An Introduction to

5G Wireless Networks

Technology, Concepts and Use-cases

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FIRST EDITION

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This book is dedicated to the engineers who make the world a better place to live, using technology.

Contents

Preface

This is the best time to be in the technology industry. With the invasion of technologies such as 5G, Artificial Intelligence, Machine Learning, Cloud and Internet of Things (IOT), technology plays a critical role in accelerating the fourth-industrial revolution. The merger of biotechnology and information technology has a direct thumbprint in the evolution of human race and our society.

The explosion of mobile devices and mobile services has brought several changes to our lifestyle. Our world has become more “app”-etized, today. The changes in our lifestyle is creating a ripple effect, transforming the way in which our networks are designed, deployed and managed. An application is as good as the network that carries it. With billion plus applications riding on our network, our network infrastructure has to be faster, more agile, more programmable, more scalable and more intelligent.

5G is the biggest technology revolution in the telecommunications industry – built with an objective of catering to the demands of the modern society. 5G would fuel the transformation needed for the fourth industrial revolution – by powering up drones, smart cities, autonomous cars and robotic surgeries. This is the first among the several generations of mobile wireless technology that is not specifically targeted at mobile phones.

This book on 5G Wireless Networks, was written to enable the several hundreds and thousands of academicians, engineers, managers, marketing and sales executives to understand the technology better, to further accelerate the transformation happening around us.

Albert Einstein once said “If you cannot explain it to a six-year-old, you do not understand it yourself”. While, it is hard to explain 5G to a six year old, this book is written with an objective of explaining complex technologies in a simple format for readers to understand better. This book captures all of the recent technological advancements in the 5G networks.

I would like to thank the contributions of the numerous researchers, standard bodies, software engineers, technology enthusiasts who have come together to standardize the 5G technology. This book would not have been possible, without their contributions.

Saro Velrajan

1. Evolution of Wireless Networks

Today, technology has become an integral part of our life and has radically changed our lifestyle. With the penetration of smartphones, and app-ification of services, we are now used to booking cars, transferring money, ordering food, and booking our flight tickets, from almost anywhere – be it from a park or from a moving train. We can avail most services online, with the click of a button. All of this is made possible by the growth of the wireless network infrastructure. While the wireless networks were originally invented for helping people to communicate with each other using voice, it has evolved to transfer data and support myriad services. Wireless networks have become ubiquitous and have grown

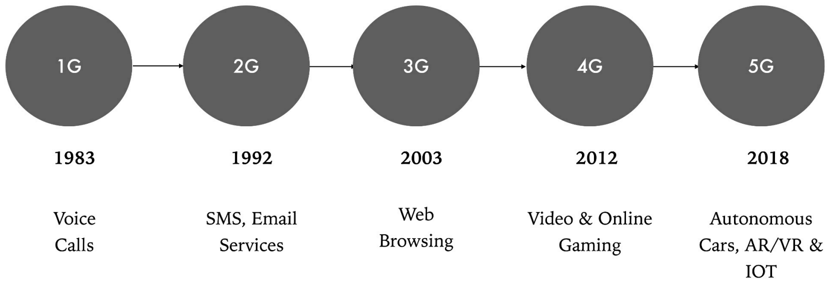

FIGURE 1.1 - EVOLUTION OF WIRELESS NETWORKS

in capacity over the years offering higher bandwidth and supporting more connections.

Today, wireless networks are not just connecting people, but also connecting businesses and almost everything in the world. In this chapter, we will look at the evolution of the wireless networks from 1G to 4G and understand the need for 5G networks.

1G Networks

FIGURE 1.2 - MOTOROLA DYNATAC PHONE

In 1983, the first-generation wireless network (also called as 1G network) was launched in US using the Motorola DynaTAC mobile phone. Later on, the 1G technology was launched in other countries such as the UK and Canada. The 1G technology was primarily used for making voice calls over wireless network. 1G network was based on analog telecommunication standards. The voice calls in 1G network were transmitted using analog systems.

Motorola DynaTAC 8000x is the first commercial mobile phone that was used for making analog voice calls. The phone looked almost like a cordless phone handset and weighed 1.75lb.

In 1G, the spectrum was divided into a number of channels, for users to make voice calls – each user gets a channel. This had limitation on the number of users who can make simultaneous voice calls. 1G technology faced other issues such as poor voice quality (due to interference), mobile phones were huge and had poor battery life, the network coverage was very limited. That led the researchers to come up with the 2G standards. The key difference between 1G and 2G networks is that, 1G used analog standards and 2G used digital standards.

2G Networks

In 1991, Global System for Mobile Communications (GSM) standard body published the standards for 2G technology. 2G technology, was launched in 1992 and had the ability to handle voice calls over digital systems. In addition to voice calls, 2G also supported Short Messaging Services (SMS). 2G offered wider coverage when compared to 1G network. It enabled users to send text messages to each other, over a wireless network.

GSM network architecture had 2 distinct layers - the Base Station Subsystem (BSS) and the Network Switching Subsystem (NSS). The BSS had the base station and the base station control function. The NSS had the core network elements. The core network elements in the NSS were responsible for the switching of calls between the mobile and other landline or mobile network users. In addition, the core network elements in the NSS supported the management of mobile services including authentication and roaming.

European Telecommunication Standards Institute (ETSI) established General Packet Radio Service (GPRS), an Internet Protocol (IP) based mobile data standard, as an enhancement to the 2G technology. The new service was called as 2.5G and it offered 56 - 114 Kbps data speed. 2.5G technology, eventually morphed into EDGE (Enhanced Data Rates for GSM Evolution) and was ideal for email services. 2.5G technology resulted in the growth of mobile phones such as Blackberry, which offered mobile email services.

3G Networks

3G cellular services were launched in the year 2003. 3G was much more advanced, when compared to 2G/2.5G and offered up to 2 Mbps speed, supporting location-based services and multimedia services. It was ideal for web browsing. Apple, which was known to be a computer maker, got into the mobile equipment business by launching iPhone, with the advent of 3G. Android, the open source mobile operating system became popular with 3G.

With 3G, the 3GPP group standardized UMTS. Universal Mobile Telecommunications System (UMTS) is a third-generation mobile cellular system for networks based on the GSM standard. Developed and maintained by the 3GPP (3rd Generation Partnership Project). UMTS uses wideband code division multiple access (W-CDMA) radio access technology to offer greater spectral efficiency and bandwidth to mobile network operators.

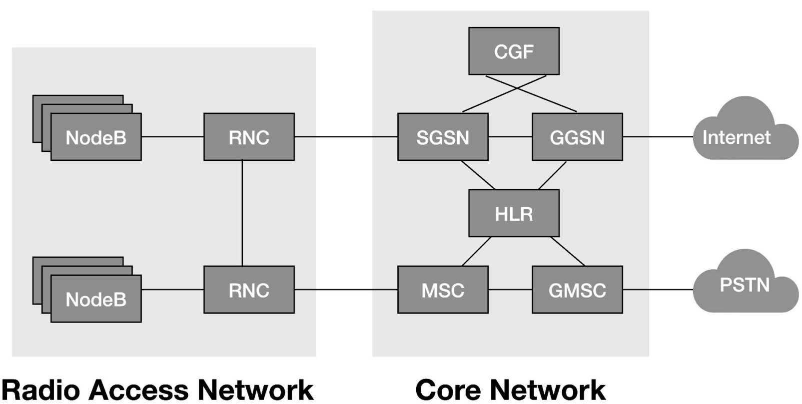

FIGURE 1.3 - 3G ARCHITECTURE

UMTS specifies a complete network system, which includes the radio access network (UMTS Terrestrial Radio Access

Network, or UTRAN), the core network (Mobile Application Part, or MAP) and the authentication of users via SIM (Subscriber Identity Module) cards.
3G network architecture has three distinct entities:

1. **User Equipment (UE):** In 2G, the handsets were called as mobile phones or cell phones, as they were predominantly used for making voice calls. However, in 3G, the handsets can support both voice and data services. Hence, the term User Equipment or UE is used to represent the end user device, which could be a mobile phone or a data terminal.

2. **Radio Access Network (RAN):** The RAN, also known as the UMTS Radio Access Network, UTRAN, is the equivalent of the previous Base Station Subsystem (BSS) in GSM. RAN includes the NodeB function and the Radio Network Controller (RNC) function. The NodeB function provides the air interface. The RNC manages the air interface for the overall network.

3. **Core Network:** The core network is the equivalent of Network Switching Subsystem or NSS in GSM and provides all the central processing and management for the system. Core network has both circuit switched and packet switched network elements.

3G core network architecture consists of the following functions:

Home Location register (HLR)

HLR is a database that contains all information about the subscriber including their last known location. The HLR maintains a mapping between Mobile Station International Subscriber Directory Number (MSISDN) and International Mobile Subscriber Identity (IMSI). MSISDN is the mobile phone number used for making and receiving voice calls and SMS. IMSI is used for uniquely identifying a SIM card and the number is stored in the SIM card. Each network can have one or more physical or logical HLRs. User equipment periodically updates its location details to the HLR, so that calls can be routed appropriately to the user. Depending upon the implementation, the HLR may also have an in-built Equipment identity register (EIR) and Authentication Centre (AuC).

Equipment Identity Register (EIR)

The EIR is the function that decides whether a user equipment is allowed onto the network or not. EIR is typically integrated with the HLR. EIR is used for blocking or monitoring calls from a stolen user equipment. Each user equipment is uniquely identified through a number known as the International Mobile Equipment Identity (IMEI). IMEI is exchanged by the user equipment at the time of registration with the network. Thus, EIR identifies a stolen equipment through its IMEI.

Authentication Centre (AuC)

AuC is used for storing a shared secret key, which gets generated and burned in the SIM card at the time of manufacturing. AuC function is typically co-located with the

HLR function. AuC does not exchange the shared secret key, but would run an algorithm on the International Mobile Subscriber Identity (IMSI), to generate data for authentication of a subscriber / user equipment. Each IMSI is unique and gets mapped to a SIM card.

