. The need for digitization of factories in the next decade will capitalize on the availability of new 5G technologies.

The latest plans and designs for reviving manufacturing and improving factories is centered on increasing the efficiency of production lines based on robotic automation and connecting distributed production sites, suppliers and logistics. The need for energy efficient communication schemes supporting data collection scenarios and providing for features such as augmented reality and remote services to enable knowledge sharing is paramount in the changing landscape of automated factories.

According to Accenture, the industrial IoT is forecasted to add about $14.2 trillion to the global economy by 2030 and will generate an economic impact of $1.2-3.7 trillion per year by 2025.[8] The following are some notable aspects of manufacturing that will be transformed by 5G technology.

Industrial Process Automation

Industrial processes, localized or geographically distributed, will be automated to ensure quality, consistency, and cost-effective production of goods or services. Automation systems for these processes broadly consist of instrumentation, control, human interface, and communication subsystems. These processes are in general spread over a large area and utilize a large number of sensors and actuators to monitor and control complex processes that are connected with each other. Connectivity is required for

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[7] *Perspectives on Vertical Industries and Implications for 5G*, NGMN. www.ngmn.org, October 2016.
[8] *Winning with the Industrial Internet of Things*, Accenture. 2015.

these sensors and actuators both indoors and outdoors with high availability and reliability to ensure seamless production and the ability to adapt processes in real-time for maximum flexibility.

Automated Production Lines

Different types of devices such as sensors, robots, actuators, etcetera, in a production line need to communicate wirelessly with low latencies to enable efficient production. Even with such a complex mix of different types of devices, a high degree of reliability is required for automation and control. This challenging combination is the key for high productivity in production lines.

Inventory and Supply Chain Optimization

The management of inventory and supply chains will leverage a large number of connected sensors and platforms that provide big data analytics to automate inventory and supply chain management decisions. 5G technologies are expected to meet the expanding scale of connections in mass numbers and enable end-to-end operation with broad coverage areas, offering advantages over the RFID technologies that are currently used. Energy constraints and efficiencies are key challenges that requires low-power technology features to support these scenarios.

Inter- and Intra-Enterprise Communication

Secure connectivity between different relevant nodes within and between enterprises are needed for real-time coordination. Globally distributed production sites and different nodes of the value chain such as the suppliers and logistics managers need to be able to interact seamlessly to maximize operational efficiency and ensure maximum value creation.

Remote-Human IoT

New technology such as augmented and virtual reality will take advantage of better connectivity to provide remote human assistance. Using videos and interactive features, they will provide guidance in tasks related to product assembly, maintenance, fault identification, etcetera. Remote control of instruments, robots, and others will be used to conduct measurements, handling of hazardous material, digging, tele-operation of industry vehicles, and more. The connectivity requirement is to provide cost efficient and reliable high-data rate and low latency communication links.

3.2 AUTOMOTIVE INDUSTRY

The transformation in the automotive industry is mainly driven by the introduction of electric vehicles and advancement towards automated driving. Currently, advanced driver assistance systems are being implemented to reduce fatal accidents and support the driver in conducting routine tasks and managing complex traffic situations by sensing nearby vehicles, road conditions and pedestrian activity.

With additional technology development, advanced driver assistance systems will be replaced by fully autonomous vehicles that are capable of both monitoring the surrounding the environment and performing driving functions. Autonomous vehicles will improve the flow of traffic, relieve congestion, reduce fuel usage, and transform how people commute. Autonomous vehicles will also enable a wide range of new business opportunities for a broad range of industries and offer environmental benefits.

5G can realize this vision of autonomous vehicles by supporting the exchange of sensor information in real time with the massive number of connections needed to communicate with thousands of cars, roadside sensors and other devices that may be in close proximity. 5G is also expected to provide high performance,

reliable and robust communications, and enhanced coverage to support collision avoidance in urban and rural areas. To make this a reality, industry trials on automated driving are currently being conducted by various automotive companies in collaboration with OTTs and Telecom operators.

Assisted Driving

By providing the vehicle with real-time maps for navigation, speed warnings, road hazards, vulnerabilities, heads-up display systems, sensor data sharing, etcetera, advanced driver assistance features will reduce fatal accidents and traffic congestion. These features will enable the vehicle to dynamically change its course on the road under certain scenarios and conditions. So-called vehicle-to-network (V2N) communications are necessary for this use case including short-range modelling and recognition of surrounding objects and vehicles plus mid- to long-range modelling of the surroundings with securing information on the latest digital maps, traffic signs, traffic signal locations, road construction, and traffic congestion.

Autonomous Driving

Fully autonomous driving involves the capability of a vehicle to sense its environment and navigate without human input under all scenarios and conditions. This is an evolving development area, but it is anticipated that by 2020, this is will be fully developed. Autonomous cars use a combination of technologies to detect their surroundings including wireless communication technologies, laser and radar sensing, GPS, odometers, computer vision, and advanced control systems.

All this data is analyzed, processed with artificial intelligence and deep learning computer systems to distinguish between different cars on the road and identify appropriate navigation paths given obstacles and considering the rules of the road. 5G technologies will enable these cooperative automatic driving use cases in an enhanced fashion where sensor information will be exchanged in real time between thousands of cars connected in the same area. The 5G features are expected to provide communications with increased coverage, reliability and performance levels with higher orders of magnitude compared to existing technologies today.

Tele-Operated Driving

Better connectivity brought about by 5G technology will allow remote driver assistance in areas where automatic driving is not possible. This would provide enhanced safety for disabled people, elderly populations and in complex traffic situations. Typical application scenarios include, disaster areas, unexpected and difficult terrains for manual driving such as in mining, construction, nuclear plants, and more.

Vehicle-to-network (V2N) communications such as sending video, sound feed information and other diagnostics from the vehicle, along with environmental information, to the remote driver and reliably transmitting control commands from the remote driver to the vehicle to maneuver the vehicle in real-time may be enabled with 5G. The requirements to support these communications consist of meeting strict constraints on latency, reliability and security in a wide coverage area.

In-Vehicle Media

The importance of providing enhanced multi-media connectivity to vehicle passengers will become an expectation in the future. This includes features such as high-definition video streaming, virtual reality, augmented reality and video conferencing. Sufficient data rates and the bandwidth to serve all passengers

in a vehicle, whether it be a single driver or a scenario involving a city bus, will need to be considered. The adoption of autonomous vehicles will only provide passengers more free time, placing greater demands on wireless networks to meet their connectivity needs.

3.3 ENERGY

The rising costs of energy production and the delivery of electrical energy to the end customers are the main reasons for a major transformation in the energy industry. There is a new drive to bring in improvements and efficiencies in energy distribution and use, scheduling appropriate levels of generation to minimize gaps between supply and demand, and provide energy only as needed to minimize waste.

5G communication technologies will enable the intelligence needed to implement the new infrastructure and support two-way energy distribution and new business models that leverage increased efficiencies in production, delivery, use and coordination of limited energy resources.

Smart Grids

Improved communication technology will enable enhanced monitoring, better management, greater control of energy generation and distribution networks leading to increased availability and resilience. Energy generation and distribution are shifting towards decentralized and smaller power generation sources with more variable power delivery that will require tighter integration and secure communication networks.

Also, new storage solutions are used as part of the delivery process with new battery materials offering higher energy storage capacities. With these new energy generation and storage scenarios emerging, there is an expansion of usage patterns and end devices such as the proliferation of electric vehicles and IoT. Low latency and ultra-reliable communication with 5G networks will meet the communication requirements for Smart Grids.

Grid Backhaul and Backbone

In the smart grid backhaul and backbone domain, networks provide the needed control monitors and fault protection. The communications are built to meet strict requirements on latency for automated fault detection, security, resilience and reliability. The reliability and security of network systems are essential for mission critical applications that includes device authentication, data protection and identity of end devices.

Grid Access Communication

The access communication systems provide efficient connectivity to a massive number of smart meters with enhanced indoor coverage requirements but relaxed requirements on latency, reliability and bandwidth compared to the grid backhaul and backbone.

3.4 HEALTHCARE

According to the Centers for Medicare and Medicaid Services (CMS), U.S. healthcare spending accounted for 17.8 percent of national Gross Domestic Product (GDP) in 2015, more than any other nation, and spending is expected to reach nearly 20 percent of GDP by 2025.[9] Limiting the cost of healthcare and providing more effective care are the main challenges in this vertical. 5G is expected to bring new

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[9] *National Health Expenditure Fact Sheet,* Centers for Medicare and Medicaid Services. 2015.

efficiencies, particularly in creating self-management capabilities and facilitating access to healthcare to minimize costs.

This will partly be accomplished via mHealth, a general term used for the application of mobile phones and other wireless technology in medical care. The most common application of mHealth today is the use of mobile phones and communication devices to educate consumers about preventive healthcare services.

Another key application is eHealth, which broadly refers to the use of information and communications technologies in healthcare. eHealth is an emerging field at the intersection of medical informatics, public health, and business, that aims to deliver health services and information through the Internet to reach people via mobile wireless technologies and broadband connections.

5G is expected to boost mHealth and eHealth applications in a major way to enable the introduction of additional services such as personalized or precision medicine initiatives with distributed, patient-centric approaches. These services would leverage the more distributed and modular 5G architecture including SDN, NFC, MEC and enhanced security features. In addition to improving connectivity with the real-time integration of a massive number of connected IoT devices, the processing of Big Data and the application of machine learning to these data sets is expected to have a dramatic impact.

The integration of data across different networks and the aggregation of services across different domains will support various care models that include billing and care accounts where patients can better control their care and allocate financial resources as needed.

5G also has huge potential to enhance the capabilities of the surgeons by utilizing robots for remote applications. This will improve healthcare in locations lacking trained specialists and impact people that do not have the means or capability to travel to the top hospitals for care. 5G technology requirements include ultra-low latencies and real-time sensing and perceptions for audio, vision, and haptics to enable these augmented or virtual reality applications.

The following healthcare areas will be strongly impacted by 5G technology.

Remote Health Monitoring

Various types of sensors and wearable devices will be used to track health-relevant indicators. Currently, devices use short range communication technologies such as Bluetooth and Wi-Fi to connect to smartphones and rely on apps on smartphone to collect data to monitor and manage wellness indicators such as heart rate and blood glucose levels.

Public health services can make use of such big data to monitor and detect the onset and spread of epidemics by combining geographic data and other data sources. Service providers could play a role in enabling connectivity between the monitoring devices and sensors and trusted third parties for data collection and analytics.

The bandwidth and latency requirements could be addressed with existing cellular technologies; however, the challenge is to support the massive increase in the number of connections per square meter while still maintaining the requisite Quality of Service (QoS).

Remote Healthcare

Moving beyond mere health monitoring, remote healthcare will enable individualized consultations, treatment and patient monitoring outside of traditional healthcare institutions like hospitals and clinics.

Patients and practitioners could use video conferencing and telepresence facilities for remote consultation and visits.

This could be complemented by remote transfer of health-related data from sensors and devices either in real-time or uploaded in advance to the cloud. Treatment could also be offered using smart pharmaceutical devices that correctly administer approved dosages of a drug on a schedule specified by the physician or practitioner.

Practitioners could also remotely monitor progress of treatment in real-time with the help of data from health sensors as well as voice and video feeds and adjust treatment as necessary. Service providers can utilize 5G technology to provide a connectivity platform to facilitate these activities that would require delivery of real-time commands and controls and possibly low latency communications with a provision for mission-critical services.

Remote Surgery

The capability of a surgeon to remotely operate a surgical robot to perform surgery on a patient will allow more uniform access to talented surgeons and better utilize their skills. The role of a service provider is provisioning of the communication link to allow video and audio feeds as well as data to be reliably transferred in real-time between the surgeon and the remote surgical robot.

Here, extremely high reliability and very low latency are necessary. In addition, transfer of high resolution images and video to the surgeon requires large bandwidth on the uplink. In event of an emergency, high availability of the necessary robots and surgeons certified for their use will also be required. QoS guarantees for extremely low latency and reliability requirements are critical.

3.5 MEDIA AND ENTERTAINMENT

There has been a profound and significant transformation happening in the media and entertainment industry especially in terms of improving the user experience and enabling access to an expanding universe of content anytime and anywhere. This vertical opportunity focuses on different types of multi-media services that include regular live/linear media, on-demand content, user generated content and gaming. Due to consumer demand, media use needs to meet both stationary and mobile end users. The end users are also consuming media on an increasing variety of devices that include TVs, smartphones, tablets, wearables and other devices.

This vertical increasingly requires higher data rates to provide high resolution multimedia content to an increasing number of simultaneous and connected users with very high QoS requirements. With more devices capable of recording and capturing our daily experiences, there has been a dramatic increase in user-generated content. The popularity of social media sharing and the growing size and scale of platforms like Facebook, Instagram, and Snapchat, among others, are also driving requirements for increased uplink data rates.

5G technologies are expected to play a key role for this vertical; it is a top priority to integrate different network technologies, including unicast, multicast and broadcast, to provide a more efficient delivery method to meet the various requirements.

4. 5G USE CASES AND SERVICES

The main reason why mobile technology became nearly ubiquitous over the past 40 years is that it supports such a wide variety of use cases, from telephony text messaging and email to telemedicine and autonomous vehicles, to name just a few. This section explores a representative sampling of use cases and their requirements, such as latency, reliability and speed.

4.1 TAXONOMY OF USE CASES

The transformation of the vertical industries outlined in the preceding section will require 5G technology to support a wide variety of applications and use cases with high variability in key performance attributes such as mobility, data rate, latency and reliability. For example, mobility could range from an application like fixed wireless service to connected vehicles that may be moving at speeds of 80 miles per hour. Data rates could vary across a similar range from bits per second for some IoT devices to gigabits per second for virtual reality. The ultra-low latency needed to enable real-time applications like industrial automation is very different from smart home applications that may be more delay tolerant. Reliability is critical for remote surgery and healthcare monitoring but maybe less so for some remote sensors and meters in smart cities.

In the previous section, a few use cases for different verticals were described and it is notable that even use cases within the same vertical can have very distinct KPIs. As an example, an automated product line use case in the industrial automation vertical requires very low latency and highly reliable communication. These are different KPIs when compared to the use case on inventory and supply chain optimization in the same vertical, which requires a very large number of sensors and the latency requirements are much less strict. Due to this fact, use cases are usually characterized based on their performance attributes.

