Capacity Estimation for 5G Cellular Networks

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Abstract— This paper outlines the requirements for 5G cellular networks driven by the combination of increasing throughput demand, improving coverage and the capacity estimation for wireless access in the next decade. Deployment of 5G networks will emerge between 2020 to 2030 in many countries and will be built upon existing sites. 5G will offer great benefits for both consumers and industries to achieve a 'hyper connected society' capable of zero-distance connectivity between people and connected machines. The applications, the use cases as well as the massive Multiple-Input-Multiple-Output technologies, for example antenna beamforming and network densification to enhance the system capacity and mobility of 5G cellular networks are discussed in this paper.

Index Terms—Capacity estimation, enhanced Mobile Broadband (eMBB), Long-Term Evolution-Advanced (LTE-A), Machine to Machine (M2M), massive Multiple-Input-Multiple-Output, millimeter wave (mmWave), spectrum efficiency.

I. INTRODUCTION

Telecommunication service providers across the globe are in pursue of 5G technology. It is the fifth generation of telecommunication technology, transcends the boundaries of physical and digital world. 5G wireless technology serve to build more capacity and faster speed than the progression of existing technology, Long-Term Evolution-Advanced (4G standard). It also provides low latency and very high data rates with 500 Mbps upstream and reaching more than 1 Gbps downstream [1].

LTE-M is a 5G standard defined by 3rd generation partnership project (3GPP) which is readily available today and is expected to improve the traffic and support long-term coverage for massive Internet of Things (IoT) and Machine to Machine (M2M) connections [2]. It supports for Frequency Division Duplex (FDD), Time Division Duplex (TDD) and half duplex (HD) modes and can be deployed in any LTE spectrum. It is software upgradable from LTE and can coexist with other LTE services within the same band and only requires a very narrow bandwidth between 1.08 and 1.4 MHz, compared to the 5, 10 or 20 MHz bandwidth of a normal LTE carrier [3]. It has capacity for up to 100,000 devices or more per base station for applications where devices have very low data-throughput requirements.

The main quality of 5G networks as compared to 4G networks will be the capacity and data rates for users. It is going to be many times larger and quicker than what we have now. The capacity is needed for the delivery of enhanced Mobile Broadband (eMBB) services between the end users and the network to enable faster connections – that the apparent distance between people and machine will minimize to a virtual "zero distance" gap [4].

5G wireless networks can support up to 1,000-fold gains in capacity with peak data rates in the order of 10 Gbps, enabling connections to at least 100 billion devices, zero latency user experiences leading to a 'hyperconnected society' for which interactive application and mobile cloud-services will play important role in our lives. Other than eMBB, the following highlights the use cases of 5G.

II. USE CASES OF 5G

A. Internet of Things

The aim of 5G technology is not only connecting more handsets; but also, to bring connections to billions of machines regardless whether at our home or in office environments. Smart phones, smart watches and printers are the most common devices and machines that can be connected wirelessly exchanging massive data through wireless medium without noticeable delay. The notifications regarding upcoming events, relevant documents or materials needed for important meetings will pop up from the user's device.

B. Massive Machine Type Communications

Machine type communications will require new architectures, ideas, and key components of the cellular network to support mobility on demand only to certain users that will need it. The capacity of cellular networks used by M2M technologies needs to be able to handle billions of nodes for differing IoT services. The M2M markets will soar up by $23 billion in 2023, driven by 5G cellular network [5].

The popularity for IoT and M2M services directly links to the capacity development of 5G cellular networks for massive data processing including high-definition images and control systems of equipment carried out by machines. Increasing the number of connected devices help to increase communication to a new higher level.

C. Ultra-Reliable and Low Latency Communication

5G provides new applications and more flexible spectrum use in the future, including frequencies that was never being used before in cellular systems. Example of applications are virtual reality, autonomous cars, remote surgeries, smart cities, real-time automation, and robots [6]. With the rapid demand for IoT, many businesses will be created for 5G networks and deployments on a huge scale. Technologies such as Cloud, software-defined networking (SDN), and network function virtualization (NFV) [4] which relies on Ultra-Reliable and Low Latency Communication (URLLC) will reshape the industrial IoT applications and entire mobile ecosystem.