Mobile switching centre (MSC)

MSC is responsible for functions such as routing calls and SMS messages. It interfaces with the HLR for keeping track of subscriber location and does call handovers, when the mobile subscriber moves from one location to another. Gateway MSC (GMSC) is a function that is present either within or outside of the MSC. A GMSC interfaces with the external networks such as the Public Switched Telephone Network (PSTN), which is our legacy land line network.

Serving GPRS Support Node (SGSN)

SGSN is responsible for mobility management and authentication of subscribers / mobile devices in a GPRS network. It performs a role which is similar to the role played by the MSC for voice calls. The SGSN and MSC are often co-located in the network.

Gateway GPRS Support Node (GGSN)

GGSN acts as a gateway to the Internet. It connects the GPRS network with the packet switched data network. GGSN receives data addressed to a given subscriber, checks if the subscriber is active and then forwards the data to the SGSN serving the particular subscriber. If the subscriber is inactive, the data is discarded. The GGSN keeps a record of active subscribers and the SGSN they are attached to. GGSN assigns a unique IP address to each subscriber. It also generates the call detail records (CDRs), which are processed by the Charging Gateway Function (CGF) or billing servers.

Charging Gateway Function (CGF)

CGF handles Call Detail Records (CDRs) generated by the GGSN in a GPRS network. There are different types of CDRs processed by the CGF, based on the network node that generates the CDR. For example, when a SGSN generates CDRs, it is called S-CDR. When a GGSN generates CDRs, it is called G-CDR. One of the key differences between S-CDR and G-CDR is, G-CDR would have insights into the subscriber data transfers (for example, volume of data uploaded/downloaded by the subscriber).

3G technology evolved over a period of time to offer higher speeds by supporting a new standard called High Speed Packet Access (HSPA). Service providers who offered 3G services with HSPA support called their services as 3.5G or 3G+. The 3.5G networks that supported HSPA standards were able to offer speeds up to 7 Mbps. With the further evolution of HSPA standard (also called as Evolved HSPA), 3G networks were able to offer speeds up to 42 Mbps.

4G Networks

In 2012, 4G services were launched, with speeds of up to 12 Mbps. 4G is an all-IP (Internet Protocol) network and it resulted in massive changes to the radio network and the core network architecture.

In 4G network,
- the radio function is based on the Long Term Evolution (LTE) 3GPP standards and
- the core network is based on the Evolved Packet Core (EPC) 3GPP standards

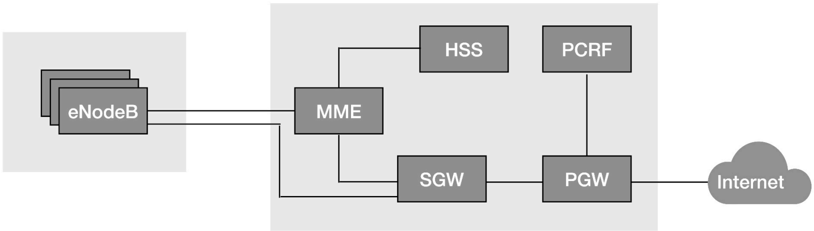

FIGURE 1.4 - 4G ARCHITECTURE

One of the significant changes introduced by the Long Term Evolution (LTE) standards in 4G networks, is the changes to the Base station functionality. In 3G, the radio resources were centrally controlled by a node called Radio Network Controller (RNC). LTE introduces a new function called the Evolved NodeB (eNodeB), which manages the radio resource and mobility in the cell.

In order to meet the 4G LTE requirements, functions of the eNodeB not only included the base station (NodeB) functions to terminate the radio interface but also the functions of the Radio Network Controller (RNC) to manage radio resources. This architecture is called Evolved UMTS Terrestrial RAN (E-UTRAN) architecture.

In 3G, the RAN function included the base station (Node B) and the antennas. In 4G LTE architecture, the base station function is split into two key functions - Baseband Unit (BBU) and Remote Radio Head (RRH). RRH is connected to BBU through optical fiber. The BBU function is moved out from the cellsite and hosted in a centralised location and called as Centralized RAN. The RRH function (i.e., the antenna function) is deployed closer to the users in a distributed fashion. The RAN architecture and the distribution of RRHs and BBUs is influenced by several factors such as quality of service, latency, throughput, user density and load demand.

The following are the key functional nodes/network elements in the LTE architecture:

Evolved Node B (eNB)

eNodeB is the entity that supports air interface and performs radio resource management. It provides radio resource management functions such as IP header compression, user data encryption, and routing the user data to the Serving Gateway (SGW).

The radio interface provided by eNodeB can be shared by several operators by having separate MME, SGW & PDN Gateway.

Home Subscriber Server (HSS)

Home Subscriber Server (HSS) is a database for storing the subscriber profile and authentication information. MME downloads subscriber profile information from the HSS, when a user equipment/mobile device attaches to the network. HSS also provides the subscriber profile information to the IP Multimedia Subsystem (IMS) Core function, at the time of the IMS registration.

Serving Gateway (SGW)

SGW serves as the mobility anchor for the user plane. It takes care of inter-eNodeB handovers & User Equipment (UE) mobility between 3GPP networks. It is responsible for routing/forwarding data packets between the eNodeB & Packet Data Network Gateway (PDN GW).

Packet Data Network Gateway (PGW)

PDN GW provides the UE with connectivity to the external packet data networks such as Internet. It serves as the anchor point for intra-3GPP network mobility, as well as mobility between 3GPP and non-3GPP networks. It takes care of Policy and Charging Enforcement Function (PCEF), which includes Quality of Service (QoS), online/offline flow-based charging data generation, deep-packet inspection, and lawful intercept.

Mobility Management Entity (MME)

MME manages mobility, UE identities and security parameters. It operates in the Control plane and provides functions such as managing session states, authentication, mobility with 3GPP 2G/3G nodes, and roaming.

Policy and Charging Rules Function (PCRF)

Policy and Charging Rules Function (PCRF) maintains the policy and charging related controls for all the subscribers. For example, a subscriber’s quality of service policy is stored in the PCRF server. The QoS policy can differ from service to service for each subscriber. The QoS for an IMS bearer may be different from the QoS for an Internet bearer for the same subscriber. Such differentiations in the QoS can be enforced by setting rules in the PCRF server. In addition, PCRF also helps the service providers in providing location-based services. PCRF allows a service provider in setting flow-based charging rules. For example, a service can be stopped, when the credit limit for the service is reached.

With higher data speeds, 4G technology allowed users to watch high-definition video and play games online. Over a period of time, multiple enhancements were made to 4G technology - LTE-M (LTE Category M1 for Machines) allowed low powered IOT devices to connect to 4G networks and LTE-Advanced standards offer a network speed of upto 300 Mbps.

Today, 4G offers adequate network speed for over the top services such as online video, gaming and social media. However, it does not support the bandwidth and latency needs of services such as Augmented Reality, Virtual Reality and Autonomous Cars. This paved the path for 5G technology research.

4G Data Connection Establishment

There is a lot of similarities between how a data connection is established in a 3G and a 4G network. This section describes the procedures involved in establishing a data connection between the mobile equipment and the 4G network.

When a mobile phone is powered on, it looks for signals from the cellphone towers in the vicinity. Based on the International Mobile Subscriber Identity (IMSI) from the SIM card, the mobile phone picks the right service provider. The phone then requests for a radio resource from the eNodeB. The eNodeB allocates a radio resource for the mobile subscriber. The moment the mobile equipment gets the radio resource, it starts displaying the wireless ‘signal bar’ on the console.

Then, the mobile device (also called the User Equipment or UE), sends an “Attach” request to the network. The “Attach Request” reaches the MME (Mobility Management Entity) in the Evolved Packet Core (EPC). The first step taken by the EPC is to authenticate the subscriber based on the SIM credentials. The MME retrieves the subscriber profile information from the HSS/HLR. The MME issues a challenge (which includes a set of encrypted keys) to the UE. The UE runs the challenge against the credentials stored in SIM card. The UE responds back to the challenge with an authentication response. The MME validates the authentication response based on the profile information

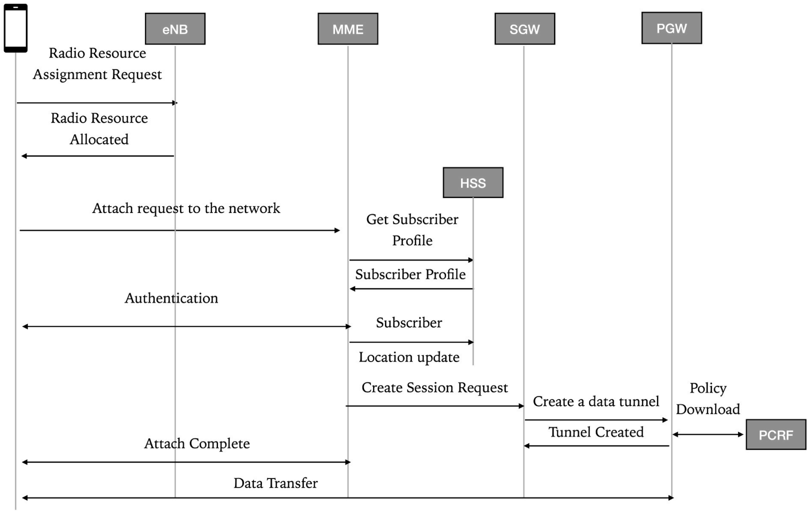

FIGURE 1.5 - 4G DATA CONNECTION ESTABLISHMENT

retrieved from the HSS/HLR. The subscriber is now authenticated.

Once the mobile subscriber is authenticated, the EPC proceeds with the session initiation process. The MME sends a “Create Session Request” to the Serving Gateway. The Serving Gateway sets up a tunnel with the PDN Gateway (PGW). As part of establishing the tunnel, the PGW downloads policy information from PCRF and applies them on the subscriber context. Once the tunnel, is created, the MME responds back to the UE with an “Attach Accept” response. The bearer / tunnel is setup based on the Internet Access Point Name (APN). APN will typically look like “internet.telco.com” and is configured in the UE by the service provider, as part of the initial configuration download to the mobile device. The moment, a tunnel is created (which means the data session is established), the mobile equipment starts displaying the ‘4G' symbol on the console.