1) *enhanced Mobile Broadband (eMBB):* These use cases generally have requirements for higher data rates and better coverage

2) *Massive Internet of Things (MIoT):* These use cases generally have requirements to support a very large number of devices in a small area, therefore, very large device density

3) *Critical communications:* These use case have very strict requirements on latency and reliability, and are also referred to as Ultra Reliable and Low Latency Communications (URLLC)

With such a large variation in performance attributes, it may be more useful to consider these very different use cases in terms of their types of interaction: between people, between machines, or between people and machines.

Considering this classification, and grouping the use cases by the primary categories that 5G will impact-- extreme mobile broadband, massive scale communication and ultra-reliable low latency service-- creates a powerful alternative visualization. It enables a vision of the way certain use cases will span across multiple types of interaction and various performance requirements. Figure 6 shows this new taxonomy for some 5G use cases.
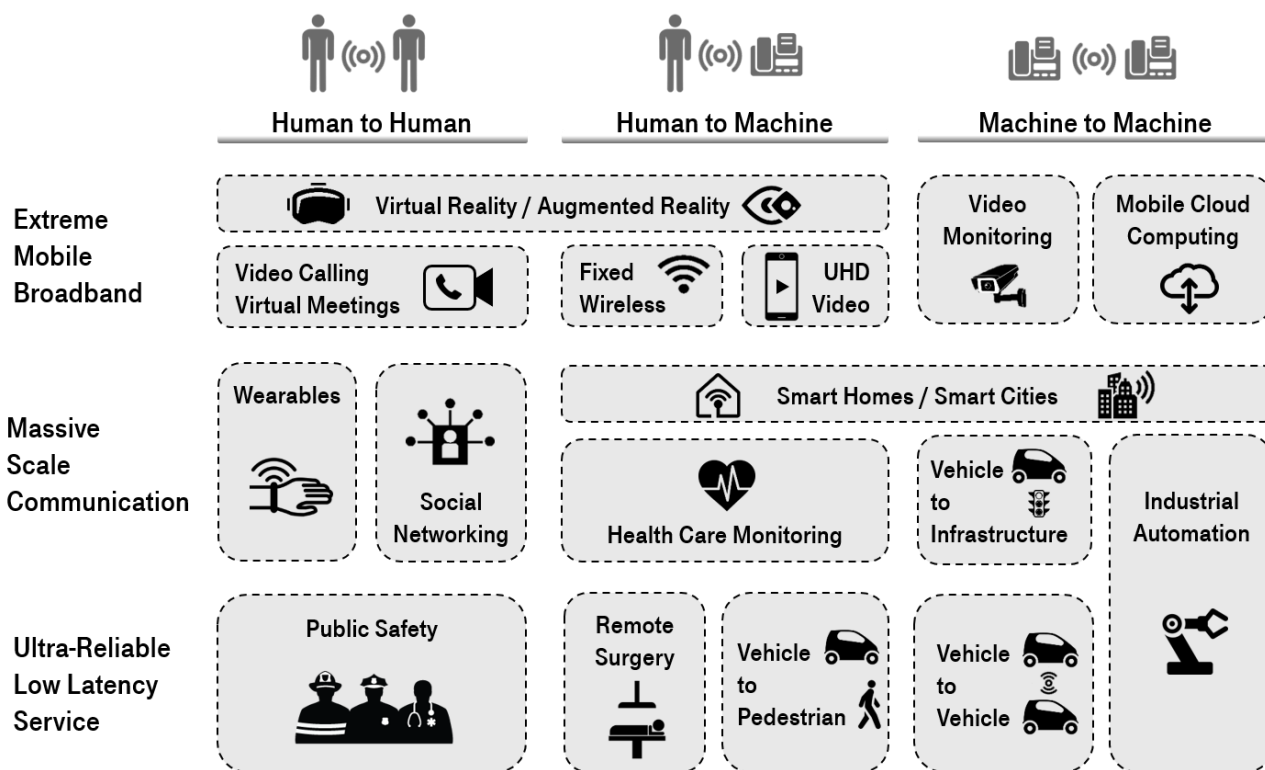
Figure 6. Some 5G Use Cases Grouped by the Type of Interaction and the Range of Performance Requirements.

4.2 USE CASE CATEGORIES

Traditionally 5G use cases have been grouped into more general use case families such as IoT or fixed wireless access. On the other hand, the alternative taxonomy of 5G use cases in Figure 6 illustrates how many use cases span multiple types of interactions and feature categories, providing a more comprehensive picture. In describing the transformation of vertical industries, there were recurring themes of the impact of use case families across multiple industries. In this section, a closer look at the traditional families of 5G use cases is provided and their key requirements and the types of interactions on which they will rely are highlighted. The following comprise the major families of 5G use cases based on multiple previous efforts.[10] [11] [12]

- Enhanced Mobile Broadband
- Connected Vehicles
- Enhanced Multi-Media
- Massive Internet of Things
- Ultra-Reliable Low Latency Applications
- Fixed Wireless Access (Early 5G Deployments)

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[10] *5G Use Cases*, Presentation by Ericsson, www.ericsson.com. July 2015.
[11] *5G Use Cases and Requirements*, white paper by Nokia, www.nokia.com. July 2014.
[12] *NGMN 5G White Paper*, NGMN, www.ngmn.org. February 2015.

4.2.1 ENHANCED MOBILE BROADBAND

This group of use cases is characterized by broadband data access across a wide coverage area in crowded locations, office areas, and high-speed public transport systems. The target is to provide maximum user experience by providing connectivity both indoors and outdoors while delivering high QoS broadband even in challenging network conditions. Multi-user interaction, Augmented Reality, and Context Recognition are essential features for this category of use cases. Following are some of the sub-use cases in this category:

Hot Spots – Broadband Access in Dense Areas

This use case relates to providing enhanced broadband access in densely populated areas such as high-rise building complexes, urban city centers, crowded areas, and etcetera. Moderate mobility and high data rates will be required.

General Broadband Everywhere

This use case relates to providing a consistent user experience, guaranteeing user speeds of 50+ Mbps everywhere towards a mobile and a connected society. The user data has to be delivered consistently across the coverage area. High mobility will be required.

Public Transport

This use case is about providing broadband access in public transport systems such as high-speed trains. The use case consists of providing robust communication link and high-quality Internet for information, entertainment, interaction or work with a high mobility component.

Smart Offices

This use case in characterized by heavy data use in an indoor environment that will require low mobility. This is a use case scenario where hundreds of users require ultra-high bandwidth to serve intense bandwidth applications.

Specific Events

This use case requires providing very high connection density in scenarios such as stadiums, concerts and large gatherings where several hundred thousand users are served at high data rate and low latency.

4.2.2 CONNECTED VEHICLES

The category of use cases involving mobile communications related to Connected Vehicles is going to be an important driver for 5G. This category of use cases entails supporting advanced safety applications mitigating road accidents, improving traffic efficiency, and improved access for emergency vehicles. These applications require a concerted framework with features supporting ultra-low latency for warning signals, higher data rates to share sensor data and information between vehicles and infrastructure, high mobility, high reliability and scalability of features. Vehicle-to-everything (V2X) communication, as defined in 3GPP, consists of four types of use cases: vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-network (V2N) and vehicle-to-pedestrian (V2P).

- V2V and V2P communications are essentially between vehicles or between vehicles and vulnerable road users (for example, pedestrian, cyclist) to provide information about location, velocity and direction to avoid accidents

- V2I includes communications between vehicles and traffic control devices in the road vicinity. V2I transmission is between a vehicle and a road side unit (RSU). An RSU is used to extend the range of a message received from a vehicle by acting as a forwarding node

- V2N transmission is between a vehicle and a V2X application server to provide connected services to a vehicle

4.2.3 ENHANCED MULTI-MEDIA

This category of use cases targets providing a high-quality media experience everywhere to meet the growing demands of consumer media consumption. The targeted users are the end viewer, pay TV operators, broadcasters, new content owners, content aggregators, and OTT providers. Recent developments of 4K and 8K video resolution, 3D video, expanded use of HD TV, streaming audio and video services and interactive video on the go over a growing number of video-capable devices are key driving factors for this family of use cases. The higher data capacity, faster data rates, and enhanced broadcast/multicast features will serve these use cases and realize the media vision for a seamless mobile TV experience. Some of the use cases include:

Broadcast Services

These services distribute content in both real time and non-real time across a wide distribution area and are typically dominated by the downlink with the uplink providing a feedback channel for interactive services. Sub-use cases consist of:

- Delivering news and information in audio and video to customers in specific geographic areas

- Delivering local services within 1 to 20 km that include scenarios such stadium events, advertisements, fairs, conventions and emergency notifications

- Delivering services in a larger distribution within 1 to 100 kms that includes scenarios such as communicating traffic jams, disaster emergency warnings, etcetera

- Delivering services at a national level as a complement to broadcast radio or television with additional benefits for the automotive industry

On Demand and Live TV

This use case is based on scaled up delivery of high resolution content via live TV or on demand video using enhanced data capacity and data rates.

Mobile TV

Defined by delivery of video streaming and entertainment media to smart phones, tablets and other devices in high mobility environments such as trains, cars, and buses.

4.2.4 MASSIVE INTERNET OF THINGS

The category of use cases in Massive Internet of Things addresses the emerging Low Power Wide Area (LPWA) needs for low cost devices, extended coverage, and long battery life. The use cases are expected to make up a large part of the new types of services that 5G systems will address by connecting the massive number of devices such as sensors, actuators, cameras, and etcetera.

This family of use cases is expected to be pervasive in urban, sub-urban and rural areas providing metering, lighting management in buildings and cities, environmental monitoring (pollution, temperature, noise, etcetera) and traffic control, among many other applications.

These services are expected to require the ability to support a very high density of devices with different characteristics in a common communication framework. The Massive IoT use case category includes applications used in a wide spectrum of industries across society, including both human-to-machine interaction and machine-to-machine interaction, as shown in the following Figure 7.
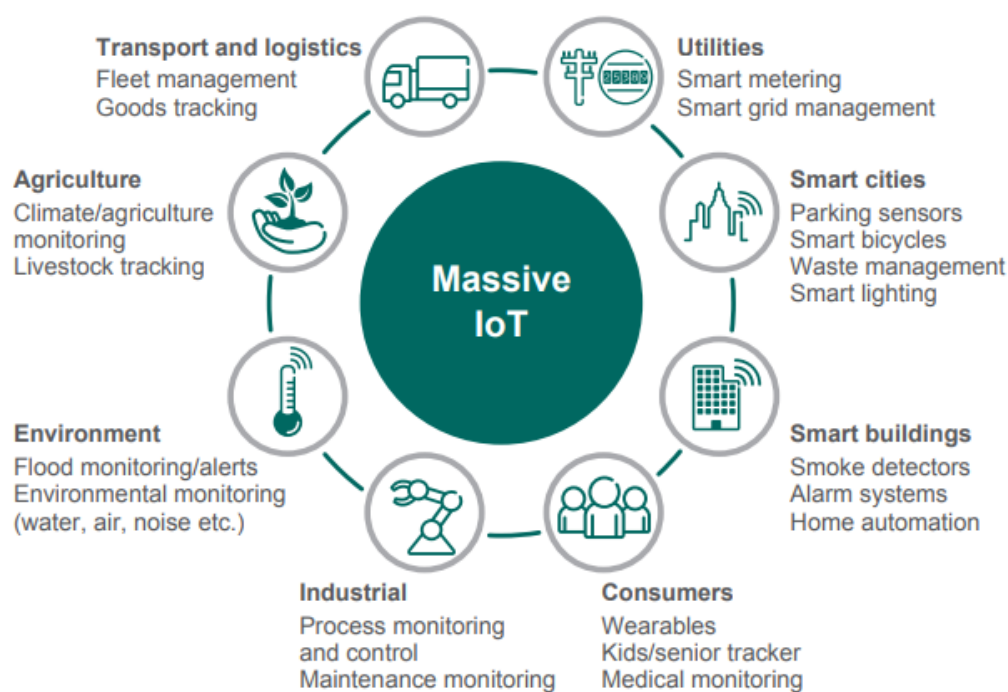
Figure 7. The Several Use Cases in Massive IoT Category Enabled by 5G Technologies.[13]

4.2.5 ULTRA RELIABLE LOW LATENCY APPLICATIONS

These use cases are the critical IoT applications that will have very high demands on reliability, availability and low latency with lower demands on the volume of data, but significantly higher business value. These use cases also fall into the category of mission-critical Machine-Type Communication (MTC).

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[13] *Celluar Networks for Massive IoT*, white paper by Ericsson, www.ericsson.com, January 2016.

The mission-critical MTC is envisioned to enable real-time control and automation of dynamic processes in various fields, such as industrial process automation and manufacturing, energy distribution, and intelligent transport systems.

These applications and use cases require communication with very high reliability and availability, as well as very low end-to-end latency going down to the millisecond level. These use cases and applications feature interactions across all categories, human-to-human, human-to-machine, and machine-to-machine. Sub-use cases in this category include the following:

Process Automation

These use cases are centered on information integration and enabling process automation useful in the oil and gas, chemicals, energy and water industries. The application here covers the pumps, compressors, mixers, monitors of temperature, pressure, flow controllers, etcetera.[14]

Automated Factories

These use cases involve communication transfers enabling time-critical factory automation that are required in many industries across a wide spectrum that includes metals, semiconductors, pharmaceuticals, electrical assembly, food and beverage, etcetera. The applications for the use cases fall into functions related to material handling, filing, labeling, palletizing, packaging, welding, stamping, cutting, metal forming, soldering, sorting, printing presses, web drawing, picking and placing, etcetera.

Tactile Interaction

These use cases involve interaction between humans and systems where humans wirelessly control real and virtual objects and the interaction requires a tactile control signal with audio or visual feedback. Robotic controls and interaction include several scenarios with many applications in manufacturing, remote medical care and autonomous cars. The tactile interaction requires real-time reactions in the order of a few milliseconds.

Emergency, Disasters and Public Safety

These use cases require robust and reliable communications in case of natural disasters such as earthquakes, tsunamis, floods, hurricanes, and etcetera. The use cases may require accurate position location and quick communication exchanges between users and systems. Energy efficiency in user battery consumption and network communications are critical in these use cases. The public safety organizations require enhanced and secured communications with real time video and the ability to send high quality pictures.