III. Requirements for 5G Networks

The 5G system capacity must be higher to gain greater access of connectivity for new applications and use cases, the 5G cellular networks must be able to cover further and beyond the previous generations of mobile communication. The users demand for data rate is increasing rapidly. Thus, to ensure users can satisfy the quality of service, the 5G networks should deliver data at lower cost and energy consumption for every bit delivered as compared to 4G.

The key feature of 5G systems is its capacity, the capability to support a much larger number of devices for future wireless communication. The new use cases envisioned for 5G include the deployment of simple sensors to enhance the overall traffic strength and further enhance the overall traffic volume. The following lists are the examples of 5G network requirements for massive system capacity.

A. Very High Data Rates Everywhere

5G networks are expected to offer very high speeds of minimum hundreds of megabits per second, up to gigabits per second for the eMBB data.

- Peak download speeds as high as 20 gigabits/second is required for remote precision medicine, connected cars, virtual and augmented reality, and IoT applications [7].

- The number of connected devices is targeted to be 100 times higher, and battery life for low power devices to last 10 times longer with an End-to-End (E2E) latency reduced by a factor of 5 hosted by the International Telecommunication Union Standardization Sector [8].

- 5G with minimum threshold data rates of 100 Mbps and above can support high-definition streaming for learning new courses through zoom online and Google classroom. This will be a new platform for students to learn new skills digitally.

The data rates have been increased since the wireless technology is upgraded from GSM (2G) to 3G UMTS, 3.5G HSPA and 4G's LTE and LTE-A. It is one of the most important aspects of 5G capabilities for the emerging pathway to economic and social opportunities. The following are the use cases for 5G networks [9]:

- 5G must provide data rates more than 10 Gbps for specific locations such as offices and indoor stadiums.

- Data rates of several 100 Mbps should be generally achievable in urban and suburban areas.

- Data rates of at least 10 Mbps should be achievable everywhere, including sparsely populated rural areas in both developed and developing countries.

B. Parameter Capacity

Previously discussed some key requirements that enable 5G cellular networks to fulfill performances. The main purpose of 5G is to enable a dramatic increase in its capacity with efficient utilization of all possible resources. Based on the well-known Shannon's theory, the total system capacity C_{sum} can be expressed by

$$C_{sum} \approx \sum_{HetNets} \sum_{Channels} B_i \log_2\left(1 + \frac{P_i}{N_p}\right) \quad (1)$$

Where B_i is the bandwidth of the ith channel, P_i is the signal power of the ith channel, and N_p denotes the noise power. Using

(1), we calculated the total system capacity C_{sum} is equivalent to the sum capacity of all heterogeneous networks and subchannels. Examples of these heterogeneous networks are macrocells, microcells, small cells, relays, MFemtocell [10] which can be implemented to increase network coverage. Increasing the number of subchannels using massive Multiple-Input-Multiple-Output or massive-MIMO can also increase C_{sum} [11]. Another technical approach to increase C_{sum} is by spatial modulation [12] with the increase number of transmit antennas which can mitigate inter-channel interference, inter-antenna synchronization, and multiple RF chains in conventional MIMO systems.

The 5G network will achieve 1000 times the system capacity, 10 times the spectral efficiency, energy efficiency and data rate at peak data rate of 10 Gb/s and 1Gb/s for low mobility and high mobility, respectively. The average cell throughput is 25 times over 4G. The following focuses some of the remaining requirement of 5G networks.

C. Extremely Low Latency

5G targets lower latency of about 1 millisecond, an order of magnitude faster than 4G which guarantees traffic safety and control of some 5G critical applications for cloud-based services [9] and Artificial Intelligence (AI) which require big data management, security, logistics and other network-enabled capabilities.

Extremely low latency and high bandwidth of 5G is suitable for cloud gaming. Robotic arm performing operation on patients is another use case of 5G utilizing low latency that that will allow doctors to control medical procedures remotely. It requires the system to responds quickly, fast scheduling, and fast link reconfiguration. Lower latencies for the end user will come from higher transmission data rates together with an appropriate design of the 5G systems [13].