Voice calls in 4G Network

There are different mechanisms available to handle voice calls in a 4G network. The two popular mechanisms to handle a voice call are Circuit Switched Fall-Back (CSFB) and Voice over LTE (VoLTE).

Circuit Switched Fall-Back (CSFB)

When LTE is just used for data transfer, voice calls are handled through the legacy circuit switched mechanisms - by falling back to a 3G or 2G network. Circuit Switched Fall-Back (CSFB) works only when the area covered by an LTE network is also covered by the 3G network. CSFB will be helpful for service providers when they are migrating from

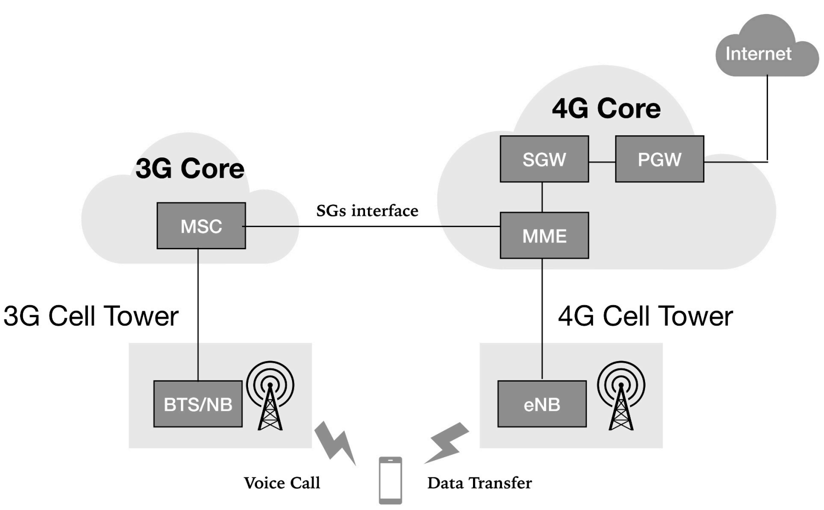

FIGURE 1.6 - CIRCUIT SWITCHED FALL-BACK

2G/3G to a 4G network. In CSFB, the 4G MME talks to the 3G MSC through the new SGs interface, to setup the voice call.

User Equipment (UE), initiates a “Combined Attach” procedure to both PS (Packet Switched) and Circuit Switched (CS) networks. MME receives the "Combined Attach” request and sets up the PS connection over the 4G Core, for data transfers. The newly introduced SGs interface between the MME and MSC is used for the CS connection setup over the 3G core, for voice calls. Once the UE is attached to both the 4G and the 3G networks, the eNodeB directs the UE to the 3G NodeB radio. The UE sets-up a voice call over the 3G NodeB. This circuit switched fallback to the 3G network, is equivalent of a handover from the 4G to 3G network, for voice calls.

Voice over LTE (VoLTE)

Voice over LTE is relatively a new concept, to support voice calls over the 4G network. While CSFB helped the service providers during the migration from 2G/3G to 4G networks, VoLTE runs completely on the 4G network. In case of VoLTE, the user equipment / mobile should be capable of initiating a VoLTE call and the network should support VoLTE. VoLTE calls are handled by the IP Multimedia Subsystem (IMS) core, in the 4G network.

Unlike the OTT (Over the Top) calling services like Skype or Whatsapp, VoLTE service uses the same dialer application used by the CSFB service. It also provides reliability, when compared to the OTT calling

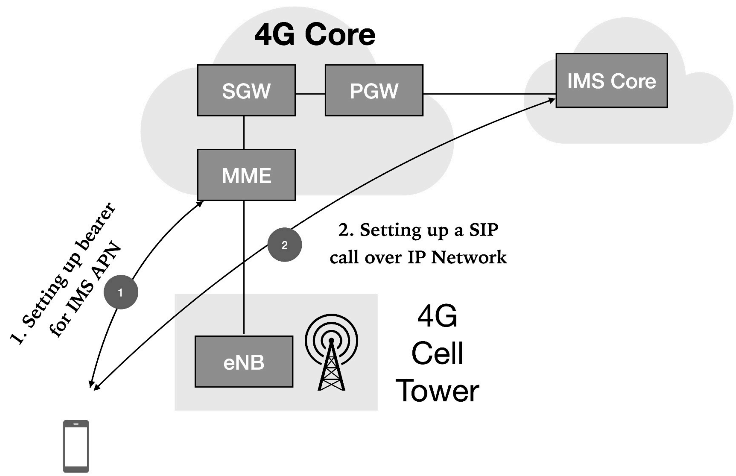

FIGURE 1.7 - VOICE OVER LTE

services. For example, when the service provider is not able to establish the call via the VoLTE, the phone would automatically switch to the 2G/3G based circuit switched calls. This helps when a customer is making an emergency call.

Setting up a VoLTE is a two-step process:

1. At first, the UE sets up a dedicated bearer/tunnel for IMS APN (Access Point Name). For example, the APN name will look like ims.telco.com. This is configured by the service provider on the UE. These settings automatically get downloaded to the mobile phone, as part of the service activation by the service provider. This bearer for IMS APN will be setup, in addition to the bearer setup for

Internet APN (i.e., for data transfers). The procedure for bearer setup is similar to the procedure outlined in the "4G data connection establishment" section.

2. Once the bearer is established, the UE sets up a Session Initiation Protocol (SIP) connection with the IMS Core. SIP is a popular protocol used for Voice over IP (VOIP) communications, over the Internet.

Unlike the OTT VOIP dialer applications, the service provider guarantees reliability and security for the voice calls made over an LTE connection. Voice over WiFi (VoWiFi) is also similar to VoLTE. However, the wireless service provider would not be able to guarantee the reliability of the voice calls made over the WiFi connection. When the Internet speeds over WiFi are high and reliable, VoWiFi calls help the service provider to offload the mobile wireless network for other applications/services. Hence, many service providers support VoWiFi capabilities.

Evolution of Radio Access Network (RAN)

The Radio Access Network (RAN) architecture has evolved across the different generations of the wireless network, to support the bandwidth and scalability requirements.

RAN has two distinct units – the Remote Radio Head (RRH) and the Baseband Unit (BBU). One end of the RRH is connected to the antenna and the other end to the BBU. RRH acts as a transceiver converting the analog signals to digital signals and vice versa. In addition, RRH also does

Generation	Architecture / Technology	Base Station
2G	GSM	Base Transceiver Station (BTS)
3G	UMTS	NodeB
4G	LTE	Evolved NodeB (eNodeB)
5G	NR	Next Generation NodeB (gNodeB)

TABLE 1.1 - EVOLUTION OF RAN

filtering of noise and amplification of signals. The Baseband Unit (BBU) provides switching, traffic management, timing, baseband processing, and radio interfacing functions. BBU is typically connected to the RRH using a Fiber link.

In the traditional 2.5G/3G networks, both the RRH and BBU functions remained in the cell site, as part of the Base Transceiver Station (BTS). In the 4G network, BBU function was moved out of the cell site to a centralized location. BBU function in a 4G network is hosted in the Central Office and is called as Centralized RAN. 4G architecture optionally supports the virtualization of BBUs and when the BBU function is virtualized, it is also called as Cloud RAN or Virtualized RAN. In a 5G network, virtualization of BBUs almost becomes mandatory as it helps the service providers to scale the network to support the various use cases.