Urgent Healthcare/ Remote Surgery

These use cases are envisioned around applications that will conduct remote diagnosis and treatment. There is a need for remote patient monitoring and communications with devices measuring vital signs such as ECG, pulse, blood glucose, blood pressure, temperature, and etcetera. The remote treatment and response based on monitored data can be life critical for a patient, requiring immediate, automatic or semi-automatic response.

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[14] ARC Advisory Group

Remote surgery applications in a mobile scenario in ambulances, disaster situations, and remote areas require providing precise control and feedback communication mechanisms for surgeons in terms of low latency and high reliability and security.

4.2.6 FIXED WIRELESS ACCESS

Fixed wireless access may be an early 5G use case, taking advantage of the combination of existing fiber footprints and 5G technology to provide localized network access. Fixed wireless networks with 5G are planned to complement fiber to provide high speed data rates without the costly provisioning of fiber all the way to the premises.

4.3 USE CASE REQUIREMENTS

The specific requirements for the different use cases are listed in Table 1.

Table 1. Use Case Requirements.

Use Case	User Data Rate	Latency	Mobility
Hotspots: Broadband Access in Dense Areas	DL: 300 Mbps UL: 50 Mbps	NA	60 km/h
Coverage Everywhere	DL: 1Mbps UL: 100 kbps	NA	0 – 120 km/h
Homes and Offices	DL: 1 Gbps UL: 100 - 500 Mbps	NA	Pedestrian
Public Transport, MBB in Cars, High Speed Trains	DL: 25 – 50 Mbps UL: 10 – 25 Mbps	NA	Up to 120 kmph
Broadband Access in Events & Large Gatherings	DL: 10 - 25 Mbps UL: 25 - 50 Mbps	NA	Pedestrian
Connected Vehicles: V2X	DL: 1 Mbps - 1 Gbps	3-100 ms	250 km/h
Moving Hotspots	DL: 10 - 50 Mbps UL: 5 - 25 Mbps	10 ms	500 km/h
Enhanced Multi-Media: Live TV	DL: 50 - 200 Mbps UL: 500 kbps	NA	0 – 8 km/h
Enhanced Multi-Media: On Demand	DL: 50 - 200 Mbps UL: 500 kbps	NA	0 – 80 km/h

Enhanced Multi-Media: Mobile TV	DL: 10 - 50 Mbps UL: 500 kbps	NA	250 – 500 km/h
Massive IoT: Sensor Networks (Connected Roads, Railways, Buildings, Smart Cities, Parking, Lighting, Environment Monitoring)	DL: 1 – 100 kbps UL: 1 – 100 kbps	50 ms - hours	0 – 500 km/h
Massive IoT: Smart Grid/Utilities	DL: 1– 100 kbps UL: 1 – 100 kbps	50 ms - hours	Pedestrian
Massive IoT: Wearables	DL: 100 kbps - 5 Mbps UL: 100 kbps – 5 Mbps	1 - 10 ms	0 – 120 km/h
Massive IoT: Agriculture	DL: 1 – 100 kbps UL: 1 – 100 kbps	1 - 10 ms	Pedestrian
Industry Process Automation	DL: 100 kbps - 10 Mbps UL: 100 kbps – 10 Mbps	0.5 – 1 ms	Pedestrian
Automated Factories	DL: 100 kbps – 10 Mbps UL: 100 kbps – 10 Mbps	0.5 – 1 ms	Pedestrian
Tactile Interaction	DL: 100 kbps UL: 100 kbps	0.5 – 1 ms	Pedestrian
Emergency Services, Public Safety	DL: 100 kbps – 10 Mbps UL: 100 kbps – 10 Mbps	1 - 10 ms	0 – 120 km/h
Urgent Healthcare	DL: 100 kbps – 10 Mbps UL: 100 kbps – 10 Mbps	1 - 10 ms	0 – 120 km/h
Fixed Wireless	DL: 100 kbps - 5 Mbps UL: 100 kbps – 1 Mbps	10 ms	Pedestrian

3GPP TS 22.261[15] specifies the service and operational level requirements for the 5G system. A summary is included in Appendix A. The different KPIs are:

- User experienced data rate requirements vary from 1 Gbps downlink and 500 Mpbs uplink for indoor hotspot environments to 50 Mbps downlink and 25 Mbps uplink for rural macro environments
- Latency targets are as low as 0.5 ms for tactile interaction
- Capacity targets can be as high as 15 Tbps/km2 with 250 000 users/km2 for indoor hotspots such as office environments

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[15] 3GPP TS 22.261, *Service requirements for the 5G system*; Stage 1 (Release 15).

These service level requirements, in turn, generate operational level requirements for the 5G systems. For example, the 5G network needs not only to be scalable to support a very large number of devices, but also customizable in order to allow for tailoring the network to the different KPIs.

The next section defines how different technologies help 5G meet its performance targets.

5. TECHNOLOGY ENABLERS AND 5G ARCHITECTURE

There are many new features being implemented in the 5G system that work in concert to meet the enhanced quality of service requirements that were discussed in previous sections. To support diverse use cases, 5G is being designed with a full software approach that will transform networks into a programmable, software-driven and holistically-managed network architecture. The 5G system utilizes technology enablers, such as NFV (Network Function Virtualization) and SDN (Software Defined Networking), which allow the efficient and scalable distribution of network functions with SDN principles, splitting the user from the control planes. In this section, an overview of some of the key technology features that are being incorporated in 5G to enable the transformation in vertical industries are reviewed. Subsequently, this section will detail the 5G system architecture defined in 3GPP to support data connectivity and services envisioned for the use cases discussed in this white paper.

5.1 5G TECHNOLOGY ENABLERS

To support the use cases and services described in section 4, the following are some key design features and enablers that are necessary for the 5G system.

5.1.2 AIR INTERFACE FRAMEWORK

Advancements in radio interface design include the utilization of antenna techniques such as massive MIMO and beamforming, new and more spectrally efficient modulation schemes, novel multiple access mechanisms, etcetera. These advancements have been pushing the limit towards theoretical boundaries of channel capacity as expressed by the Shannon Theorem. Nonetheless, employing such new techniques is the means through which spectral efficiency of 5G systems are expected to increase even further.[16]

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[16] *5G Spectrum Recommendations*, whitepaper by 5G Americas. April 2017.

How Do We Achieve Goals of 5G?

Spectral Efficiency

- Massive MIMO and FD-MIMO concepts are central to the 5G theme.
- Potentially large capacity and coverage improvement.
- FD-MIMO work in LTE-advanced is a starting point for developing these concepts for 5G
- Other spectral efficiency improvement through new waveform and overhead reduction

Densification

- Densification via small cell build-out key to RAN evolution.
- Current small cell solution is not scalable beyond a certain point.
- Radically new concepts such as separation of control and data plane, new system architecture are key to achieving an ultra-dense network

Spectrum

- Design system to operate in much larger channel bandwidth. This requires a careful tradeoff between spectral efficiency and power efficiency
- Operate across new licensing scenarios such a unlicensed, or shared licensed
- Operation in low frequency and in mmWave

SDN/NFV

- A key and central requirement to AT&T as a part of Domain 2.0 efforts.
- Apart from implementation challenges of SDN/NVF for 5G, we also need to develop the 5G RAT which allows for L1/L2/L3 functionality to be distributed

Massive Connectivity

- Design the 5G RAT to allow for network slicing down to the physical layer.
- Lightweight or weightless protocol to support massive connectivity.
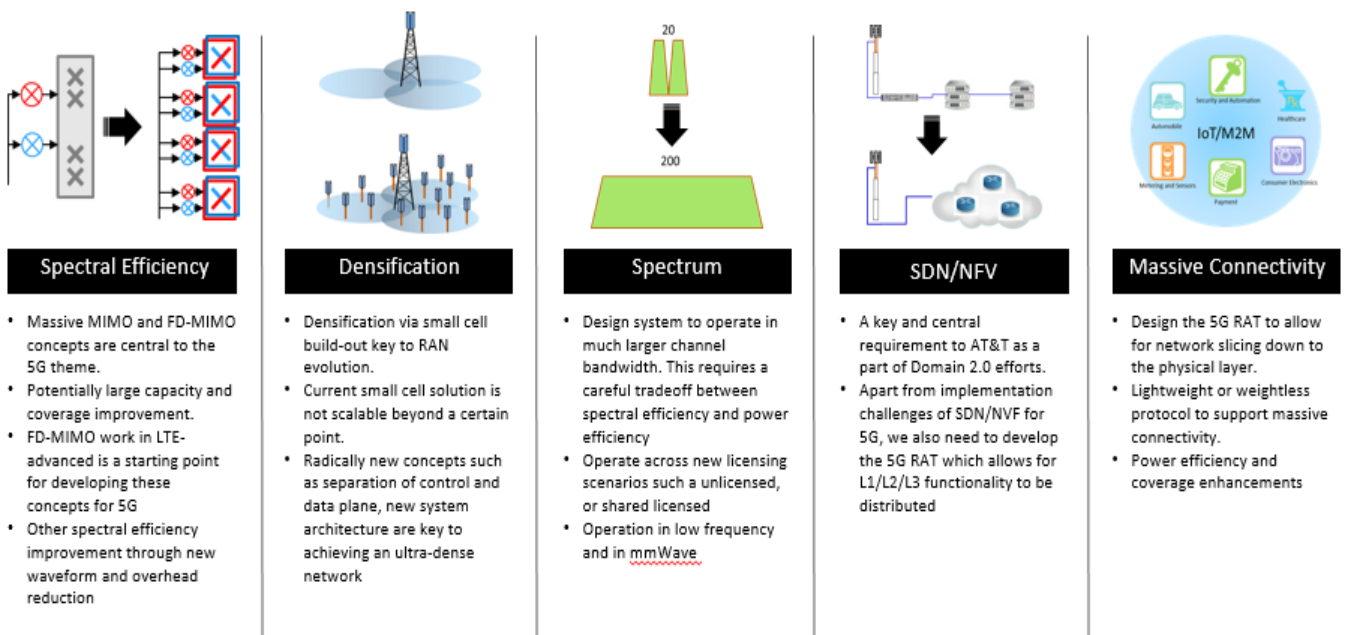- Power efficiency and coverage enhancements

Figure 8. Different Factors Constituting the Air Interface Framework in Achieving 5G Goals.[17]

Densification is a major component of the 5G network, especially in dense urban areas. In order to provide the high data rates and support the system capacity levels expected for 5G systems, densification of the radio access network is required. Densification allows for higher use and obtaining the peak data rates 5G offers in the available limited spectrum resources.

Spectrum is the lifeblood for mobile, which means it's also the lifeblood for all of the mobile applications and services upon which nearly every person and business depends. New spectrum is critical for the success of fifth-generation (5G) terrestrial mobile service. Globally, there are significant on-going activities to identify suitable spectrum, including bands that can be used in as many countries as possible to enable global roaming and economies of scale. Various efforts around the world are underway to find harmonization around spectrum to be used for 5G.

As mentioned previously, 5G services are expected to cover a wide range of applications, generally categorized into enhanced Mobile Broadband (eMBB), Ultra-reliable and Low Latency Communications (URLLC) and massive Machine-Type Communications (mMTC, also referred to as MIoT). In addition to setting different requirements on the network features, applications will drive a wide variety of deployment scenarios. The different physical characteristics of spectrum (for example, range, penetration into structures and propagation around obstacles) leads to some applications being more suitable for, and expected to be deployed in, certain spectrum ranges.[18]

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[17] AT&T
[18] *5G Spectrum Recommendations*, whitepaper by 5G Americas. April 2017.

5.1.3 LTE-NR DUAL CONNECTIVITY

The concept of dual connectivity was introduced in Long Term Evolution (LTE), allowing User Equipment (UE) to receive data from multiple cells. In 5G, the support of dual connectivity is between LTE and 5G New Radio (NR). This is referred to as LTE-NR Dual Connectivity.

Dual connectivity depends on the fact that both LTE and NR coverage exist in a geographical area. Even though the coverage overlaps, the LTE and NR cells (therefore, the base stations) may be co-located or non-co-located. Figure 10 shows three scenarios: in the top figure, scenario 1) LTE and NR cells are overlaid and co-located providing similar coverage (both LTE and NR are macro cells). In the bottom figure, are scenarios 2 and 3, with NR being a small cell and LTE a macro cell. In scenario 2) LTE and NR cells are overlaid and co-located but providing different coverage and in scenario 3) LTE and NR cells are non-co-located. A non-co-located cell refers to a small cell together with a macro cell for which their enhanced NodeB (eNB) is installed at the different location. LTE-NR Dual-Connectivity (DC) supports both the co-located and the non-co-located scenarios.
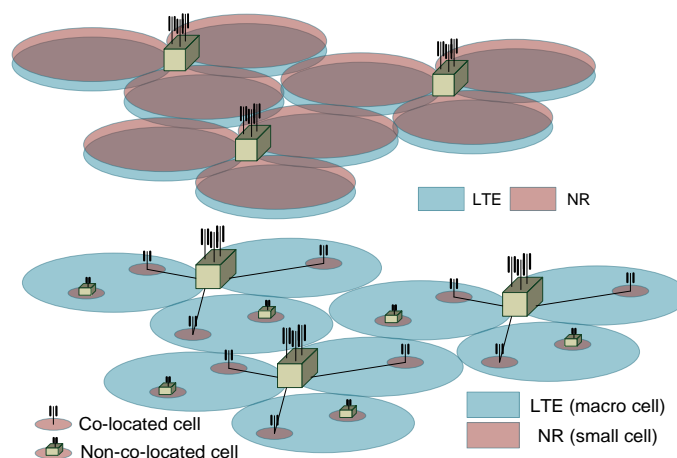

Figure 9: Cell layout where NR and LTE Coverage Co-exists.[19]

Dual connectivity means that the UE is connected to both cells at the same time, and receives and transmits data to each cell. This allows for an increase on the possible data throughput experienced by the UE.

5.1.4 ULTRA-RELIABLE LOW LATENCY DESIGN

Another important aspect of 5G is high reliability and latency reduction techniques. Reliability refers to the capability of guaranteeing a successful message transmission within a defined latency budget. Latency reduction not only contributes to data rate enhancements but also enables new use cases.