In the sense of connection attributes to end user, 5G should enable huge capacity to multiple vendors at all levels. Privacy and security are also fundamental for the 5G system design where user identity and location must be protected from unlawful disclosure [14]. For these use cases, multiple-hop security, where intermediate nodes need to decrypt and re-encrypt data, should be avoided.

D. Ultra-High Reliability and Availability

Apart from low latency, 5G should also enable connectivity with ultra-high reliability and availability. The reliability of a communication is defined as the amount of sent packets successfully delivered to the destination within the time constraint required by the targeted service, over the total number of sent packets.

The ultra-high reliability of the link is vital for mission-critical services such as monitoring power plants, autonomous driving cars as well as robotics in medical and industrial applications. Therefore, 5G networks with real time critical connectivity must offer high availability rates of 99.999 % or higher for guaranteed services ensuring minimal service is available for emergency communication and public safety in day-to-day basis protecting users from risk of danger in case of disaster [14].

IV. 5G CHALLENGES

Certainly, there are potential benefits and some huge challenges for higher date rate 5G networks, for the most part, such as finding suitable sites for powering base stations and backhauling the data. This paper highlights some of the challenges faced by 5G [15] as listed below:

a) Extreme densification and offloading with denser networks of small cells with many active nodes to improve the area capacity.

b) Propagation loss at higher frequency using millimeter wave (mmWave) technologies.

c) Require many massive MIMO antennas up to 256 separate antennas to deliver the advanced beam steering and enhance data rates may be physically quite large.

d) Delivery of extremely low latency of 1ms for critical services.

e) The cost needed for deployment of 5G systems and health concerns adopting with new technologies.

f) Managing good quality of service (QoS) across different types of connections for billions of users and machines.

Privacy and security concerns will be increasing as more and more devices are placed on the network [6]. As the number of sensors are increased, the users' location and movements will be monitored for surveillance. Recent tensions between the

United States and China has caused the fragmentation of Huawei's 5G technology in other countries.

V. 5G IN OTHER COUNTRIES

A. China and South Korea

The governments of China and South Korea have been aggressively in pursue of 5G development not only to deploy 5G nationwide but also to dominate the global market share.

The Chinese government has already set up its national research and development programs and carefully calibrating the Chinese companies towards the international standards-setting bodies to achieve global standards recognition. Huawei, China Mobile, and ZTE are the three largest telecommunication equipment companies that participated international standard-setting bodies to coordinate all 5G activities in China. As per research conducted by the Australian Strategic Policy Institute in April 2019 [16], China already has involved in fifty-two 5G initiatives in 34 countries aiming for enterprise deployments in the 2020-time frame.

Meanwhile in South Korea, 5G Forum was established which is like EU's 5G public-private partnership (PPP). The spectators of the 2018 Winter Olympics in PyeongChang was the first to witness the 5G network trial.

Intel (INTC) and South Korean mobile carrier (KT) have set up 5G booths at Pyeong Chang to show spectators the new way of watching Olympic athletes closely and to broadcast ice arena on live in virtual reality respectively [17].

B. Japan

Like South Korea, Japan is hoping to launch 5G trial network and its technology at Tokyo Summer Olympic games in 2020 but was pushed back to 2021 due to global pandemic. Japan's telecommunication operator, NTT DoCoMo has embarked on several experimental trials together with Huawei [18]. The two companies have successfully completed a long-distance trial for 5G mobile communications using the 39 GHZ mmWave band in Yokohama. Furthermore, the representatives from both companies are collaborating with Tobu Railway for 5G trial of mmWave system at Tokyo Sky-Tree Town. These 5G trials are heavily funded and supported by Japan's Ministry of Internal Affairs and Communications (MIC).

Meanwhile, SoftBank, the rival of NTT DoCoMo, is also taking the lead in areas of 5G by partnering with Huawei. They aim to demonstrate potential 5G use cases for its enterprise partners. The demonstration included ultra-high definition (UHD) video transmission in real-time, remote control of a robotic arm using ultra-low latency transmission and remote rendering via a GPU server using edge computing [18]. The real-time throughput for UHD video transmission was over 800 Mbps.