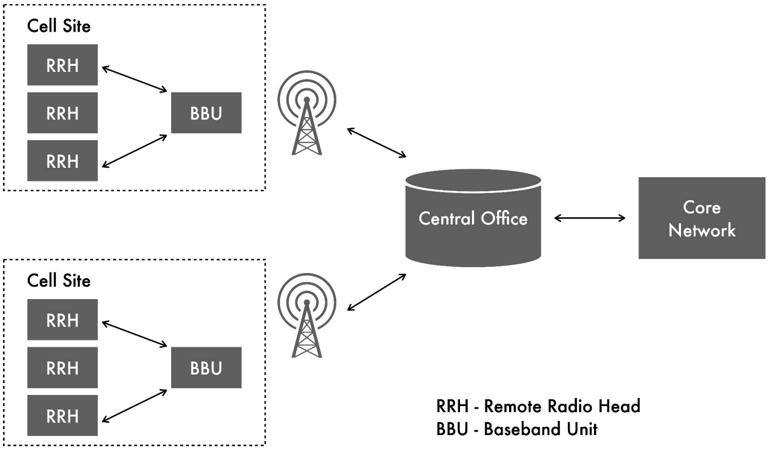

FIGURE 1.8 - TRADITIONAL RAN

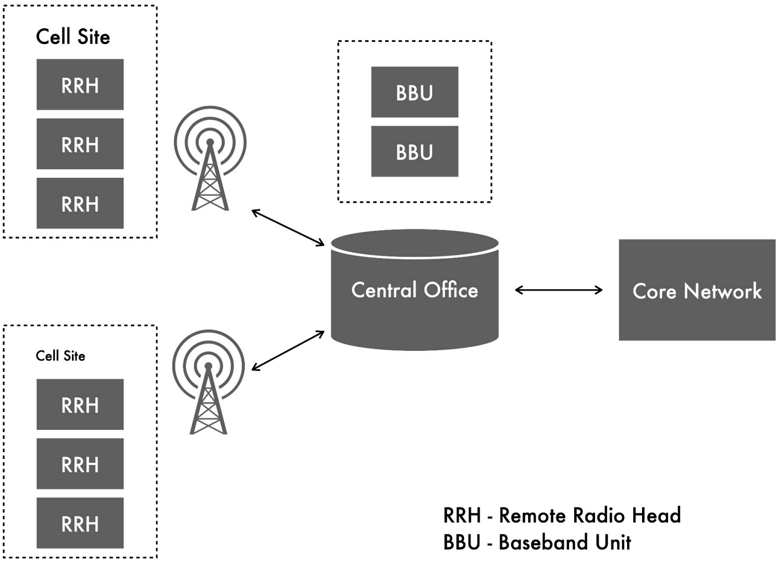

FIGURE 1.9 - CENTRALIZED RAN

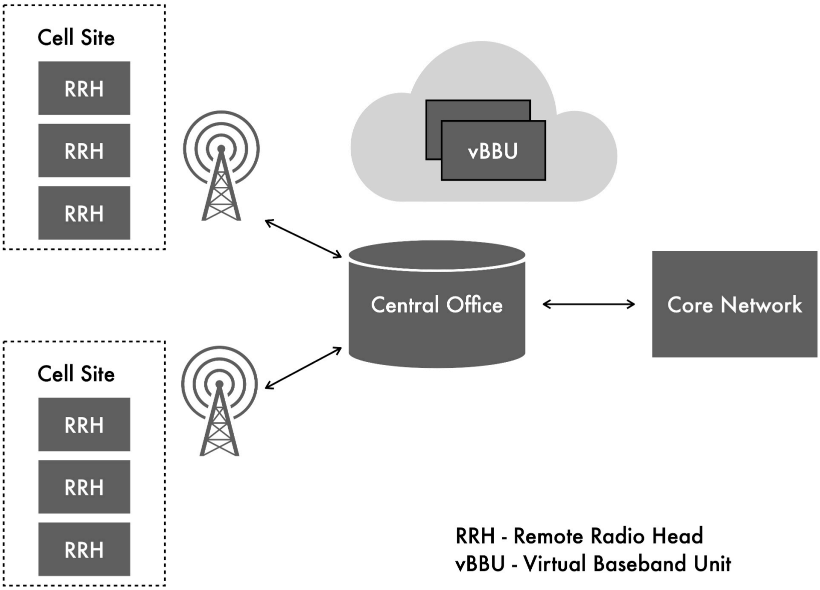

FIGURE 1.10 - VIRTUALIZED RAN

Need for 5G

Most of the previous generation wireless technologies (such as 3G and 4G) were focused on increasing the speed of the wireless technology. 4G technology initially supported speeds of up to 12 Mbps - which was adequate for online video streaming and gaming services. However, 4G does not address the technology needs of some of the emerging use cases, in the areas of Internet of Things (IOT) and Virtual Reality.

Here is the list of factors that drive the need for 5G technology:

- Internet of Things (IOT) will require an infrastructure that can handle several billions of network devices connecting to the wireless network, and at the same time energy efficient

- 3D video and Ultra High Definition Video streaming applications are hungry for additional bandwidth

- Virtual Reality and Augmented Reality enabled gaming, video streaming and industrial applications require sub-millisecond latencies

- Network operators have immense pressure to upgrade their networks continuously, to handle the growth in the mobile data traffic - and at the same time, reduce operational expenses

- Enable new revenue streams for wireless service providers, by supporting new applications and use-cases

In 2016, several service providers partnered with network equipment vendors to kick start 5G trials. Starting 2018, 5G services were commercially launched by multiple service providers across the globe.

Review Questions

1. What is the first mobile wireless phone? Which vendor manufactured it?

2. What are the various use-cases supported by different generations of wireless technology?

3. How much speed does 4G provide?

4. What are the differences between 3G and 4G systems?

5. What is a Radio Access Network (RAN)? What are the functions provided by the RAN?

6. How has the RAN evolved across the different generations of wireless networks?

7. What are the different types of RAN deployment?

8. What is LTE?

9. What are the differences between LTE-M and LTE-A?

10. What are the mechanisms by which voice calls are supported in a 4G network?

11. Why do we need 5G?

2. 5G Overview

5G is the fifth-generation wireless technology, standardised by the 3rd Generation Partnership Project (3GPP). 5G supports upto 1 Gbps speed, 1-10 milliseconds latency and scales to several millions of network devices. 3GPP standardised 5G technology as part of their Release 15 specifications, in 2018.

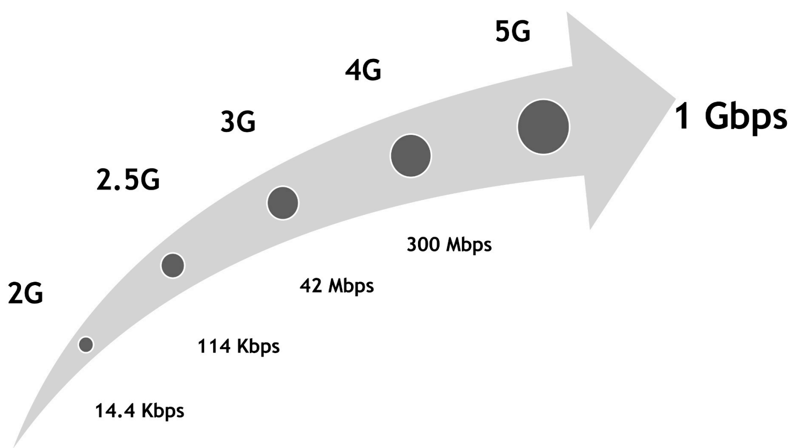

FIGURE 2.1 - SPEED OF WIRELESS NETWORKS

5G brings significant changes to speed, latency and scale. 5G services are expected to make a huge impact on service providers, businesses, consumers and the society at large. 5G is not just an evolution from 4G technology - it is revolutionary. The most visible changes in 5G are on the radio - 3GPP defined the new radio specification called 5G New Radio (5G NR) for 5G services. However, 3GPP also has revamped the core network infrastructure to support the speed, latency and scalability requirements of 5G, by introducing 5G Next Generation Core (5G NG-Core). The 5G NG-Core will be the heart of the 5G network and acts as an anchor point for multi-access technologies. It delivers a seamless service experience across fixed and wireless access technologies.

Characteristics of 5G

There are a few key characteristics of 5G technology, that are notably different from the previous generation wireless technologies.

- **Spectrum:** 5G supports a wide range of spectrums from low bands below 1 GHz, to mid bands from 1 GHz to 6 GHz, to high bands 24 / 30 GHz to 300 GHz (also, known as millimeter-wave).

- **Bandwidth**: 5G supports up to 1Gbps throughput, today. However, the industry aims to support a peak data rate of 10 Gbps.

- **Programmability:** 5G can be customized to meet the requirements of a diverse set of use-cases and deployments (for ex., a high-bandwidth and latency agnostic mobile broadband use-case to a low-bandwidth and latency sensitive Industrial IOT use-case). This is achieved through capabilities such as "network slicing".

- **Latency:** 5G supports 1 – 2 milliseconds latency, which enables use-cases such as mobile gaming, augmented reality and virtual reality.

- **Virtualization:** 5G infrastructure is built on virtualized network functions such as Virtual RAN, Virtual EPC and Virtual IMS. It enables services providers to dynamically scale the network infrastructure to meet the demands of the customers.

- **Connection Density:** 5G aims to provide connectivity to nearly 1 million devices in an area of 1 square kilometre.

5G Use Cases

2G technology was for phone calls and SMS services. 2.5G or EDGE technology was for email services, 3G technology was for web, 4G technology was for video and 5G is for use cases that we cannot possibly imagine.

5G technology caters to the needs of multiple industries such as the following:

- Public Safety
- Broadcasting / Media Delivery
- Automotive Industry (Public Transport Systems)
- Aeronautical (Drones)

- Health / Wellbeing
- Utilities
- Education

Some of the key 5G use cases are:

- Enhanced Mobile Broadband (eMBB)
- Fixed Wireless Broadband Services
- Robotic Surgery
- Autonomous Cars
- Massive Internet of Things (IOT) Services
- Live TV
- Virtual Reality / Augmented Reality
- Private Wireless Network for Enterprises
- Holographic Calls

A detailed explanation of the use-cases will be given in ‘5G Use-cases” chapter.

4G versus 5G

4G network infrastructure is based on Long Term Evolution (LTE) architecture. 5G network infrastructure is based on 5G Next Generation Core (5G NG-Core) architecture. There is a significant difference between both the technologies in terms of speed, latency, frequency ranges of the spectrum, use cases that are supported, support for network slicing, RAN architecture, and Core network architecture.

Table 2.1 captures the differences between 4G and 5G technologies.

Criteria	4G	5G
Speed	300 - 400 Mbps (lab) 40 - 100 Mbps (real world)	1000 Mbps (lab) 300 - 400 Mbps (real world)
Latency	50 ms	1 - 2 ms
Frequency	2 - 8 GHz	Sub 6 GHz (5G macro optimized), 3-30 GHz (5G E small cells) 30-100 GHz (5G Ultra Dense)
Use Cases	Voice over LTE Mobile Broadband Online Video Online Gaming	Enhanced Mobile Broadband Augmented Reality / Virtual Reality Internet of Things (IOT) Holographic Calls Fixed Wireless Autonomous Cars Robotic Surgeries
Network Slicing	No	Yes
Cell Towers	Large Towers in concentrated communities	Small Cells installed in almost every street corner, in addition to mobile towers
Service Architecture	Connection Oriented	Service Oriented
Architecture	Long Term Evolution (LTE)	Next Generation Core (NG-Core) New Radio (NR)

TABLE 2.1: 4G VERSUS 5G

Review Questions

1. What is 5G?

2. What are the differences between 4G and 5G?

3. How much speed does 5G support?

4. What is the latency supported by 5G?

5. What are the spectrum ranges supported by 5G?

6. What are the changes in 5G, when compared to 4G?

7. What are the use cases enabled by 5G?

3. 5G Architecture

Building a wireless network that supports a diverse set of services is quite challenging. The scope for 5G goes beyond just supporting mobile handheld devices. 5G architecture should support use cases that were not handled by the previous generation wireless technologies.

5G System Architecture

5G architecture is developed based on the following key aspects:

- Support for service-based architecture and service-based interfaces
- Built on network virtualization principles
- Support for mechanisms to logically partition the network into slices
- Expose network functions through Application Programming Interfaces (APIs) to third parties (vendors, partners and customers)
- Support both backward & forward compatibility with networks

5G architecture consists of two sets of critical network functions - Next Generation Radio Access Network (NG-RAN) and Next Generation Core Network (NG-Core). NG-RAN includes the Radio Access Network (RAN) function hosted on the service provider cloud and the antennas, supporting the 5G New Radio (NR) specification. NG-Core includes several network functions that provide services such as authentication, mobility management, policy control and network slicing. Communication between network functions use simplified HTTP based RESTful APIs.