There are two enhancements targeted for 3GPP Release 15 to lower latency. The first is reduced processing time: making the terminal respond to downlink (DL) data and uplink (UL) grants in three milliseconds (ms) instead of four ms. The second is the introduction of shorter transmission time intervals (sTTI). Traditional LTE TTI is 14 symbols which is 1 ms scheduling interval. However, with sTTI, both 7

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[19] TR 38.804, Study on New Radio Access Technology; Radio Interface Protocol Aspects, Rel-14.

symbols (0.5 ms) as well as 2 symbols (0.142 ms), scheduling interval is supported. Peak data rate is unchanged and still supported with only 8 HARQ processes, which means that Hybrid Automatic Retransmission reQuest Acknowledgement (HARQ-ACK) / Negative Acknowledgement (NACK) feedback and re-transmission roundtrip time needs to be 2x and 7x faster with the 7 symbol and 2 symbol sTTI respectively.

5G also aims for further reduction of signaling between terminals and network nodes (RAN and Core Network (CN)).

5.1.5 STRONG SECURITY

5G faces far more dramatic cybersecurity challenges than 2G/3G/4G. Drivers for 5G security include:

- New service delivery models
- Evolving threat landscape
- Increased focus on privacy
- New trust models

5G will implement a number of security enhancements over 4G:

- Increased Home Network Control for Authentication
    - Home network verifies the UE is actually present and requesting service from the serving network

- Unified Authentication Framework
    - Same authentication for 3GPP and non-3GPP access

- Introduction of Security Anchor Function (SEAF)
    - Allows of re-authentication of the UE when it moves between different access networks

- Subscriber Identity Privacy
    - Use of the home network public key to encrypt the subscriber identity (for example, International Mobile Subscriber Identity (IMSI))

5.1.6 NETWORK FUNCTION VIRTUALIZATION (NFV)

Open platforms offer better flexibility and scalability than the purpose-based hardware used in existing networks, so the 5G network is moving away from the traditional specialized hardware used in previous network generations and towards open platforms. Open platforms consist of COTS (Commercial off-the-Shelf) hardware, where applications are installed, forming what is called a Virtual Network Function (NFV). Network functions can be executed in any physical hardware, and therefore the physical location can dynamically change based on current demand and also the service requirements such as latency. This also enables cloud computing, where the network nodes share compute, storage and network resources, dynamically and independently of their physical location.

5.1.7 SOFTWARE DEFINED NETWORKING

Another new feature of 5G networks is what is called SDN (Software Defined Networking). SDN provides the separation of the control plane from the user plane. The usage of SDN allows for a high level of programmability, enabling the separation of the network in different slices within the same hardware. Each slice can then be dedicated to a different type of service.

The combination of NFV and SDN technologies enable a lower capex as compared to traditional networks, accelerating time to market. According to recent research,[20] businesses utilizing such technologies can implement new services 13 times faster than with traditional networks. Operational cost is also reduced due to automation and the scalability of such networks. Based on an analyst firm estimate,[21] operational costs of running a network implemented with such technologies can be reduced by as much as 50 percent.

The usage of Network Slicing (NS) allows for the creation of multiple virtual networks and network resource pools within the same physical network. Each slice can then be optimized based on the characteristics of the services being provided in that slice and the applications that can be delivered on it. A slice can be thought of as a dynamic Infrastructure as a Service (IaaS) custom made for a service. Slicing can be enabled by combining cloud technologies with SDN and NFV capabilities.

5.1.8 MULTI-ACCESS EDGE COMPUTING (MEC)

Multi-access Edge Computing (previously known as Mobile Edge Computing technology is also being leveraged in 5G. MEC systems bring the service close to the network edge, therefore, close to the device's point of attachment. This entity contains the applications and a virtualization infrastructure which provides compute, storage, and network resources, and also the functions needed to applications. MEC helps to satisfy the demanding requirements for the 5G era in terms of expected throughput, latency, scalability and automation. By offering cloud-computing capabilities and an IT service environment at the edge of the network, MEC allows for ultra-low latency and high bandwidth. Furthermore, it can provide access to real-time network and context information. MEC also offers additional privacy and security and ensures significant cost efficiency. The integration of MEC into the 5G architecture will result in added value, ensuring highly efficient network operation, service delivery and the ultimate personal experience.

MEC and NFV are two different concepts and they can be implemented independently. That means they may share the same virtualization infrastructure, or they may have independent ones, depending on the deployment option (MEC standalone or MEC in NFV environment). In any case, from a standardization point of view, MEC technology reuses the NFV virtualization infrastructure and the NFV infrastructure management to the largest extent possible.

5.1.9 CARRIER AGGREGATION

During the standardization of 4G, it was already recognized that to increase the experienced data rates, more spectrum or bandwidth would be necessary. The solution developed by 3GPP LTE was called Carrier Aggregation (CA), whereby multiple bands in different regions of the spectrum are combined, resulting in broad aggregated transmission. Carrier aggregation concepts will continue in 5G, and in addition the system will utilize spectrum which is available in the frequencies of tenths and hundreds of gigahertz.

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[20] *The Quantitative and Qualitative Benefits of the New IP Network*, ZK Research. July 2015.
[21] *Ibid.*

Wireless systems operating on frequencies between around 20 to 100GHz are commonly called millimeter wave (mmWave).

5.1.10 MASSIVE MIMO

Multiple-Input Multiple-Output (MIMO) wireless systems, in general, allow network capacity to increase in terms of higher data rates and a higher number of user served. The multiple transceivers can be employed to provide spatial diversity, or improve the received signal strength by employing, for example, beamforming. When the number of antennas at the base station is increased to a hundred or a thousand elements, the term massive MIMO is employed. Massive MIMO are also known as Large-Scale Antenna Systems, Very Large MIMO, Hyper MIMO, Full-Dimension MIMO and Advanced Research and Global Observation Satellite (ARGOS).

The combination of massive MIMO and mmWave allows for a reduction in the total transmission latency. The combination of very large bandwidths in mmWave and massive MIMO contributes significantly to fulfill the 5G requirements of peak experienced data rate, area traffic capacity and low latency.

The 5G system architecture in 3GPP is defined to support data connectivity and services enabling deployments using these techniques and technology enablers. The following section provides more details on the 5G architecture.

5.2 3GPP 5G CORE NETWORK ARCHITECTURE

The 5G core network (5GC) architecture is defined to enable the deployments to use techniques such as NFV, MEC and SDN. The architecture leverages service-based interactions and separates the User Plane (UP) functions from the Control Plane (CP) functions. This separation allows for independent scalability, evolution and flexible deployments, for example, centralized location or distributed (remote) location.

The architecture is also defined with a converged core network with a common interface between Access Network (AN) and the Core Network (CN). This minimizes the dependencies between the AN and the CN and allows for the integration between different 3GPP and non-3GPP access types.

Network functions tend to be Central Processing Unit (CPU) intensive, and in some cases memory intensive but not storage intensive, thereby allowing resources to be allocated efficiently, for example, store configuration and logs in a separate location than the network function.

To support low latency services and access to local data networks, UP functions can be deployed close to the Access Network.

Figure 10 shows the overall architecture of the 3GPP CN.[22]

In the control plane, the mobility management and session management functions are split between two different network functions: the AMF (Access and Mobility Management Function) and the SMF (Session Management Function). The NEF (Network Exposure Function) provides an interface for outside applications to communicate with the 3GPP network. Unified Data Management (UDM) is responsible for access authorization and subscription management. Network Repository Function (NRF) and Policy

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[22] 3GPP TS 23.501, Technical Specification Group Services and System Aspects; System Architecture for the 5G System; Stage 2, Release 15.

Control Function (PCF) contains the policy rules. Authentication is handled by the AUSF (Authentication Server Function).

In the user plane, the User Plane Function (UPF) is responsible for handling the packets, such as buffering packets, packet filtering, packet routing, etcetera. The Data Network (DN) provides operator services, 3rd party services, or access to the internet.
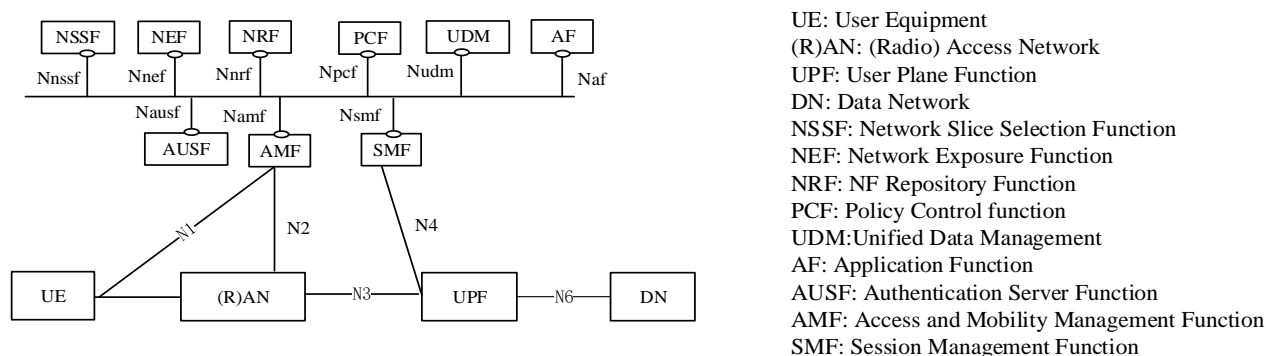

UE: User Equipment
(R)AN: (Radio) Access Network
UPF: User Plane Function
DN: Data Network
NSSF: Network Slice Selection Function
NEF: Network Exposure Function
NRF: NF Repository Function
PCF: Policy Control function
UDM:Unified Data Management
AF: Application Function
AUSF: Authentication Server Function
AMF: Access and Mobility Management Function
SMF: Session Management Function

Figure 10. Overall 3GPP 5G Core Network (5GC) Architecture.[23]

In order to support traffic offloading for Edge Computing the SMF may control the data path of a PDU (Packet Data Unit) session so that the PDU session may simultaneously correspond to multiple N6 interfaces (interface with the application server). In cases where the offload starts in the RAN, then the AMF and SMF have to coordinate the data path diversion in the RAN.

The UPF that terminates each of these interfaces is said to support a PDU session anchor functionality. Each PDU session anchor supporting a PDU session provides a different access to the same DN. This can be achieved in essentially three ways:

- Usage of an UpLink Classifier functionality for a PDU session
- Usage of an IPv6 multi-homing for a PDU session
- Support for Local Area Data Network (LADN)

The following sub-sections briefly describe these three approaches. Details on ETSI MEC architecture can be found in the Appendix.

5.2.2 UPLINK CLASSIFIER

The "UL CL" (Uplink Classifier) is a functionality supported by an UPF that aims at diverting (locally) some traffic matching traffic filters provided by the Session Management Function (SMF). The SMF may decide to insert in the data path of a PDU session an UL CL. The UL CL applies filtering rules (for example, to examine the destination IP address of IP packets sent by the UE) and determines how the packet should

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[23] TS 23.501. System Architecture for the 5G System; Stage 2, Release 15.

be routed. The UE uses the same IP address to access either network and is not aware with which DN it is communicating. This is illustrated in Figure 11.
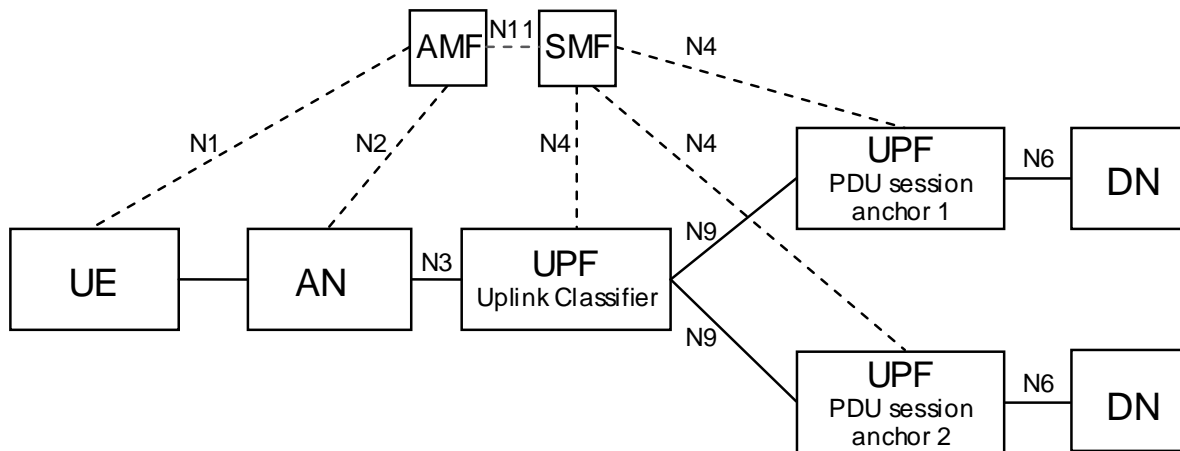

Figure 11. MEC Architecture in 3GPP with Uplink Classifier.

5.2.2 IPV6 MULTI-HOMING

In this case, a given Packet Data Unit session is associated with multiple IPv6 prefixes. A "common" User Plane Function referred to as "branching point"is responsible for steering the UL traffic towards one or the other IP anchor based on the Source Prefix of the packet. A branching point for a given PDU Session may be inserted or removed by the SMF on the fly.
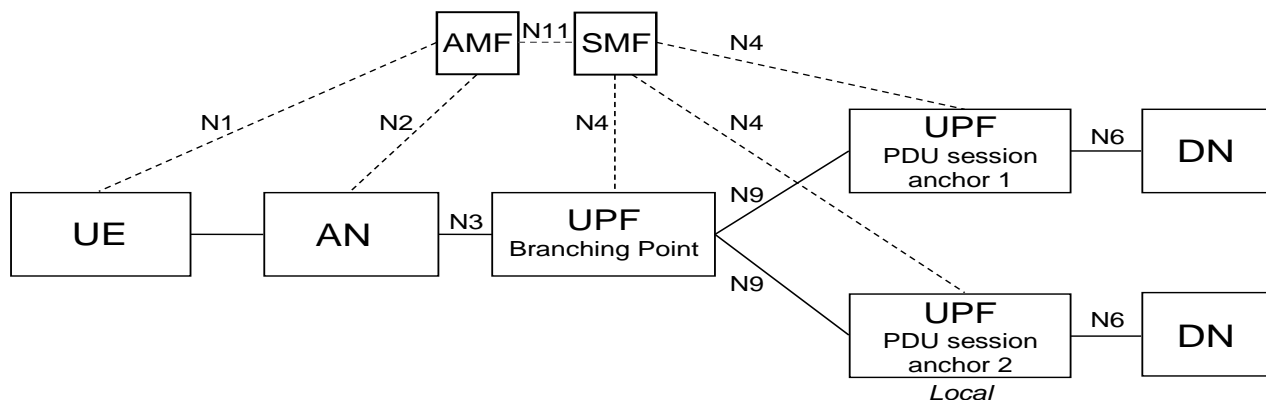
Figure 12. MEC Architecture in 3GPP with IPv6 Multi-Homing.