SoftBank has been working closely with Ericsson, ZTE and Wireless City Planning in execution of 5G trials and commercializing massive MIMO technology, respectively in Japan.

C. United States

In October 2018, Verizon officially launched 5G Home, the first ever commercial 5G service known as Fixed Wireless Access (FWA) broadband [19] for home connectivity with speed from 300 Mbps up to 1 Gbps, depending on location. Verizon's network is based on the mmWave technology at 28 GHz licensed spectrum suitable for high data rates. In addition to that, Verizon has demonstrated several trials such as the 5G video call at the 2018 Super Bowl, 5G NR two-way signal transmission to a moving vehicle with Nokia, as well as multi-carrier aggregation including very high speeds outdoors [19]. Verizon expects to offer coverage up to roughly 30 million households with 5G Home services by 2026.

Recently, T-Mobile company is augmenting the low-band coverage at 600 MHz with a mid-band layer of 2.5 GHz to demonstrate the new strategy that mid-band 5G can reach wider coverage of 410 towns and cities [20] becoming the world's best 5G network.

VI. IMPROVEMENTS NEEDED FOR 5G

There are several improvements for 5G's future based on the challenges such as peak data rate and spectral efficiency as discussed earlier so that the users can experience the new and effective way of communication.

A. New services and opportunities

1) Gaming and Industrial Applications

a) *High throughput*: to improve users real-life experience through multimedia streams at anywhere and anytime. Users will be able to watch, download and play UHD videos and games on their smart phone.

b) *Ultra-high numbers of sensors*: for sending just small data packages. Since they require very low energy consumption to save battery life, the network will have to support this effectively.

c) *Ultra-low latency*: to support online gaming and to perform mission-critical services and to control industrial machines and appliances remotely from hundred or thousand miles away.

2) Capacity and end user data rates: estimation

a) *Requirements*: significantly increase the required system capacity using new network technology such as network slicing, spectrum management and utilizing larger bandwidth by allocating more frequency resources of 5G system to improve the users' experience.

b) *Spectrum range*: the 5G system requires additional spectrum at higher carrier frequency that can be integrated with other existing radio access technologies. Deployment of small cells as to re-use spectrum efficiently without wasting resources. When deploying 5G networks in rural areas, the sub-1 GHz band at 700 MHz is considered to offer wide coverage but unable to provide high data rate because of narrow spectrum availability. The mid-band spectrum for 5G deployment ranges from 1 GHz to 6 GHz especially at 3.5 GHz, and 3.7 – 4.2 GHz band which support a total bandwidth of ≥ 840 MHz suited well for urban macro cells. And finally, the unlicensed spectrum band for higher band sourced from 6 GHz and above provide higher data rates than the sub-1 GHz band and mid-band. There is huge contiguous bandwidth of spectrum available in those bands [21]. The only limitation for this spectrum is the wireless signal propagation to reach the users and more susceptible to attenuation than other bands. Therefore, this band is often used for urban hotspots and FWA.

c) *Cell coverage*: the future of 5G will include both terrestrial and aerial locations. Drones may be used for logistics replacing humans for delivering packages such as delivering medical supplies to the injured patients with drones finding the way automatically.
d) *Availability*: expansion of multiple small-cells and the development of backhaul infrastructure and the new radio base station equipment will meet the 1000 × capacity demand over the next decade. The operators are encouraged to share these equipment and spectrum will likely reduce the cost of deployment and allow higher coverage as an enabler for IoT and M2M services.
e) *Techniques*: Beamforming increases the Signal-to-Noise Ratio (SNR) link through the coherent addition of the transmitted signal from the antenna array to increase capacity and coverage. Spatial multiplexing increases system capacity by forming multiple parallel spatial channels between the Access Points (AP) and one or more User Equipment (UE) at a time.

B. Network Operation, Deployment, and Maintenance

5G networks need to support massive capacity to handle the explosive data for mobile Internet and IoT users. The deployment of 5G small cells network must make use of spectrum efficiently. The backhaul infrastructure, utilizing flexible spectrum, and equipped with advanced MIMO capabilities could improve the energy efficiency and cost per bit of the network.