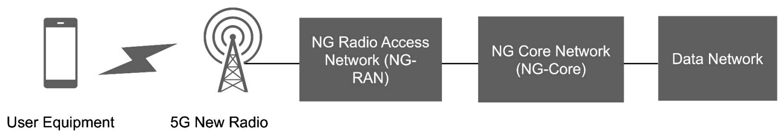

FIGURE 3.1: 5G SIMPLIFIED SYSTEM ARCHITECTURE

The initial 5G launches were based on Non-Standalone (NSA) architecture - where the 5G radio infrastructure, will still rely heavily on the 4G core infrastructure for various services. The 5G Standalone (SA) architecture will support both the 5G NR and 5G NG-Core specifications, providing an end-to-end 5G infrastructure.

5G Deployment Architectures

4G consists of two significant architectural components - the Long Term Evolution (LTE) for the access network and Evolved Packet Core (EPC) for the core network. However, 4G's access and core network components cannot interwork with other legacy network components belonging to the previous generation wireless networks. However, 5G provides interoperability with 4G networks.

Considering the huge investment that has gone in to build 4G networks and the huge investment required to build a 5G network, it makes logical sense for the 5G and the 4G networks to interwork with each other. It also provides a migration path for the customers. 5G architecture supports both a Standalane Architecture (SA) and a Non-Standalone Architecture (NSA) implementations. The NSA implementation allows 5G network to interwork with 4G network. The SA implementation is an end-to-end 5G network. The initial deployments of 5G will adopt the Non-Standalone architecture.

Standalone Architecture (SA)

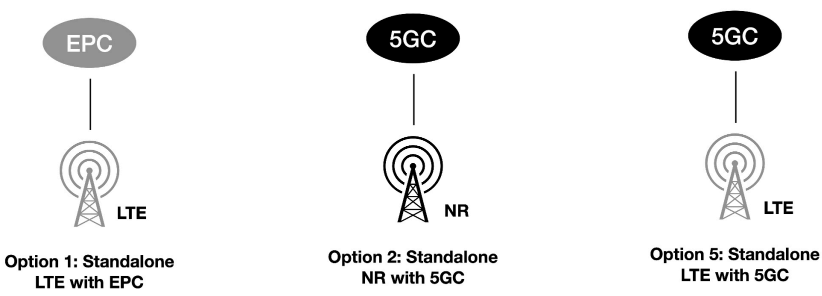

FIGURE 3.2 - STANDALONE DEPLOYMENT OPTIONS

Standalone architecture uses only one radio access technology – either 4G or 5G. The radio cells connect to either a 4G EPC or a 5G Core. Architecturally, deploying a standalone solution is simple for service providers. However, it involves a lot of costs – as an end-to-end 5G network infrastructure has to be deployed. When a user equipment switches between 5G and 4G networks, service continuity is achieved through inter-generation handovers.

In a standalone architecture, there are three deployment options:

- **Option 1:** Wireless service is provided by 4G LTE eNodeB and 4G EPC. This deployment option is supported by the existing 4G networks. It supports higher bandwidths of up to 400 Mbps and is adequate for mobile broadband needs. Some service providers are marketing this as 5GE (5G Evolution).

- **Option 2:** Wireless service is provided by 5G NR gNodeB and 5G NG-Core. This is a full end-to-end 5G service and it will take a few years for networks to adopt this deployment model.

- **Option 5:** Wireless service is provided by enhanced 4G LTE ng-eNodeB (Next Generation eNodeB, which can communicate with the 5G NG-Core) and 5G NG-Core. This deployment option will be helpful for service providers during the migration from a full 4G network to a full 5G network.

Non-Standalone Architecture (NSA)

3GPP release 15 standardized the Non-Standalone (NSA) mode of deployment. In NSA mode, 5G networks will be supported by existing 4G infrastructure. For example, a 5G-enabled smartphone will be able to connect to the network using 5G radio cells for data-throughput improvements but

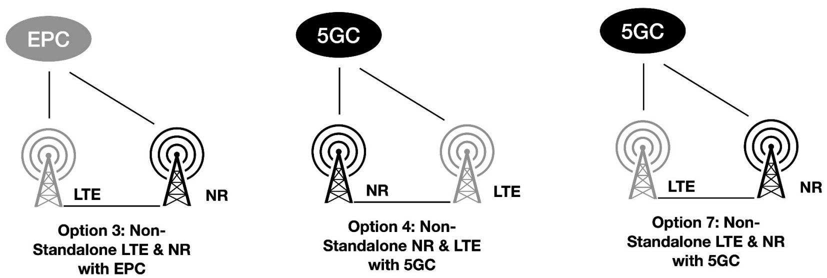

FIGURE 3.3 - NON-STANDALONE DEPLOYMENT OPTIONS

will still use 4G radio cells for regular low-throughput data transfers. NSA uses a capability called “dual-connectivity”, defined by the 5G NR standards where a given UE consumes radio resources provided by at least two different network points – for example, 5G gNB and 4G eNB. NSA enables service providers to deploy 5G, without much of disruption to their existing networks and services. It also helps the service providers to leverage the investments done in the 4G network.

In a non-standalone deployment, there are three deployment options:

- **Option 3:** 4G LTE eNodeB acts as the master node and 5G NR en-gNodeB (enhanced gNodeB, which can communicate with the 4G EPC) acts as the secondary node. Both of these RAN functions connect to the 4G EPC. Option 3 deployments will be helpful in scenarios where the UE can connect to the large 4G cell towers for ubiquitous access to Internet services, and connect to a 5G small cell for high data throughput.

- **Option 4:** 5G NR gNB acts as the master node and 4G LTE ng-eNB acts as the secondary node. Both of these RAN functions, connect to the 5G Core. Option 4 will be helpful in scenarios where 5G NR coverage is high, for providing mobile broadband services. 4G is used as a fallback option, in areas where 5G NR coverage is not available. This deployment option, may not be very relevant in the short term, where 4G coverage is higher than 5G NR coverage.

- **Option 7:** 4G LTE ng-eNodeB acts as the master node and 5G NR acts as the secondary node. Both of these RAN functions communicate with the 5G NG-Core. Option 7 builds on top of Option 5. The need for Option 7 is very limited in the short term, as it benefits only the mobile broadband use-cases.

Next Generation Core (NG-Core)

NG-Core for 5G is the equivalent of Evolved Packet Core (EPC) in a 4G network. 5G NG-Core architecture supports virtualization and allows the user plane functions to be deployed separately, from the control plane functions. In addition, the user plane and control plane functions can be scaled independently. 5G NG-Core supports both International Mobile Subscriber Identity (IMSI) based and non-IMSI based identities for authentication of services. NG-Core has support for capabilities such as network slicing, which allows the partition of network resources across different customers, services or use-cases.

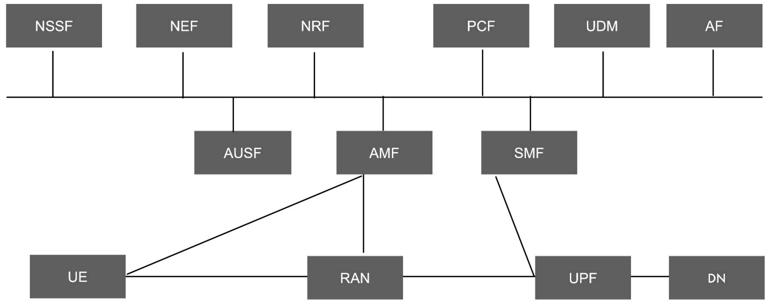

FIGURE 3.4: 5G DETAILED SYSTEM ARCHITECTURE

Network Functions in NG-Core

5G NG-Core architecture comprises of the following network functions:

1. Authentication Server Function (AUSF)
2. Access and Mobility Management Function (AMF)
3. Data Network (DN)
4. Network Exposure Function (NEF)
5. Network Repository Function (NRF)
6. Network Slice Selection Function (NSSF)
7. Policy Control Function (PCF)
8. Session Management Function (SMF)
9. Unified Data Management (UDM)
10. User Plane Function (UPF)
11. Application Function (AF)

Authentication Server Function (AUSF) - AUSF acts as an authentication server, performing UE authentication using Extensible Authentication Protocol (EAP). EAP is a popular protocol used in WiFi networks for authenticating WiFi clients. In the 4G network, AUSF function was part of the Home Subscriber Server (HSS) function.

Access and Mobility Management Function (AMF) - Responsible for connection management, registration management and mobility management (handling of reachability and idle/active mode mobility state). It also takes care of access authentication and authorization. AMF also supports Lawful intercept function for AMF events. In the 4G network, this function was part of the Mobility Management Entity (MME).

Data Network (DN) - DN offers operator services, internet access and third party services.

Network Exposure Function (NEF) - NEF is a proxy or API aggregation point for the core network and provides security when services or external application functions access the 5G Core nodes. This is a new function introduced in 5G architecture.

Network Repository Function (NRF) - NRF supports service discovery, and maintains/provides profiles of network function instances. This is a new function introduced in 5G architecture.

Network Slice Selection Function (NSSF) - NSSF supports the selection of network slice instances to serve the User Equipment (UE), based on the Network Slice Selection Assignment Information (NSSAIs) configured or allowed for a given UE. This is a new function introduced in 5G architecture.

Policy Control Function (PCF) - PCF provides a unified policy framework and shares policy rules to control plane functions, to enforce them. It also accesses subscription information relevant for policy decisions from the Unified Data Repository (UDR). PCF was part of the PCRF function in the 4G network.

Session Management Function (SMF) - SMF provides session management, UE IP address allocation & management and DHCP functions. It also provides traffic steering configuration for User Plane Function (UPF) for proper traffic routing. SMF function was split between the MME and Packet Gateway (PGW) function in 4G network.