RFC 4191 is used to configure rules into the UE to influence the selection of the source address. This corresponds to Scenario 1 defined in IETF RFC 7157, *IPv6 Multi-homing without Network Address Translation*.

5.2.3 LOCAL AREA DATA NETWORK (LADN)

In this approach, the UE explicitly requests a PDU session to a special Access Point Network/ Digital Data Network (APN/DDN) in order to get access to the locally provided service. To support this, the Access and Mobility Management Function (AMF) provides to the UE the LADN information about the LADN availability. The AMF tracks the UE and informs the SMF whether the UE is in the LADN service area (therefore, the area of availability of the LADN).

LADN Information is provided to the UE by the AMF during registration. This information consists of LADN DNN and LADN service area information. The LADN service area information includes a set of Tracking Areas that belong to the current Registration Area of the UE (i.e. the intersection of the LADN service area and the current Registration Area). The UE may then request a PDU session establishment for an available LADN when the UE is located in the LADN service area.

5.3 5G RADIO NETWORK ARCHITECTURE

In the previous section, the overall architecture of the 5GC was reviewed and it was noted that the Radio Access Network (RAN) node connects to the UPF and AMF. The RAN node is the point of attachment for the UE. In 5G, the RAN node is referred to as the Next Generation RAN (NG-RAN). The NG-RAN node is either a gNB or a ng-eNB, as follows:

- gNB provides NR user plane and control plane protocol terminations towards the UE
- ng-eNB provides E-UTRA user plane and control plane protocol terminations towards the UE

The gNBs and ng-eNBs are interconnected with each other by means of the Xn interface. The gNBs and ng-eNBs are also connected by means of the NG interfaces to the 5GC, more specifically to the AMF by means of the NG-C interface and to the UPF by means of the NG-U interface.

The NG-RAN architecture is illustrated in Figure 13.[24]

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[24] 3GPP TS 38.300, *NR; NR and NG-RAN Overall Description*; Stage 2, Release 15.
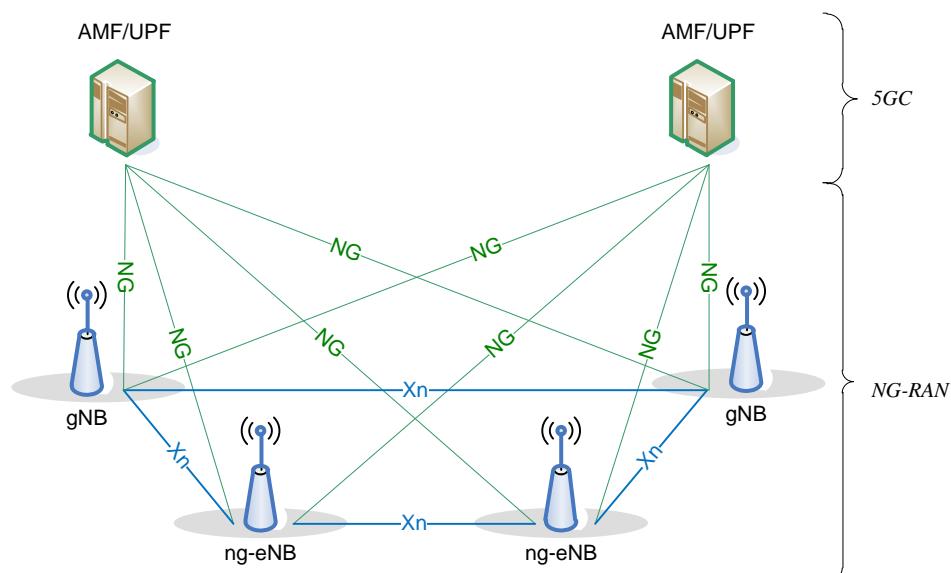
Figure 13. Overall 3GPP RAN Architecture.

The gNB hosts the functions for Radio Resource Management (RRM) such as Radio Bearer Control (RBC), Radio Admission Control (RAC), Connection Mobility Control (CMC), and Dynamic allocation of resources to UEs in both uplink and downlink (scheduling). The geNB is also responsible for the selection of an AMF at UE attachment and the routing of control plane information towards the selected AML. In the use plane, the gNB is responsible for the routing of User Plane data towards UPF(s), transport level packet marking in the uplink, IP header compression and encryption of the user data stream.

The functional split between the 5GC and NG-RAN is illustrated in Figure 14.
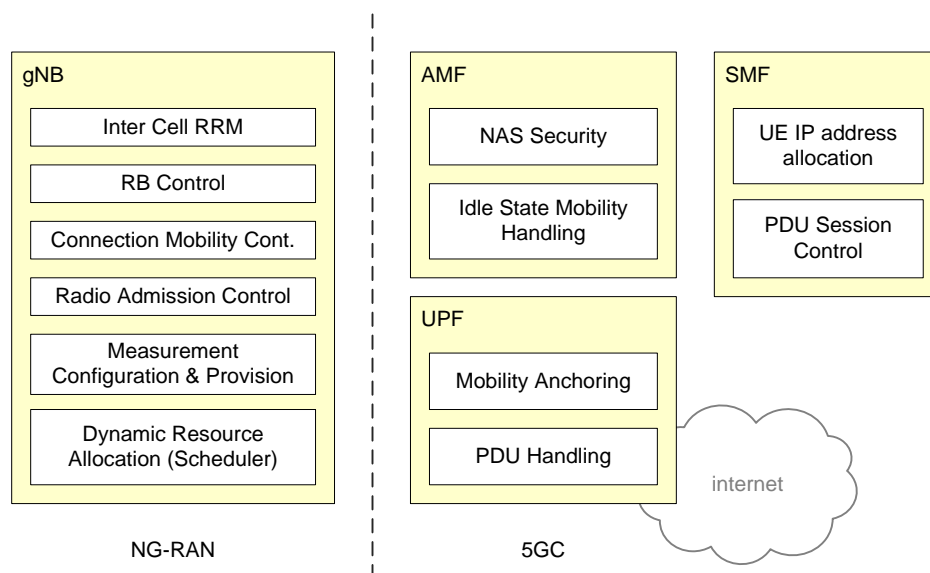
Figure 14. Functional Split between NG-RAN and 5GC.[25]

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[25] 3GPP TS 38.300.

The details of the 5G physical layer are still ongoing in 3GPP, but there are some preliminary agreements at this time. The physical layer is defined in a bandwidth agnostic way based on resource blocks, allowing it to adapt to various spectrum allocations, and making it very flexible.

Resource block spans 12 sub-carriers with a given sub-carrier spacing. The radio frame has a duration of 10ms and consists of 10 sub-frames with a sub-frame duration of 1ms. A sub-frame is formed by one or multiple adjacent slots, each having 14 adjacent symbols. The small sub-frame duration allows for much smaller latencies than what we observed in previous generations cellular systems.

More details on physical channels and physical signals, such as modulation scheme, channel coding, etcetera, can be found in 3GPP TS 38.201.[26] The work in 3GPP is ongoing and the document is not completed at this time.

In the next section, more details are provided on how the different technology enablers and the choices of network topology help the 5G system reach the expected quality of service and meet its required KPIs for the different verticals and different use cases within a vertical.

6. NETWORK TOPOLOGY FOR CORE AND RAN DEPLOYMENT

The current 4G networks are designed to be extremely thorough. The development cycles include extensive evaluation, impact analysis and testing. The result is high specification networks which meet defined standards for even the most demanding services. The downside to such an approach, is that it requires a substantial amount of investment of time and money. Release cycles are slow, which leads to significant delay before new features are made available.

Technology advancement from 4G to 5G is a revolution in terms of the use cases and number of devices. Often the use cases have very different and sometimes orthogonal requirements in terms of latency, throughput, power consumption and security. It is important to transform the network to be more flexible, scalable and reliable in order to support these varied use cases, requirements, and KPI's and also to reduce the duty cycle, and reduce the cost of network upgradation and maintenance.

6.1 NEED FOR FLEXIBLE, SCALABLE AND RELIABLE NETWORK FOR 5G

Data demand for the communications world is increasing exponentially. Billions of smart and connected devices fueled by the Internet of Things, along with new data-rich services and cloud apps are bringing exciting and unexpected experiences to every part of our lives.

From wearable devices embedded in athletes' equipment for real-time information, robots and autonomous vehicles, to smart cities, telemedicine and more, the human need for connectedness is placing unprecedented demands on wireless networks. Only a new generation of optimized IoT networks and devices – 5G IoT networks and devices – will be able to meet the speed, latency and energy efficiency needs of these IoT experiences of the future. 5G is about devices connecting to the best network seamlessly irrespective of the location of these devices. It's about delivering fast broadband to homes in a new way, connecting areas that were under-served before. It's about connecting things that haven't been connected before—like collecting data from parking meters or traffic lights to help make our everyday lives easier or connecting machines in an industrial setting to improve efficiency and safety.   It's about cars sharing data with each other to improve safety. And it's about deploying cloud computing closer to the users who need it, distributing intelligence throughout the network to improve services.

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[26] 3GPP TS 38.201, NR; *Physical layer; General description*, Release 15.

5G represents a significant shift for the industry where mobility and computing converge and become indistinguishable. Wireless networks must transform to become more powerful, agile and intelligent to realize the potential for the IoT and enable richer experiences throughout daily life.

Hence 5G encompasses multiple application needs with different End-to-End (E2E) requirements (latency, throughput, security, mobility, and etcetera). It is not practical to implement separate networks for different QoS requirements, hence 5G networks need to be flexible, scalable and reliable.
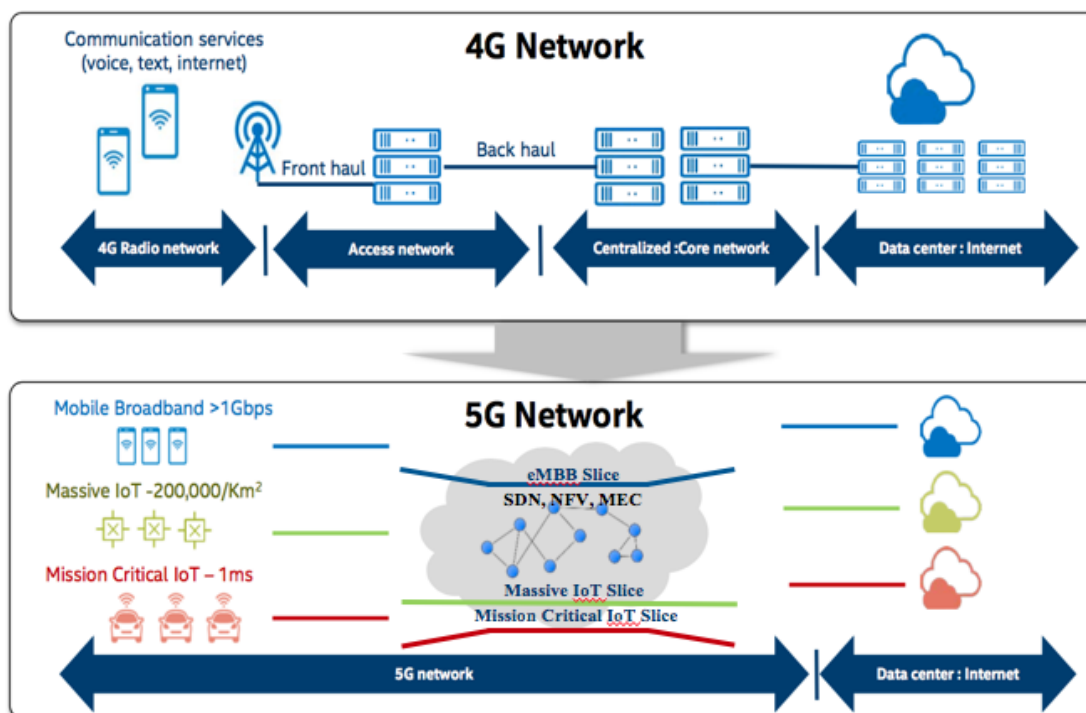
Figure 15. Network Transformation from 4G to 5G Networks.

6.2 CENTRALIZATION OF COMPUTE – WORKLOAD CONVERGENCE

The 5G system is expected to deliver significant improvements in cost efficiency and performance. One way this is achieved is through *centralization of compute*, where network functions are brought together in a way that optimizes usage of physical resources and enables tight coordination between processes.

The pooling of processing resources achieved by centralization enables the network to provide services using less hardware. This in turn reduces the complexity and environmental footprint of the network infrastructure, leading to lower Total Cost of Ownership (TCO).

C-RAN is one important example of centralization, where the RAN architecture is split into centralized baseband units (BBUs) and distributed radio units. In addition to the pooling gains, network performance can be improved through the introduction of features such as distributed MIMO that are able to exploit the high computational capacity and the tight interconnection of BBUs within the pool. C-RAN has already proven to be effective in some existing 3G and LTE deployments, where typically the RF functionality is distributed in remote radio heads (RRH) that are connected to the centralized BBU via Common Public Radio Interface (CPRI) over a high-quality front haul network (for example, fiber).

C-RAN is expected to be further advanced by the 5G radio access network architecture being defined in 3GPP, which agreed to support centralization of the upper layers of the new 5G radio protocol stack (called "NR" for New Radio). 3GPP has studied various possible functional splits of the NR protocol stack between a central unit (CU) and distributed unit (DU), considering factors such as benefits, complexity, and transport network requirements (therefore, throughput and latency). 3GPP has decided to specify a higher layer functional split that allows pooling of Radio Resource Control/ Packet Data Convergence Protocol (RRC/PDCP) resources, for example, in a data center that may host tens of thousands of NR cells. From a network performance perspective, this enables centralization of some RRM functions such as traffic load management, interference management, and handovers.