Figure 1 shows an overview of the 5G cellular network integration of Multi-Radio Access Technology (Multi-RAT) network. The carrier aggregation of licensed and unlicensed bands will help in increasing the available system bandwidth [22] and to insure more deployment flexibility.

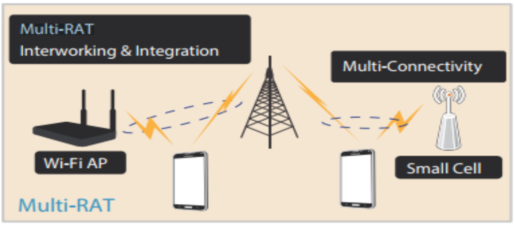

Figure 1. Overview of 5G cellular network involving Multi-Radio Access Technology (Multi-RAT) network [22].

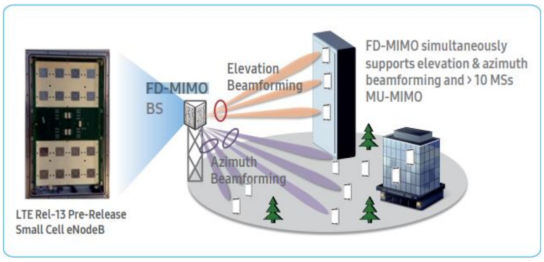

Figure 2. Overlaid network of Full Dimension MIMO system [22].

Full-Dimension MIMO (FD-MIMO) system can significantly improve the system performance combined with many active antennas in a two-dimensional grid at the radio base stations. Therefore, it can promise the delivery of very high data rate anywhere and ultimately improve users' experience and satisfaction.

C. Features and Trends

TABLE I provides brief information of the emerging technologies that could shape the design of future 5G cellular networks. The key ideas for each of the technologies are stated, along with the potential impact on 5G requirements.

TABLE I. FEATURES AND TRENDS OF 5G [23]

5G expectations and features	Trends/proposal
Capacity and throughput improvement, high data rate (~1000× of throughput improvement over 4G, cell data rate ~10 Gb/s, signaling loads less than 1~100%)	Spectrum reuse and use of different band (e.g., mmWave communication using 28 GHz and 38 GHz bands), Cloud-RAN, massive-MIMO
Reduced latency (2~5 milliseconds end-to-end latencies)	Full-duplex communication, Cloud-RAN, device-to-device communication
Network densification (~1000× higher mobile data per unit area, 100~10000× higher number of connecting devices)	Heterogeneous and multi-tier network
Advanced services and applications (e.g., smart city, service-oriented communication)	Cloud-RAN, network virtualization, M2M communication
Improved energy efficiency (~10× prolonged battery life)	Wireless charging, energy harvesting
Autonomous applications and network management, IoT	M2M communication, self-organizing and cognitive network

VII. CONCLUSION

The capacity for 5G is important feature in the future development of cellular network. By improving the capacity and bandwidth can further increase the peak data rate, connecting higher number of users and connected devices, simultaneously require reduction in latency. Further integration of multi-antenna enabling technologies can bring great benefits to people, businesses, and the society. The 5G networks will be extremely flexible, reliable, fast, secure, sustainable, and affordable with scalable technology to handle anticipated dramatic growth in number of connected devices and people without causing dramatic increase of power consumption and management complexity within heterogeneous networks. It will fully integrate into the supply chains across industry, sector, and national boundaries.

A new way of thinking is needed about 5G networks and devices creating zero-distance connectivity that include computing and content being distributed closer to the humans and machines. The 5G system will be able to use spectrum band at 700 MHz from sub-1 GHz, 3.5 GHz for below 6 GHz, and mmWave at 26 and 28 GHz higher bands, supporting a wider range of new services. This will offer new deployment models to users, government, and enterprises, respectively.

Multimode devices and simultaneous Wi-Fi, 4G, and 5G connectivity will enable a seamless and phased 5G cellular networks whereas the core network will ensure the operators of current and future investments being protected.

Telecommunication vendors have already started the planning and working together for the upcoming 5G networks which is the next generation of wireless networks to enable new services, new user experiences, and connect new industries.

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