Unified Data Management (UDM) - UDM provides Authentication and Key Agreement (AKA) credentials, user identification handling, access authorization and subscription management functions. UDM was part of the HSS functionality in the 4G architecture.

User Plane Function (UPF) - UPF provides packet routing and forwarding functions. In addition, it also handles QoS services. UPF function was split between Serving Gateway (SGW) and PGW in the 4G architecture. Separating the user plane from the control plane in both SGW/PGW, enables the service providers to deploy the UPF closer to the network edge. In 5G, UPF function can be deployed at the network edge, in addition to the network core, to improve the network performance and to reduce latency.

Application Function (AF) - AF function is similar to the AF function in the 4G network. It interacts with the 5G core to provide services such as application influence on traffic routing, accessing Network Exposure Function (NEF) and interacting with policy framework for policy control.

Control and User Plane Separation in 5G Core

CUPS stands for Control and User Plane Separation. It was introduced by 3GPP, for Evolved Packet Core (EPC) as part of their Release 14 specifications.

Need for CUPS

Service providers across the globe are seeing a jump in the mobile data growth, year-after-year, due to the growth in the consumption of video, online gaming and social media services. 5G is not only facing the challenge of supporting higher data speeds, but also has to reduce the network latency for customers. Network latency has a direct impact on the customer experience and almost a non-negotiable thing for the new 5G use-cases.

The architects of 5G were looking at multiple ways of bringing down the network latency for customers, to meet the requirements of emerging 5G use cases such as Smart Cars, AR/VR and Holograms. 5G architecture tries to reduce the network latency through multiple mechanisms such as Network Slicing, Massive MIMO, Small Cells and Multi-access Edge Computing (MEC). MEC infrastructure, being closer to the user, plays a critical role in bringing down the network latency by providing a compute infrastructure for Over-The-Top (OTT) and Internet of Things (IOT) services. CUPS is another technique in 5G, that helps to bring down the network latency.

The multiple deployment options supported by CUPS, provide great flexibility to the service providers, to deploy user-plane functions in one or more locations to meet the bandwidth and latency requirements of customer services. For example, a service provider may have to deploy more instances of the user plane function near a college dorm, where several 100s of students are watching video and playing online games. However, in a stadium, there will be several 1000s of mobile users who would be checking their emails, browsing Internet and uploading pictures. In such locations, the control plane has to scale to support several 1000s of customer sessions. So, the service provider may have to deploy more control plane functions in such geographies to support the 1000s of mobile users.

CUPS in 4G architecture

CUPS was originally introduced in the 4G Evolved Packet Core (EPC) architecture. EPC with CUPS support separates the control plane function from the user plane function in the network. Network functions within 4G EPC such as Packet Gateway (PGW), Serving Gateway (SGW) and Traffic Detection Function (TDF), were split into control plane and user plane functions. EPC with CUPS support had PGW-U/PGW-C, SGW-U/SGW-C and TDF-U/TDF-C.

When EPC supports CUPS, service providers would have the option of

- deploying the control plane functions co-located with the user plane functions (i.e., in the same data center)
- deploying the control plane functions and user-plane functions in a distributed fashion, across multiple locations
- deploying the control plane function in a centralized location and deploy the user-plane functions in multiple locations

5G adopts CUPS based architecture for the 5G Core. 5G Core has a distinct User Plane Function (UPF) that handles all of the user-plane functions performed by SGW-U and PGW-U in 4G EPC. 5G's control plane functions are distributed across different network functions such as Authentication Server Function (AUSF), User Data Management (UDM), Policy and Charging Function (PCF) and Session Management Function (SMF). This gives a lot of flexibility for the service providers to decide the network functions which have to be deployed at the edge of the network versus the core of the network.

Since 5G supports cloud-native network services, it becomes easy for the vendors and service providers to implement CUPS in the 5G network architecture (when compared to the 4G network).

Communication approach for Core Network Functions

5G architecture brings a significant difference in the way in which core network functions communicate with each other. 5G architecture supports two approaches for the communication between the core network functions – Point to Point and Service Based Architecture (SBA).

- **Point to Point** - In the traditional 4G network, core network functions communicated with each other based on reference points and interfaces connecting those reference points. The communication between core network functions in 4G network was point to point. That is, there will always be one sender and one receiver for any communication between the 4G network elements. 5G network also supports the traditional point-to-point architectural approach.

- **Service based Architecture (SBA)** - In addition to supporting the Point-to-Point architecture, SBA is a new approach introduced with the 5G network architecture. In SBA, the core network functions are either producers or consumers of various network services. In the producer-consumer model, there can be one producer and multiple consumers. They communicate with each other using Restful APIs. 5G architecture provides a framework for different network functions to effectively produce and consume services. There are two types of communication models supported by the SBA:

    - Request-Response model - This is used for exchanging simple information requests and responses between the network functions. This model uses synchronous requests and responses. For example, authentication of a subscriber in the network.

    - Subscribe-Notify model - This is used for requests that would take a long time to process or for getting notified upon an event. One or more network functions in the core network can subscribe to notifications. For example, if a network function wants to get notified when a subscriber moves from one geography to another, it can use the Subscribe-Notify mechanism, to register for the subscriber mobility event and get notified about the subscriber's location.

The SBA framework provides functionality needed for efficient use of the services such as registration, service discovery, availability notifications, de-registration, authentication and authorization.

Next Gen Radio Access Networks (NG-RAN)

In 5G, the RAN architecture evolved further and is called the Next Generation Radio Access Networks (5G NG-RAN). 5G NG-RAN provides packet processing, baseband processing, radio signals processing and radio control functions.

NG-RAN provides capability to configure and scale RAN nodes dynamically through software. The signalling and data transport network (i.e., the control plane and user plane functions) of the NG-RAN are logically separated. NG-RAN supports seamless management of radio resources, including mobility of radio resources.

NG-RAN architecture provides the flexibility to deploy RAN nodes based on spectrum efficiency and performance requirements. For example, functions that influence the latency of services are deployed closer to the radio resources.

A 5G NG-RAN node functions as one of the following:

- Next generation eNodeB (ng-eNB)
- Next generation NodeB (gNB)

Next Generation E-NodeB (ng-eNB)

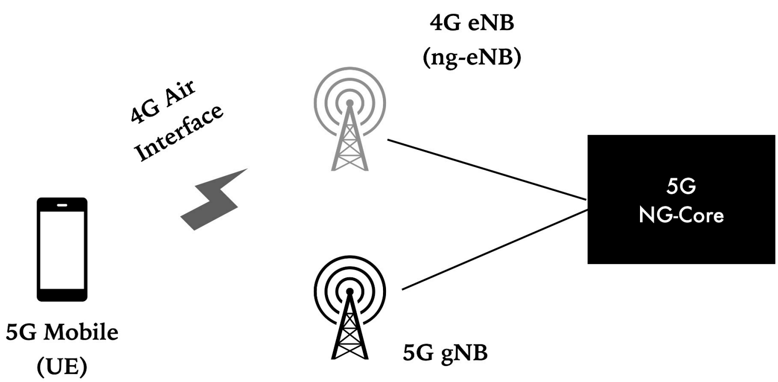

FIGURE 3.5 - NEXT GENERATION ENODEB (NG-ENB)

Next Generation E-NodeB (ng-eNB) is an enhanced version of the 4G eNodeB which connects a 5G user equipment to the 5G Core network using enhanced 4G LTE air interfaces. The user equipment would use the 4G LTE radio resources to connect to the ng-eNB. ng-eNB provides E-UTRAN user plane and control plane protocol terminations towards the user equipment and connected via the NG interface to the

NG-Core. During the transition to 5G, there is going to be lot more 4G networks when compared to 5G networks. So, there may be localities without any 5G coverage. In such geographies, ng-eNBs would allow the 5G subscriber to connect to the network using 4G air interface.

Next Generation NodeB (gNB)

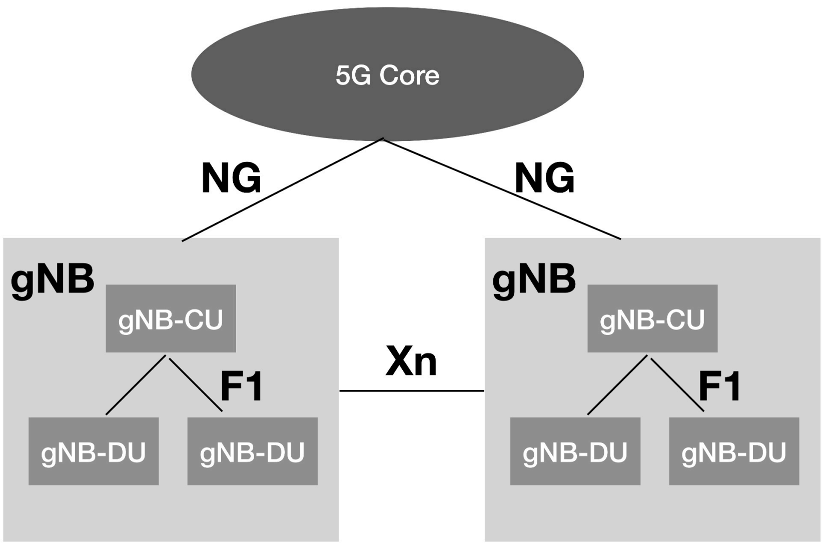

FIGURE 3.6 - NEXT GENERATION NODEB (GNB)

Next Generation NodeB (gNB) is the radio node, which is equivalent of the eNB in the 4G architecture. gNB connects the 5G capable user equipment using the 5G New Radio (NR) air interfaces. gNB provides 5G New Radio (NR) user plane and control plane protocol terminations towards the user equipment and connected via the NG interface to the NG-Core.

gNB has three functional modules – Centralized Unit (CU), Distributed Unit (DU) and the Radio Unit (RU). The Baseband Unit (BBU) function from the traditional 4G architecture is now divided into CU and DU, in a 5G architecture. This gives the flexibility for the service providers to selectively deploy BBU's CU and DU functions either near the cellsite or in the central office/Edge location. gNB-CU is responsible for mobility control, radio resources management and session management. gNB-DU provides Media Access Control (MAC) and physical layer services (PHY). The functionality split between the CU and DU is implementation dependant.