In future 3GPP releases, additional functional split options may be standardized. For example, 3GPP is currently studying lower layer functional split options that would allow pooling of RRC/PDCP/Radio Link Control/Medium Access Control (RLC/MAC) resources or even some Physical Layer (PHY) resources. This would therefore enable centralized scheduling and joint transmission. Eventually, a network may support configuring multiple functional splits based on the offered services, load, or transport network performance.

6.3 CONTROL/USER PLANE SPLIT

Aggressive 5G network performance requirements (therefore, low latency and high throughput) influence the research, development and exploration of specific architecture decisions for RAN and Next Generation (NG) core which can help to address desired flexibility and capability for the whole range of users. The way this can be achieved is via functional split and separation of the control plane (CP) and user plane (UP) for both RAN and NG core network.

In addition to fulfillment of mentioned performance requirements, this separation can lead to reduced costs of the system deployments, simplified management and configuration, consistent control, reduced number of interfaces and finally provide the ability to build more flexible, adaptable and agile network.

Continuous network evolution, including independent scaling and adaptability, requires modifications and replacements of CP and UP elements. In the case of separated planes, replacement and upgrade of elements on one plane can be performed with minimum impact to elements on another plane. In the study of energy efficiency aspects, 3GPP emphasizes to leverage separation of the CP and UP traffic in order to enhance energy efficiency by enabling separate handling of signaling traffic from data traffic.[27]

For the C-RAN CP and UP separation several options can be considered ranging from decentralized CP and UP to fully centralized depending on the different deployment scenarios.

3GPP has already studied the separation of the CP and UP for the EPC[28] in the evolved 4G core. The study describes the architecture reference models for non-roaming/roaming and combined SGW/PGW architecture, the way of splitting for the Serving Gateway (SGW), Paging Gateway (PGW) and Trunk Distribution Frame (TDF) with definition of the interfaces between planes. Taking into account that some operator will want to use existing 4G deployments for the fast 5G network rollout EPC can be reused with some extensions and modifications. It is essential that NG core will be cloud-native and use NFV and SDN. In the 3GPP document[29] which describes the system architecture for the 5G systems, the general concepts and requirements for separation of the UP functions from the CP functions allow independent scalability,

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[27] 3GPP TR 21.866: *Study on Energy Efficiency Aspects of 3GPP Standards.*
[28] 3GPP TS 23.214: *Architecture enhancements for control and user plane separation of EPC nodes.*
[29] 3GPP TS 23.501: *System Architecture for the 5G Systems.*

evolution and flexible deployments. Figure 16 shows non-roaming 5G system reference architecture with service-based interfaces used within Control Plane (CP).
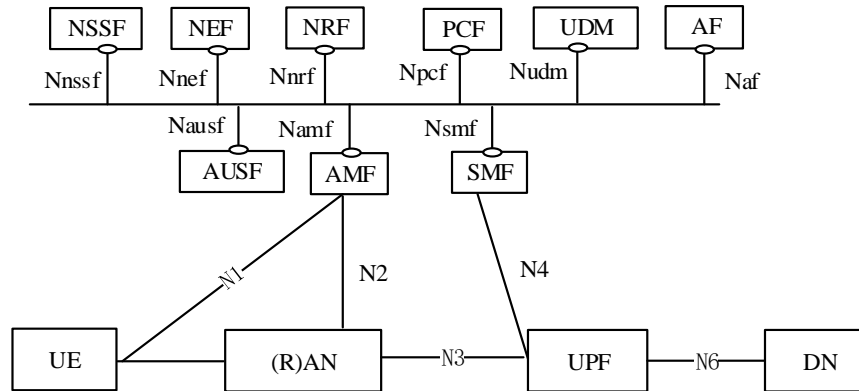

Figure 16. Non-roaming 5G System Reference Architecture.[30]

The N1, N2 and N4 reference points represent connections to the CP functions in the 5G NG core network. The Access and Mobility Management Function (AMF) provides termination of Non-Access-Stratum (NAS) functions via N1, NAS ciphering and integrity protection, termination of RAN CP interface via N2, registration/connection/reachability management, access authentication/authorization and other functions. N4 reference point is used by the Session Management Function (SMF) to control and manage User Plane Function (UPF) which handles the user plane path of Protocol Data Unit (PDU) sessions including packet forwarding and routing.

3GPP also defined CP and UP protocol stacks for different reference points. The N2 reference point and CP protocol stack between RAN and AMF is a good example. On top of IP, SCTP guarantees delivery of control and signaling messages between AMF and RAN. NG Application Layer Protocol (NG-AP) consists of Elementary Procedures (EPs) [31] units of interactions between gNB and the 5G NG core.
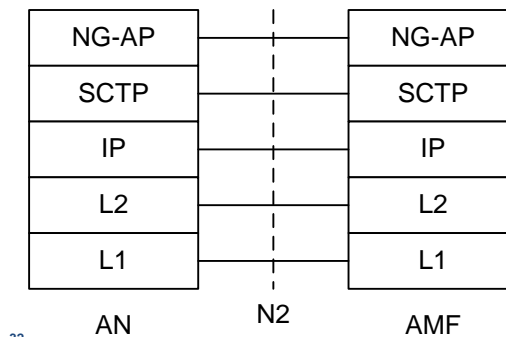

Figure 17. Control Plane Protocol Stack between the AN and the AMF.

UP protocol stack is based on UDP/IP and does not guarantee delivery of the UP PDUs. GRPS tunneling protocol for user plane (GTP-U) supports multiplexing traffic of different PDU sessions (via N3) and carries QoS marking.

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[30] *Ibid.*
[31] 3GPP TS 38.413: *NG Application Protocol (NGAP).*
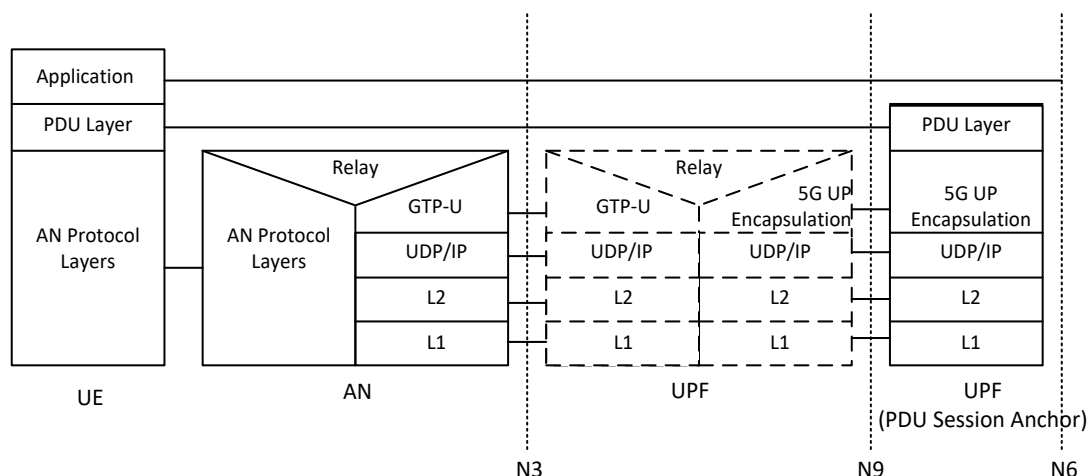[32] 3GPP TS 23.501.

Figure 18: User Plane Protocol Stack. [33]

Considering all the pros in results, there can be cons during implementation of the CP/UP split; it can lead to increased testing efforts and especially in terms of interoperability testing. In addition to that, the full separation would require more efforts to implement and can introduce additional complexity.

6.4 ORCHESTERATION AND MANAGEMENT

To efficiently manage and support the foreseen scope of 5G services, a fully automated, ideally autonomic system that is capable of true end-to-end, real-time and secure service fulfillment and assurance, will be required.

It is obvious that the scale and complexity of 5G networks cannot be managed by human operators alone deciding on the basis of a dozen of aggregated KPIs that have been manually defined by using static models to analyze rudimentary and discrete set of data such as SNMP queries and traps, reading raw log file data.

Creating and maintaining 5G services on an extremely dynamic SDN/NFV infrastructure, while including physical networks for the radio and underlay transport layers, will require an automated end-to-end Resource- Infrastructure- and Service- Orchestration as well as fully correlated Service Assurance capabilities. Such an architecture will have to provide the following high-level functions:

- Service delivery, design and run time frameworks, using common information model based service definitions
- Multi-domain Service Orchestration (spanning across administrative and also operator domains)
- Consistent inventory (of services, resources, infrastructure and geo/topology)
- End-to-end Service Assurance including FCAPS (Fault, Configuration, Accounting, Performance, Security) with automated Analytics (AI supported)
- Security (trusted platform, OS and application layers, tenant privacy and isolation)

ETSI's NFV Management and Orchestration (MANO), MEF's Lifecycle Services Orchestration (LSO), TMF's Zero-touch Orchestration, Operations and Management (ZOOM) -- to name the most prominent working groups, are all working on definitions of the required software architecture, APIs and data models to manage self-aware, self-optimized, self-healing, closed-loop-controlled networks. Open-source

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[33] 3GPP TS 23.501.

communities such as OSM and ONAP are building code and artifacts on top of these foundational works. "Cloud native" technologies, such as Kubernetes, offer new availably and scaling methodologies that can be incorporated into the 5G ecosystem.[34]

Another study around management automation was issued by the 5G-PPP Architecture Working group, showing a path to a cognitive network management for 5G[35] considering Machine learning as a key technology to facilitate self-adaptation.

All of these approaches have a common goal – to implement a fully autonomous management and orchestration system that can accommodate user-driven self-service requests, machine-to-machine communication as well as closed loop control to scale in/out and up/down as, and when, dynamic traffic profiles are required. However, also to be able to recover from failures or to react on security breaches.

While some of this has already been trialed for fixed network services, there are many challenges yet to be solved to accommodate even more dynamic 5G services, such as network slicing, MEC, fog networks and etcetera.

6.4.1 COMMON INFORMATION MODEL

One of the main, yet-to-be-standardized, requirements is the need for a common information model. In order to build and operate a multi-domain, multi-vendor network and even support cross operator network services, the service and resource orchestrators need to work with common data models.

Standardized Service and Network Function modeling and packaging also decouples the development cycle of network functions by software vendors from the service deployment cycles of service providers and enables faster lifecycle management of new 5G services.

Figure 19 represents a CI/CD workflow (continuous development/continuous integration) where a common information model can further accelerate feature velocity by making the "deployment" phase simpler to coordinate across devices.

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34 http://cncf.io
35 *Cognitive Network Management for 5G*, Robert Mullins/Michael Taynnan Barros, Waterford Institute of Technology, March 09, 2017.
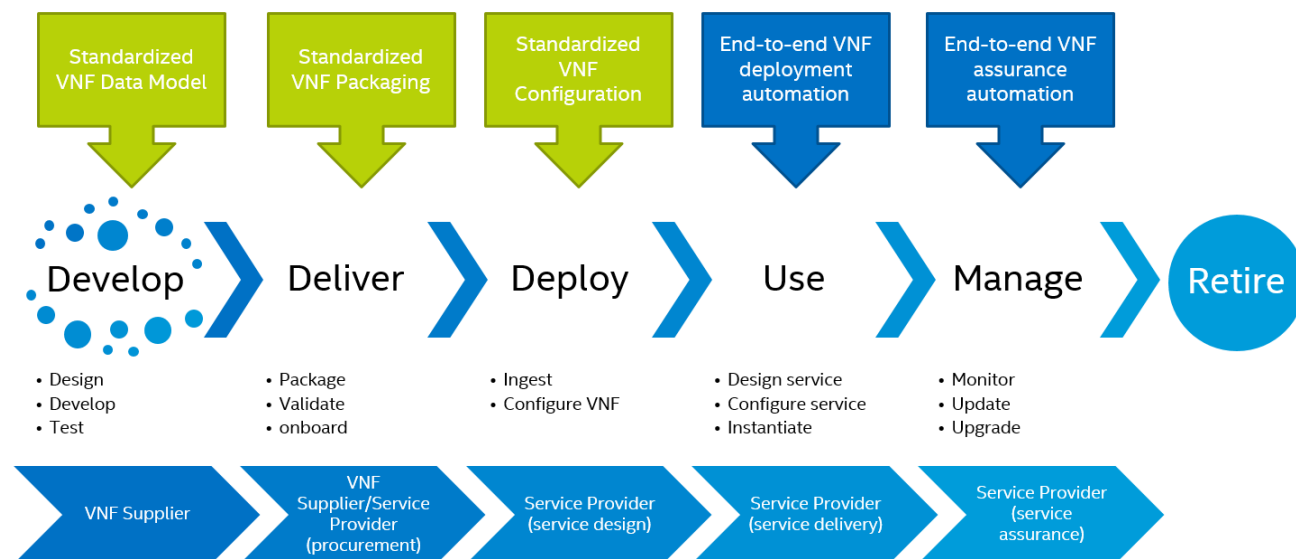
Figure 19. Enabling VNF Life Cycle Automation.

An Information model is a conceptual/abstract model for designers and operators while a data model is a concrete and detailed model for implementers of the information models. ETSI NFV IFA011 and IFA014 provide a good definition of an information model. The data models can be described in modeling languages such as Yang or TOSCA.

These models inherently address both the design time requirements and run time instantiations. Examples of design time requirements are automation policy requirements, operational requirements, functional requirements and infrastructure requirements. Examples of run time instantiations include keeping track of service to infrastructure mapping, deployed topologies, monitoring operational states and applying automation policy rules at run time.

6.4.2 NETWORK SLICING

Network slicing refers to the ability to create multiple logical instances on the same underlying network. The parameters for each network slice are optimized according to different criteria and possibly used by different tenants or organizations. Network slices can be viewed as 'on demand' networks. Slicing may also include a fine-grained allocation of resources, such as compute, memory and disk space, in addition to network separation. In this view, the slice can represent a dynamic and logically independent application delivery infrastructure (IaaS). If an operator wishes to save costs by sharing slice resources (for example, oversubscribing slice resources) then it is possible, and a cost/risk study has to be conducted for each use case. However, at the management layer the resources are always logically separated.

The intention of a 5G slice is to provide only the traffic treatment that is necessary for the use case, and avoid all other unnecessary functionality. The flexibility behind the slice concept is a key enabler to both expand existing businesses and create new businesses.
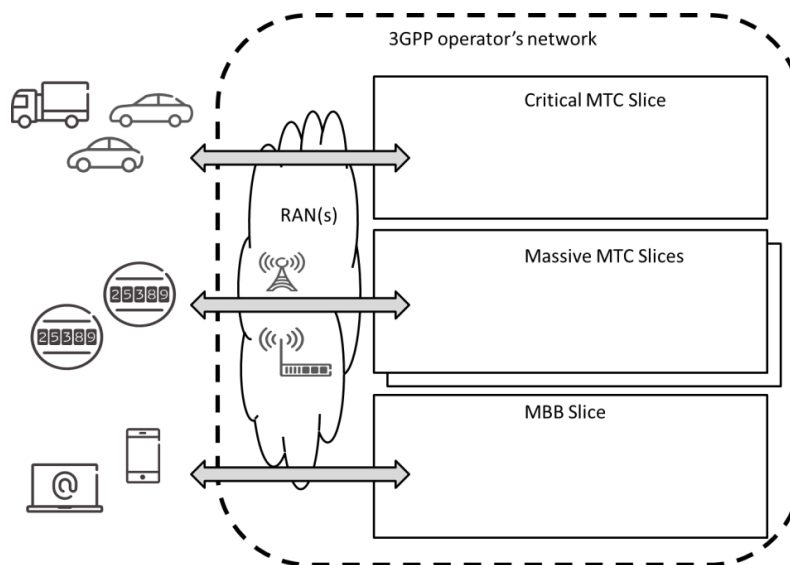
Figure 20: Network Slicing mechanism catering for different use cases at operator's network.[36]

Third-party entities can be given permission to control certain aspects of slicing via a suitable API, in order to provide tailored services.

To enable full automation of network slice management, NFV MANO functions need to be complemented and interwork with the network slice management functions. These management functions can consume the APIs exposed by the NFV Orchestration (NFVO) layer as well as other APIs exposed by other management entities enabling full FCAPS of the network functions involved in the instance of that network slice. Network slice management can be viewed as a functional area that needs to be standardized on top of NFV.[37] Multi operator inter working will require model harmonization and this is once such area where a common top down model will be required to serve as an industry business requirement. Network slicing also impacts the NFVI (Network Function Virtualization Infrastructure) because it places requirements on security, resource usage and fault isolation at the infrastructure layer

6.4.3 TOWARDS COGNITIVE ANALYTICS

To operationally assure these highly dynamic services including their respective SLAs, a new approach to FCAPS with minimal human intervention will be required.

Today's static measurements of network and application performance will not be capable to surveil the dynamic landscape of SDN/NFV based 5G networks and functions, nor create any form of automatism to create self-adapting closed loops. The pace at which these environments change, requires sophisticated analysis of real-time counters, telemetry streaming, flow-based information in combination with user profile and behavior data. Creating a dynamic model to correlate the resulting big data, requires AI/ML technology that will pave the way from today's transaction process based analytics towards predictive, descriptive and finally cognitive analytics required for self-optimizing, self-healing networks and applications.

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[36] 3GPP TR 22.891.
[37] *Network Functions Virtualization*, white paper on NFV priorities for 5G, ETSI. Feb 21, 2017.
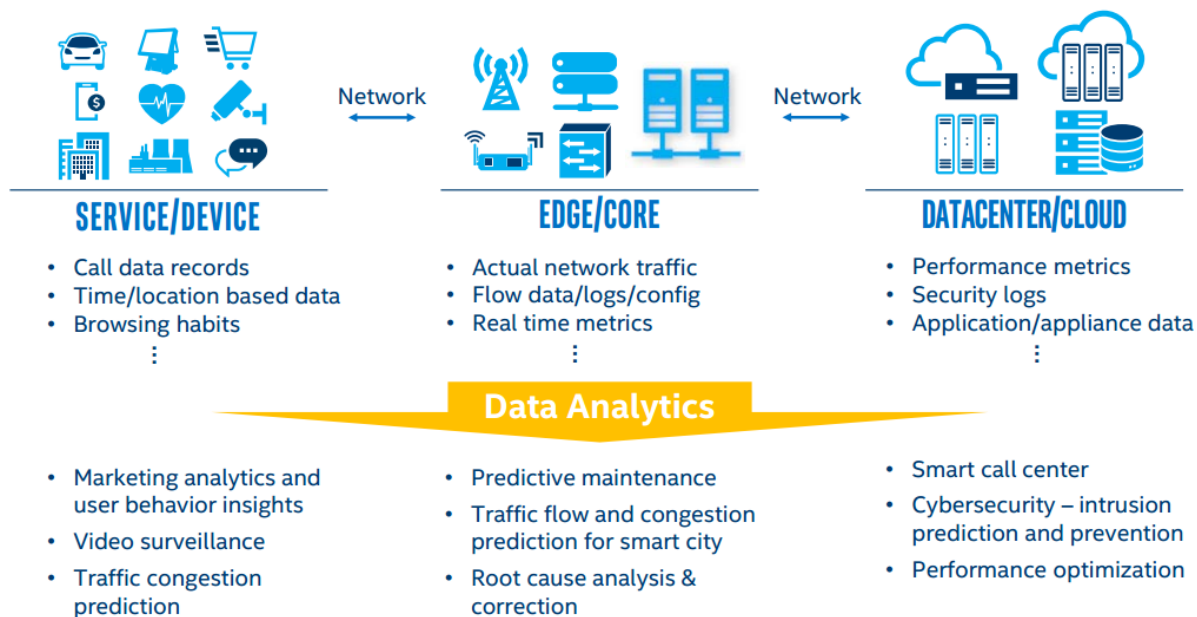
Figure 21: Analyze Data from Everywhere and Everything.

6.4.4 SDOS AND OPEN SOURCE COMMUNITIES

Management and Orchestration (MANO) has been identified to become a critical component of NFV and an initial framework was defined by ETSI in early 2013. The framework has since evolved significantly and a large set of specifications (interfaces, APIs, data models, etcetera.) have been published.

In parallel, various open source communities started to build implementations (code) and even extend the ETSI functional blocks to include additional OSS (Operation Support System)/BSS (Business Support System) domains. Namely OSM (Open Source Mano) and ONAP (Open Network Platform Automation) have emerged as the two major communities, each backed by a large membership including major Tier 1 operators, driving development of open source artifacts for a fully automated (zero-touch) management stack, with the goal to realize all the benefits of NFV. TMForum (Tele-Management Forum) and MEF (Metro Ethernet Forum), all composed of Telco suppliers and consumers (Service Providers) are defining real world use case requirements and solution frameworks.

While there has been significant progress made in defining requirements and proposing foundational guidelines up to formal architecture and API definitions, a closer aligned strategy and common definitions are yet to be condensed out of the great work being done so far. Newer initiatives such as the Zero-touch-NSM project including Deutsche Telekom, China Mobile and Telefonica, but also all major telco suppliers, are founding to define a next generation architecture network and service management system inspired by SDO specs but also considering best practices of cloud native principles from the likes of Google, Facebook, Netflix and etcetera.

6.4.5 SUMMARY

Software Defined Networks (SDN) and Network Function Virtualization (NFV) are having an enormous impact on network operations today, the Internet of Things (IoT) with massive numbers of devices, the dynamic nature of the underlying networks and QoS requirements, and finally the end customers who

continue to expect an improved level of communication experience. To unleash the benefits of virtualization and software defined technologies, while increasing the efficiency of network operations, the industry must enhance Network and Service Management (NSM) automation. Developments in edge computing, low latency networks, Artificial Intelligence (AI), and Machine Learning (ML) offer additional benefits that again can only be realized with NSM automation. The introduction of 5G further raises the stakes towards a next generation NSM architecture.

The evolution of network and control technology will enable more flexibility in service creation, capacity and change management as well as more efficient network operations. This also adds more complexity to networks, particularly in the area of network and service management. To offset this complexity, our industry needs to ensure all network and service management functions are based on open standardized solutions. Harmonizing standards approaches regarding information modeling across industry standard organizations such as ETSI, TM Forum, ONF, MEF and other SDOs are important enablers – while there are also other creative approaches to be considered to actually build and deploy this new technology.

7. NETWORK DEPLOYMENT CHALLENGES AND POLICY IMPLICATIONS

Naturally, the deployment of innovative 5G technology will not be without its challenges. Many of these challenges will be affected by regulatory and policy decisions at nearly all levels of government. Given that cellular services and the telecommunications infrastructure that enables them are so deeply integrated in our lives, it is logical that government policies will have a large impact on the deployment of 5G technologies. Recognizing this enables the telecommunications industry to identify ways to work with the various levels of government to develop policies and regulation that will be beneficial for all parties: consumers, industry, and government. The two principle challenges will be securing adequate spectrum to enable the use cases that are envisioned for 5G technology and facilitating infrastructure development and deployment to meet the growth in demand for cellular services.

7.1 SPECTRUM

Spectrum, particularly licensed spectrum, has historically played a key role in the deployment of new cellular technologies. The U.S. Federal Communications Commission allocated the 850 MHz frequency band for the first generation of cellular services in 1981. 2G service benefitted from additional PCS spectrum band (1900 MHz) which was auctioned in 1995. 3G service utilized newer spectrum in the AWS-1 bands (1700 MHz and 2100 MHz) which were auctioned in 2006. More recently, 4G service has been augmented by the additions of the 700 MHz band auction in 2008 and the AWS-3 band auction in 2015. The 600 MHz broadcast incentive auction that was completed in the first half of 2017 will further enhance 4G service. In the U.S., licensed mobile spectrum bands often have been re-farmed to utilize spectrum for the latest mobile wireless technology.

For each successive generation of cellular technology, additional spectrum has been needed to meet the growing consumer demand and catalyze technological development. 5G will be no exception. The rapid growth in cellular data usage is expected to continue and the wide range of new 5G use cases in Section 3 and the impact to entire industry verticals in Section 4 has already been documented. 5G will need additional spectrum to meet these needs and be successful in providing consumer benefits and maximizing economic gains.

Aside from the consumer benefits, the economic benefits are often under-appreciated, despite the fact that cellular technology has had an enormous impact on the United States and world economies. Research from the Boston Consulting Group shows that the mobile value chain was directly responsible for 11 million

jobs in 2014 and generated $3.3 billion in global revenue.[38] Not surprisingly, this revenue is projected to increase with mobile's share of gross domestic product (GDP) growing at 10-20 percent annually in the countries that were analyzed.[38] And this trend will continue with 5G technology. Accenture estimates that the deployment of 5G technology in the United States will lead cellular operators to invest up to $275 billion, boost GDP by $500 billion, and create up to 3 million jobs.[39]

However, without adequate spectrum resources it will be difficult to realize these benefits. Over the years there have been significant technological advances like 4x4 MIMO, 256 QAM, and carrier aggregation that have contributed to higher spectral efficiencies and therefore higher throughputs and capacity. But these technological advances can only go so far without the underlying spectrum assets on which they function. There are already heavy demands on the existing spectrum in use by cellular operators for 4G services and these demands will not lessen as 5G technology continues to be developed in 2018 and starts to be deployed in 2019. A shortage of additional spectrum could force cellular operators to prioritize spectrum to deliver 4G services, greatly hindering investment in 5G technology and limiting its benefits.

Governments and regulators can do their part to ensure that this does not happen by creating a spectrum pipeline to fulfill future cellular needs. Identifying suitable spectrum bands across all ranges, from low-band to mmWave, will be critical in enabling the success of 5G technology. The efficient utilization of these scarce spectrum resources should be the primary goal and can be accomplished via spectrum auctions. In the United States, spectrum auctions have been highly successful and mutually beneficial for consumers, the cellular industry, and the government. Collectively the auctions for PCS, AWS-1, 700 MHz, AWS-3, and 600 MHz spectrum bands raised $100.6 billion dollars for the US treasury.[40] The competitive bidding system has incentivized infrastructure investment, required efficient spectrum utilization by the cellular operators and ensured that they continue to focus their businesses on meeting consumer demand.

Since 5G is targeting improvements across three fronts, enhanced mobile broadband, massive-scale connectivity, and ultra-reliable low latency service, there will be different spectrum needs than previous generations of cellular technology. To meet the new and emerging use cases it will be necessary to utilize a portfolio of spectrum assets consisting of low-band, mid-band, and mmWave spectrum. It is envisioned that low-band spectrum, with its superior propagation and penetration characteristics, will be used to provide in-building coverage in urban areas and wide-area coverage in more rural areas. Mid-band spectrum will be utilized for capacity and high speed in both urban and suburban zones. The large bandwidths available in the mmWave bands can achieve extreme speeds but the limited propagation distances and penetration at these higher frequencies will likely confine usage to more concentrated urban areas. Just as the properties of these different spectrum bands vary, so does their applicability to the range of 5G use cases and industry verticals, as has already been discussed in Sections 3 and 4. To meet the requirements for all use cases cellular operators will need both breadth of spectrum assets across these bands and depth of spectrum assets within bands to meet the projected demand.

Ensuring that there are available spectrum assets in all these bands is critical and will require a concerted government effort and strategic planning in conjunction with industry to identify under-utilized candidate bands that will meet the requirements. While these decisions will likely be made at the national government level, they should not be made in isolation. The importance of creating a global ecosystem for 5G with harmonized spectrum bands cannot be understated. Common spectrum bands help realize economies of scale and accelerate the development, deployment, and adoption of cellular technologies. For example, among Korea, Japan, China, and the European Union, there is already alignment on utilizing the 3.5 GHz band (~3.3 – 4.2 GHz) for 5G services and 3GPP is including this band in the first 5G standard, Rel-15.

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[38] *The Mobile Revolution: How Mobile Technologies Drive a Trillion Dollar Impact,* Boston Consulting Group. 2015.
[39] *Smart Cities: How 5G Can Help Municipalities Become Vibrant Smart Cities*. Accenture Strategy, 2017.
[40] *Auctions Summary,* Federal Communications Commission.