Radio Unit (RU) is the radio node. The Remote Radio Head (RRH) function from the 4G architecture is now called the RU, in a 5G network.

Typically, there are one or more gNB-DUs that connect to a gNB-CU. The gNB-DUs and gNB-CU are connected using the F1 interface. F1 interface supports signalling exchange and data transmission between the gNB-CU and gNB-DU functions. F1 interface also separates radio network layer and transport network layer. The gNB nodes communicate with each other through the Xn interface. The Xn interface which connects the user-planes together is called Xn-U and the Xn interface which connects the control-planes together is called the Xn-C.

Optical fiber link is the most ideal fronthaul link for connecting RRHs with BBUs. However, it is not available in all locations. Hence, in order to maximize the performance of the RAN, certain RAN functions can be split between the cellsite and the central office. There are 3 options available to split the functions across RRH and the BBU;

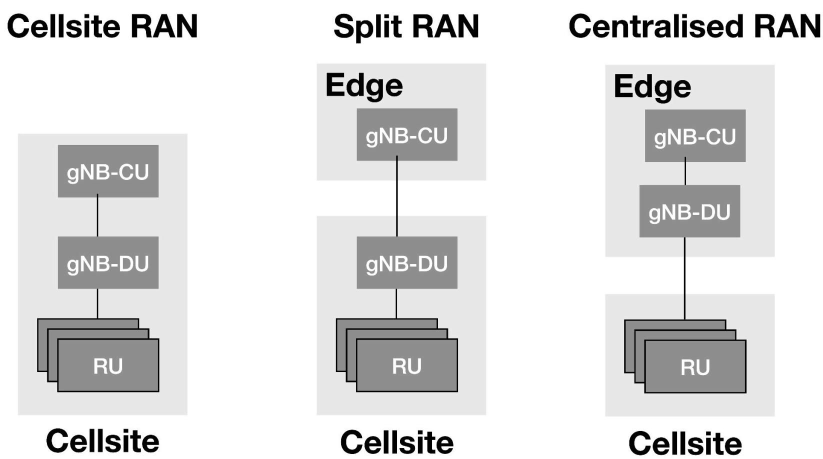

FIGURE 3.7 - NG-RAN DEPLOYMENT OPTIONS

- **Cellsite RAN**: In this deployment mode, all the 3 functions – RU, CU and DU are deployed at the cellsite near the tower. This could also be a monolithic deployment where all the 3 functions are present in a physical Base station. Cellsite RAN helps the service provider to guarantee ultra low latencies (<1ms), when the cellsite does not have a fiber link in the fronthaul. Cellsite RAN deployment is ideal for industrial automation use-cases.

- **Split RAN**: In this deployment mode, the DU function is deployed along with the RU and the CU function is deployed at the Central Office / Edge location. The Centralized Unit (CU) can further be split into CU-User Plane (UP) and CU-Control Plane (CU-CP). Optionally, the edge location can also host a Multi-access Edge Computing (MEC) cluster. This type of deployment is suitable for applications such as Augmented Reality or Virtual Reality.

- **Centralized RAN**: In this deployment mode, the CU and the DU functions are located at the edge. They are connected to the cellsite via high-speed or low-speed links, supporting a latency of < 10 ms. This type of deployment is suitable for applications such as Enhanced Mobile Broadband (eMBB).

5G New Radio (5G NR)

One of the significant changes to the 5G architecture is the radio specification. 5G introduces a new radio specification called 5G New Radio (5G NR).

Some of the key changes to the radio function in 5G are:

- **Spectrum:** 5G supports a wide range of spectrums from low bands below 1 GHz, to mid bands from 1

GHz to 6 GHz, to high bands 24 / 30 GHz to 300 GHz. This high band is called as millimeter-wave.

- **Latency:** 5G NR supports lower latencies less than 10 milli seconds

- **Beamforming:** 5G NR supports a large number of multiple input multiple output (MIMO) antennas, which would allow it to work in a high interference environment through a technique called “beamforming”. It enables 5G radios to provide both coverage and capacity.

- **Interworking with 4G:** Coexistence with LTE (by supporting LTE NR), by bringing an overlay network, in cases where 5G coverage is not available.

5G Spectrum

In order to achieve high speed and scalability, 5G supports a wide range of spectrums from low bands below 1 GHz, to mid bands from 1 GHz to 6 GHz, to high bands 24 / 30 GHz to 300 GHz (also, known as milli-meter-wave or mmWave).

Lower frequencies typically travel long enough and can propagate deeper than higher frequencies. Lower frequencies offer a better coverage. Higher frequencies will travel short distance, however can offer higher bandwidth. 5G has to offer both better coverage and higher speeds - and hence, millimeter wave is very important for 5G to offer higher speeds. In addition to deploying large towers, 5G will also require service providers to deploy a large number of small cell towers - to meet the speed and latency requirements.

5G promises ubiquitous wireless coverage – by supporting both licensed and unlicensed spectrums.

5G NR-U is called Unlicensed Spectrum. 3GPP has categorized the use of 5GHz and 6GHz spectrum bands as 5G NR-U. The use of unlicensed spectrum significantly reduces the cost of deploying 5G networks. There are two types of NR-U implementations:

- Licensed Assisted Access (LAA) NR-U
- Standalone NR-U

Licensed Assisted Access (LAA): In the LAA deployment, service providers aggregate the licensed spectrum with the unlicensed spectrum to provide wireless services to customers. The point of aggregation can be a small cell which supports the licensed and unlicensed frequencies. Alternatively, the mobile device can establish dual connectivity, one with the macro-cell operating in the licensed spectrum and the other with the small-cell which is operating in the unlicensed spectrum. LAA in 5G is very similar to how LAA is implemented in 4G LTE network. LAA can help service providers in boosting the capacity of the network.

Standalone NR-U: 5G NR-U standalone implementation is unique and it may appear to be competing with existing WiFi technology (which is using the 5GHz frequency). 5G NR-U standalone implementations will help to accelerate the deployment of 5G in private networks such as enterprises and industries. This will eliminate the overhead for enterprises to maintain a separate WiFi network for wireless connectivity. 5G NR-U standalone deployments can support IOT use cases in enterprises, industries and communities.

5G NR supports Dynamic Spectrum Sharing (DSS), a new standard introduced in 5G, that helps service providers to migrate from 4G LTE to 5G NR, without a noticeable service quality degradation to customers. Dynamic Spectrum Sharing allows the service providers to share spectrum between their 4G and 5G users. For example, a 4G user can use a given spectrum for 10 milliseconds and the same spectrum can then be taken by a 5G user for 1 millisecond. Dynamic allocation of spectrum, improves the utilisation of the spectrum across 4G and 5G services.

Traditionally, when service providers migrated from 3G to 4G, they carved out a chunk of the 3G spectrum and dedicated that to 4G. This may starve the users in the 3G network. However, Dynamic Spectrum Sharing enables a smoother migration from 4G to 5G. Initially, it is expected that more users will be in 4G and very few users will be in 5G. Over the next few years, the ratio between 4G and 5G users will change. More and more users are expected to migrate to 5G. Based on the capacity needs, the network can dynamically allocate spectrum to users. This would result in speedy services to both 4G and 5G users.

Technologies accelerating 5G Radio

MIMO

MIMO stands for Multiple Input and Multiple Output, where several small antennas are grouped together at the transmitter and at the receiver. Before the introduction of MIMO, radio devices in wireless networks used a single antenna at the source and a single antenna at the destination for sending and receiving signals. When signals had to penetrate through walls and objects in between, they get scattered and lost before reaching the destination. This would result in errors and also affects the network performance, especially the speed.

After the introduction of MIMO technology, radio devices were able to send or receive multiple signals at the same time - to minimize the errors and to improve the speed. MIMO uses a technique called multi-path propagation, where the radio signals are transmitted via two or more paths to reach the destination. Multi-path propagation approach increases the chances of signals reaching the receiver. When signals are sent via multiple paths, the overall strength of the signal received by the radio device is equal to the sum of all the signals received by the different antennas. At times, the overall signal strength would be higher when there are no interferences and at other times, the overall signal strength would be low, when there are interferences due to the presence of terrestrial objects in the path. Even a small difference in the space between the antennas would

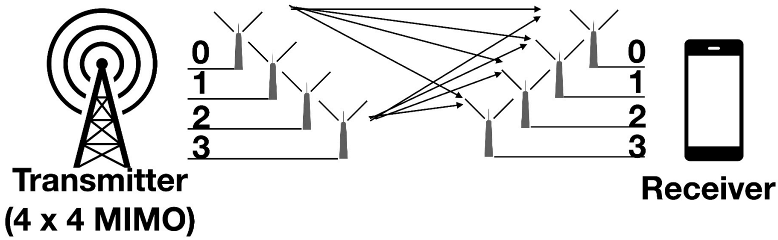

FIGURE 3.8 - HOW MIMO WORKS?

dramatically change the path traversed by a signal. So, in order to minimize the interferences, MIMO uses antennas that are spatially distributed. MIMO uses the additional paths to its advantage, by strengthening the signals to increase the data throughput.

Massive MIMO

5G adopts massive MIMO technology where a few tens to several hundreds of antennas are used for propagating radio signals. The Massive MIMO enabled radio devices use algorithms to calculate the best possible transmission route through the air, to reach the receivers without any interference or with reduced interference.

Coordinated Multipoint (CoMP)

Coordinated Multipoint (CoMP) is a technique used to improve radio performance, at cell edges by utilising the capability of more than one base station to enable the communication. Using CoMP, radio access nodes dynamically coordinate the transmission and reception of signals from the UE to multiple base stations.

In the past, inter-cell interference used to be a challenge for wireless service providers. CoMP leverages inter-cell interference to improve the quality of service for the user, as well as improving the utilisation of the network resources.

CoMP has multiple advantages:

- Helps the service provider to improve the utilization of network resources. For example, data can be passed through a base station which is not loaded.
- User notices lesser call drops, as several cell sites come together to provide service to the user
- User notices higher bandwidth, as multiple base stations serve the user, at a given time. The impact of the interference gets reduced and interference is used constructively.