The United States cannot afford to fall behind in this regard. The FCC had indicated that it would make 150 MHz of spectrum in the 3.5 GHz CBRS band accessible, but only 70 MHz available as licensed spectrum. Such a narrow bandwidth split between multiple operators may not be sufficient mid-band spectrum and could negatively impact the development of 5G in the United States. Recognition of this has led to a notice of inquiry by the FCC to consider expanding availability to the adjacent 3.7-4.2 GHz band, the 5.925-6.425 GHz band, and the 6.425-7.125 GHz band.[41] This could provide sufficient mid-band spectrum, but is only part of what is needed.

Additional mmWave spectrum is also required for the extreme speeds that 5G is expected to deliver. The 24 GHz, 37 GHz, and 66-71 GHz band should be considered for cellular use and could be assigned to multiple spectrum auctions over the coming years to help continuously replenish the supply of available spectrum. Similarly, existing low-band spectrum availability is constrained and should be supplemented by targeting additional bands such as 1300-1350 MHz, 1675-1695 MHz, and 1780-1830 MHz.

This holistic approach to creating a sufficient supply of spectrum assets across all frequency ranges will encourage investment in 5G technology and promote its adoption. It will be difficult to fully realize the economic potential of 5G without the necessary licensed spectrum assets; but making spectrum available is merely the first step. To put that spectrum to use it is necessary to have policies and regulation that promote the development of 5G infrastructure and allow the timely build-out and deployment of network architecture.

7.2 INFRASTRUCTURE DEVELOPMENT AND DEPLOYMENT

5G technology will have unique infrastructure needs because it will address challenges across enhanced mobile broadband, massive-scale connectivity, and ultra-reliable low latency services. The different frequency bands that will be used across the range from low-band to mmWave each have unique characteristics and will impact the infrastructure that is needed.

A prime example would be the use of mmWave spectrum to provide fixed wireless services and extreme speeds. While fixed wireless service may be compelling, there will be inherent challenges in realizing this at scale. The limited propagation of mmWave spectrum and its limited object penetration will require a much greater number of sites to provide coverage than current cellular network designs. The need for a greater number of sites has obvious capital implications, driving up the cost to provide such a service and requiring a sufficient population density and market share to be profitable. These constraints will likely limit the usage of mmWave spectrum to urban or possibly dense suburban areas; it is doubtful that it could be a successful solution for the rural areas already feeling the greatest impact of the digital divide. Even in the urban and dense suburban areas the volume of new site deployments needed combined with the typically lengthy and complicated processes will strain operators and local or state governments alike.

Focusing on mid-band spectrum, it is predicted that spectrum in this range will be used to provide network capacity and higher speeds. However, mid-band spectrum also covers a large frequency range with very different characteristics. It is expected that mid-band will provide a blend of both speed and additional network capacity. Given the reduced range of spectrum in the 3.5 – 7.0 GHz range as compared to the traditional cellular bands around 2.0 GHz and below, that additional capacity is likely to come in the form of densification. This will involve using small cells in a targeted and precise manner to alleviate congestion and augment cellular networks, likely employing more low-to-the-ground and smaller antennas. In some ways, this approach could be viewed as a more efficient use of capital for network improvements, but it will also require a large volume of new sites and deployments, which under current regulations is likely to be a burdensome and slow process.

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[41] *Exploring Flexible Use in Mid-Band Spectrum Between 3.7 GHz and 24 GHz,* Federal Communications Commission, GN Docket No. 17-183; July 13, 2017.

It is also likely that 5G services will take advantage of innovative techniques such as edge computing and centralized radio access networks (C-RAN). C-RAN will create centralized pools of baseband processing to optimize the user experience and improve spectral efficiency, particularly at cell edges, through better coordination of resources. Edge computing has the potential to reduce latency and improve speed by moving data processing capabilities traditionally located in the core network closer to the end user. Integration of these two techniques will place further pressure on existing siting and deployment processes.

These examples point to a need to streamline a siting and deployment process that has historically been impeded by varying requirements and regulations at multiple levels of government. Uncertain approval criteria, long decision periods, and demanding limitations on accessing public rights-of-way have resulted in a framework that limits the ability of network operators to respond to changing customer demand. While regulation is necessary to protect the diverse interests of multiple stakeholders, too much regulation can stifle investment and growth and frustrate consumers. As 5G technology develops, it is necessary to strike a regulatory balance that takes this into account.

At the state and local government levels, it should be a priority to clearly define site application processing guidelines and the reasons for application denials. Time limits should also be implemented on application processing and reasonable cost-based fees assessed for access to state and local utility poles and rights-of-way. At the federal government level, there should be greater access to federal properties; land for antenna siting and small cells, due to their limited visual impact, should not be subjected to stringent environmental and historic review. Making these improvements to the siting and permitting processes will reduce barriers to the expansion of cellular networks allowing them to meet consumer demand and the needs of 5G.

Telecommunications infrastructure for 5G could also benefit from aligning tax policy to facilitate access to antenna sites. There are some programs under which the United States government collects taxes and then remits funds to the states for expenditures. One example of this is the federal gas tax, which the current Administration has suggested could be increased to help fund the nation's transportation infrastructure. Since 5G technology is expected to play an integral role in improving transportation safety and roadway efficiency through connected vehicles and machine-to-machine communication, proceeds from an increased federal gas tax could assist in developing 5G networks. A potential approach would be to award states funds for infrastructure projects after they demonstrate siting policies beneficial towards creating robust 5G networks. This would incentivize states to play a role in shaping 5G networks that would contribute to the public good.

Working to improve siting processes and revise tax policy and will ensure consumers and the government maximize the benefits they derive from the spectrum resources that are made available for 5G services. For a truly successful approach these actions need to be undertaken collectively and guided by a strategic plan with the goal of creating reliable, flexible, and scalable 5G networks that will satisfy consumer demand for cellular services and serve as innovation platforms that fuel economic growth.

8. CONCLUSION

As we near the introduction of 5G technology and the first network deployments, the aspect of pervasive connectivity is rapidly creating a new revolution in use cases and applications. It is expected that 5G networks will vastly improve the value of connected products as smart devices are likely to enable new services such as remote monitoring, usage tracking, automated repair, and new modes of interaction, while giving rise to numerous opportunities in delivering, managing and responding to data and content.

With the enormous capabilities of 5G wireless networks, connecting different kinds of devices to the Internet will be easier than before. Virtually all products imaginable from wearables to cars to medical diagnostic machines can make use of 5G features like high reliability, ultra-low latency, low- to high- bandwidth and mobility to enable a larger portfolio of applications.

It is important to note that many industrial, energy, healthcare, and business-critical market sectors have tended to invest heavily in direct process innovation and automation rather than focusing on indirect measures such as incorporating new communication technology features to create efficiencies. This has resulted in conservative adoption and use of wireless and internet technologies. These markets have also been highly fragmented and competitive but now many industrial and business-critical market segments are undergoing dramatic change. This will only accelerate as 5G continues to develop and bring performance connectivity improvements and vastly enhanced operational support that can truly integrate the Internet of Things and smart systems technologies. Industries are recognizing that the adoption of smart connected systems utilizing 5G technology will not be optional but rather a solution necessary to meet the growing demands of competitive markets.

This white paper chronicles and categorizes a growing list of use cases, services and applications that will be enabled by 5G technology and provides the requirements and performance indicators for the implementation of these use cases. The white paper also enumerates the changing market, technology and societal trends that are driving the evolution of cellular communications to meet the needs of a fully connected and mobile society.

This white paper also provides an overview of the various 5G technology enablers and the network architecture and topology that will support the wide range of use cases with diverse performance requirements. Finally, the white paper probes into the challenges of deploying 5G networks and the impact of regulatory and policy decisions at various levels of government. It is vital for the cellular industry to secure adequate licensed spectrum to enable the use cases envisioned for 5G technology and ensure that there are regulatory frameworks that facilitate infrastructure development and deployment to meet the growth in demand for cellular services.

While 5G technology will provide some tools to meet the growing demand for cellular services, it is also expected that 5G technology will generate even more demand by expanding connectivity capabilities and improving mobile access. It is envisioned that 5G technology will also provide a platform for innovation that will help to transform vertical industries, improve efficiency and functionality, expand economic productivity, and impact nearly all aspects of society.

APPENDIX A

5G SERVICE AND OPERATIONAL KEY PERFORMANCE INDICATORS

The service and operational level Key Performance Indicator (KPIs) for 5G systems are specified in 3GPP TS 22.261 and is reproduced in the tables below for easy reference.[42]

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[42] 3GPP TS 22.261, *Service requirements for the 5G system*; Stage 1. Release 15.

Table A1: Performance Requirements for High Data Rate and Traffic Density Scenarios

	Scenario	Experienced data rate (DL)	Experienced data rate (UL)	Area traffic capacity (DL)	Area traffic capacity (UL)	Overall user density	Activity factor	UE speed	Coverage
1	Urban macro	50 Mbps	25 Mbps	100 Gbps/km² (note 4)	50 Gbps/km² (note 4)	10 000/km²	20%	Pedestrians and users in vehicles (up to 120 km/h	Full network (note 1)
2	Rural macro	50 Mbps	25 Mbps	1 Gbps/km² (note 4)	500 Mbps/km² (note 4)	100/km²	20%	Pedestrians and users in vehicles (up to 120 km/h	Full network (note 1)
3	Indoor hotspot	1 Gbps	500 Mbps	15 Tbps/km²	2 Tbps/km²	250 000/km²	(note 2)	Pedestrians	Office and residential (note 2) (note 3)
4	Broadband access in a crowd	25 Mbps	50 Mbps	[3,75] Tbps/km²	[7,5] Tbps/km²	[500 000]/km²	30%	Pedestrians	Confined area
5	Dense urban	300 Mbps	50 Mbps	750 Gbps/km² (note 4)	125 Gbps/km² (note 4)	25 000/km²	10%	Pedestrians and users in vehicles (up to 60 km/h)	Downtown (note 1)
6	Broadcast-like services	Maximum 200 Mbps (per TV channel)	N/A or modest (for example, 500 kbps per user)	N/A	N/A	[15] TV channels of [20 Mbps] on one carrier	N/A	Stationary users, pedestrians and users in vehicles (up to 500 km/h)	Full network (note 1)
7	High-speed train	50 Mbps	25 Mbps	15 Gbps/train	7,5 Gbps/train	1 000/train	30%	Users in trains (up to 500 km/h)	Along railways (note 1)
8	High-speed vehicle	50 Mbps	25 Mbps	[100] Gbps/km²	[50] Gbps/km²	4 000/km²	50%	Users in vehicles (up to 250 km/h)	Along roads (note 1)
9	Airplanes connectivity	15 Mbps	7,5 Mbps	1,2 Gbps/plane	600 Mbps/plane	400/plane	20%	Users in airplanes (up to 1 000 km/h)	(note 1)

NOTE 1: For users in vehicles, the UE can be connected to the network directly, or via an on-board moving base station
NOTE 2: A certain traffic mix is assumed; only some users use services that require the highest data rates [2]
NOTE 3: For interactive audio and video services, for example, virtual meetings, the required two-way end-to-end latency (UL and DL) is 2-4 ms while the corresponding experienced data rate needs to be up to 8K 3D video [300 Mbps] in uplink and downlink
NOTE 4: These values are derived based on overall user density. Detailed information can be found in [10]
NOTE 5: All the values in this table are targeted values and not strict requirements

Table A2. Performance Requirements for Low-latency and High-reliability Scenarios.[43]

Scenario	End-to-end latency (note 3)	Jitter	Survival time	Communication service availability (note 4)	Reliability (note 4)	User experienced data rate	Payload size (note 5)	Traffic density (note 6)	Connection density (note 7)	Service area dimension (note 8)
Discrete automation – motion control (note 1)	1 ms	1 µs	0 ms	99,9999percent	99,9999%	1 Mbps up to 10 Mbps	Small	1 Tbps/km^2	100 000/km^2	100 x 100 x 30 m
Discrete automation	10 ms	100 µs	0 ms	99,99percent	99,99%	10 Mbps	Small to big	1 Tbps/km^2	100 000/km^2	1000 x 1000 x 30 m
Process automation – remote control	50 ms	20 ms	100 ms	99,9999percent	99,9999%	1 Mbps up to 100 Mbps	Small to big	100 Gbps/km^2	1 000/km^2	300 x 300 x 50 m
Process automation – monitoring	50 ms	20 ms	100 ms	99,9percent	99,9%	1 Mbps	Small	10 Gbps/km^2	10 000/km^2	300 x 300 x 50
Electricity distribution – medium voltage	25 ms	25 ms	25 ms	99,9percent	99,9%	10 Mbps	Small to big	10 Gbps/km^2	1 000/km^2	100 km along power line
Electricity distribution – high voltage (note 2)	5 ms	1 ms	10 ms	99,9999percent	99,9999%	10 Mbps	Small	100 Gbps/km^2	1 000/km^2 (note 9)	200 km along power line
Intelligent transport systems – infrastructure backhaul	10 ms	20 ms	100 ms	99,9999percent	99,9999%	10 Mbps	Small to big	10 Gbps/km^2	1 000/km^2	2 km along a road
Tactile interaction (note 1)	0,5 ms	TBC	TBC	[99,999percent]	[99,999%]	[Low]	[Small]	[Low]	[Low]	TBC
Remote control	[5 ms]	TBC	TBC	[99,999percent]	[99,999%]	[From low to 10 Mbps]	[Small to big]	[Low]	[Low]	TBC

NOTE 1: Traffic prioritization and hosting services close to the end-user may be helpful in reaching the lowest latency values.

NOTE 2: Currently realised via wired communication lines

NOTE 3: This is the end-to-end latency the service requires. The end-to-end latency is not completely allocated to the 5G system in case other networks are in the communication path

NOTE 4: Communication service availability relates to the service interfaces, reliability relates to a given node. Reliability should be equal or higher than communication service availability

NOTE 5: Small: payload typically ≤ 256 bytes

NOTE 6: Based on the assumption that all connected applications within the service volume require the user experienced data rate

NOTE 7: Under the assumption of 100percent 5G penetration

NOTE 8   Estimates of maximum dimensions; the last figure is the vertical dimension

NOTE 9: In dense urban areas

NOTE 10: All the values in this table are targeted values and not strict requirements

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[43]   3GPP 22.261.

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