CoMP falls under two categories:

- **Joint Processing:** When there is coordination between multiple gNBs to simultaneously transmit or receive signals to or from a UE, it is called Joint processing.

- **Beamforming:** In beamforming, instead of sending a signal in different directions, the radio device sends the signals concentrated in one direction towards a specific receiver. This reduces the loss of signals, and improves the efficiency. Beamforming is very important when using milli-meter waves, as milli-meter waves get weakened when they get blocked or when they travel over long distances. When radio signals are sent in a concentrated form in one direction, it increases the strength of the signals that get transmitted. This approach increases the chances of the receiver receiving the signals, intact and reduces interferences from other devices.

Small Cells

5G, because of the reliance on mmWave technology (which has a shorter wavelength) requires several thousands of small cells be deployed around the cities. Small Cells are mini base stations that handle the radio signals, like the mobile towers. Small Cells require very minimal power and space, unlike the large mobile towers in the neighbourhood. Small Cells can be installed on the top of a light pole or a building. Small Cells are not new to the wireless world. They were deployed in 4G networks too. However, in 4G networks, Small Cells were predominantly used to improve the indoor wireless coverage. There are three categories of small cells that exist today:

- **Femtocells** – Femtocells help the operators in quickly solving the network coverage problem. It takes a very long time for a service provider to install a mobile tower. However, it takes only a few days to power up a femtocell in the network. So, if there is a residential or an enterprise customer that requires extended wireless coverage, the operator can quickly deploy a

Femtocell. Femtocell provides multiple benefits such as helping the service provider to offload the network congestion, provide better coverage and increase the data transfer rates. A Femtocell typically caters to 16 users and can provide coverage for a distance between 10 and 50 meters.

- **Picocells** – Picocells are similar to Femtocells in terms of functionality. However, their coverage area is 100 – 500 meters. Also, they can support 32 – 64 users at a time. Picocells are well suited for small enterprise applications.

- **Microcells** – Microcells are designed for providing wireless coverage to a large geographic area and suited for providing network coverage to outdoor applications such as smart communities. Microcells provide coverage for a distance between 500 meters and 2.5 kilometers. Microcells can support nearly 200 users at a time.

Review Questions

1. What are the various core network functions in 5G?

2. What are the radio frequency ranges used by 5G?

3. What are some of the architectural requirements of 5G?

4. What are some of the key changes to the radio functions in 5G?

5. What are the different communication models supported by the Service Based Architecture (SBA)?

6. What are the benefits of using Massive MIMO in 5G?

7. What is beamforming?

8. What are the advantages of using CoMP techniques?

9. What is Dynamic Spectrum Sharing?

10. What are the different types of Small Cells?

4. NFV in 5G Networks

Service providers across the globe are busy building their 5G network foot print and Network Functions Virtualization (NFV) plays an integral part of the 5G infrastructure. While many telcos have been virtualizing their network infrastructure since 2015, 5G makes NFV, almost mandatory. While 4G's Evolved Packet Core (EPC) was an evolution from the 3G packet core networks, the 5GC (5G Core) has been designed from its inception to be “cloud native”. 5G Core inherits many of the technology solutions used in cloud computing. NFV plays a critical role in the success of 5G implementation.

What is NFV?

Network Functions Virtualization (NFV) transforms the network architecture of service providers, by borrowing IT virtualization techniques to virtualize network functions and run them as software on top of standard servers, storages and switches.

European Telecommunications Standards Institute (ETSI) published NFV requirements in a white paper in 2012, and jump started the NFV momentum. NFV requirements published by ETSI, enabled network equipment vendors to start virtualising their network functions, separating their control plane from the data plane and exposing APIs for orchestration of network services.

Traditionally, service providers had purpose-built hardware such as firewalls, load balancers and routers deployed in their network for providing services to customers. This approach increases the complexity of the network architecture, introduces a lot of administrative overhead and also increases the capital / operational expenses.

NFV allows service providers to increase the utilization of their hardware, reduce operational costs and reduce the time it takes to activate a service for the customer.

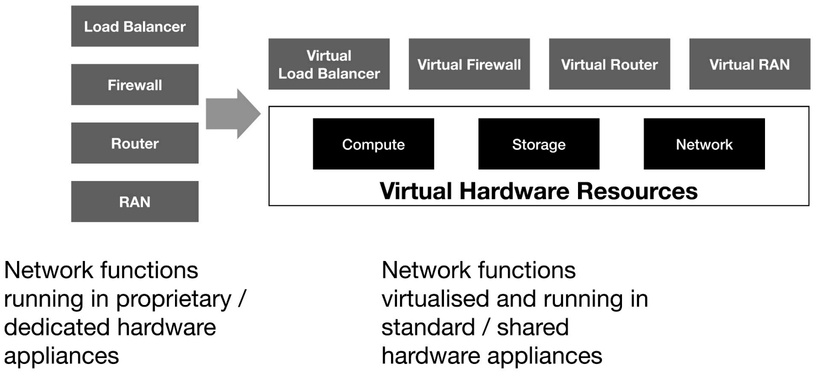

FIGURE 4.1 - NETWORK FUNCTIONS VIRTUALIZATION

During the initial phases of network virtualization, most network equipment vendors took the short cut of taking their hardware-based network functions and converted them to software that runs on the telco cloud. This approach did not provide the intended agility to the service providers - in fact, it raised the operational expenses. Recently, network equipment vendors started developing cloud-native virtualized network functions, based on micro services approach. Most 5G core network services are cloud-native and are run on telco cloud environments as virtualised software components.

Need for NFV

There are multiple reasons for service providers to virtualize their network infrastructure :

- **Cost Savings:** Today, IT workloads are run on commodity servers in datacenters, helping service providers to reduce costs. However, network functions are still run on purpose-built, proprietary and expensive hardware. The bandwidth needs of customers is continuously growing. The only way for service providers to handle the increase in the network load, is to deploy additional purpose-built hardware. But, that does not translate to increase in the revenue. Customers are not willing to pay for the extra bandwidth and hence, the price per GB is continuously coming down. Service providers have to handle the dual edged sword where CAPEX is going up on one side and revenue is coming down, on the other side. In order to bring down the CAPEX of the network, without affecting the customer experience – service providers have to look at virtualizing their network.

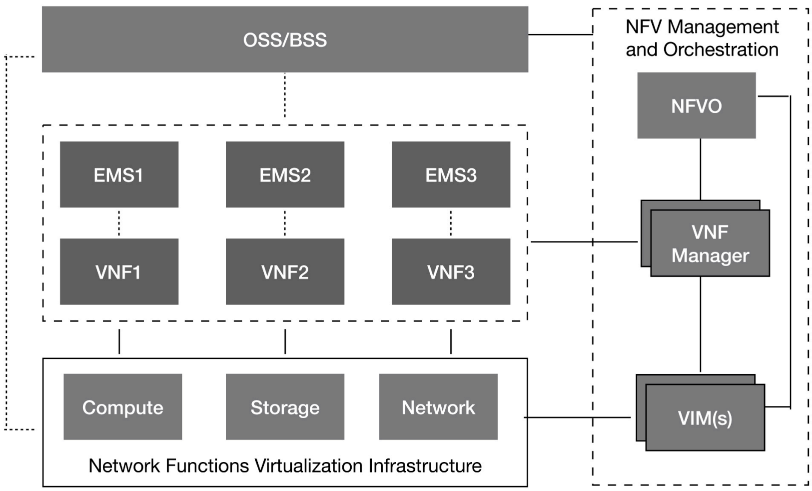

FIGURE 4.2 - NFV ARCHITECTURE

- **Speed to Market:** It takes 6 months to 1 year for a network equipment vendor to introduce new features in their product. Subsequently, it takes another 6 months to 1 year for the service provider to test / certify / integrate the new functionalities in the network. By the time a service provider rolls-out a new feature / function in the network, it becomes obsolete. In a continuously changing world, customer's expectations change rapidly. Hence, agility is key for the service providers to thrive.

- **Lesser Downtime during Maintenance:** Upgrade / Downgrade of software or hardware is quite complex and, in most cases, require the network service to be brought down. This has an impact on the customer experience and SLAs. Service providers want to have a seamless, non-disruptive network upgrade / downgrade process.

NFV Architecture

NFV architecture introduces multiple logical entities such as NFV Infrastructure (NFVI), Virtual Infrastructure Manager (VIM), VNF Manager (VNFM), NFV Orchestrator (NFVO) and Virtual Network Functions (VNFs). Each VNF may have its own dedicated Element Management System (EMS). The different components in the NFV architecture are integrated with the OSS/BSS for service provisioning and activation.

Network Functions Virtualization Infrastructure (NFVI) - NFVI consists of the physical compute, storage and network hardware resources. VIM partitions those resources and makes them available as virtual compute, virtual storage and virtual network instances. NFVI provides the virtual execution environment for the Virtual Network Functions (VNFs). The same physical hardware appears like multiple tenants to the higher-level compute, storage or network functions. NFVI can be hosted on Commercial Off-The-Shelf (COTS) hardware platforms to reduce the cost of the infrastructure.

Management and Network Orchestrator (MANO) - NFV MANO includes three distinct functions - Virtual Infrastructure Manager (VIM), VNF Manager (VNFM) and the NFV Orchestrator (NFVO).

Virtual Infrastructure Manager (VIM) – NFVI is managed by Virtualized Infrastructure Manager (VIM). VIM is used for partitioning the physical hardware resources and for managing the virtual infrastructure. OpenStack is a popular open source VIM. OpenStack is capable of managing both the virtual and physical infrastructure in a hybrid cloud environment.

VNF Manager (VNFM) - VNFM is typically provided by the VNF vendor to manage the VNFs that run on the NFVI. VNFMs perform lifecycle management (LCM) of the VNFs - which includes starting/stopping VNFs, automatically restarting a VNF when it goes down, software upgrade/ downgrade and scale-in/scale-out of VNFs based on load. There are two types of VNFMs available in the market today – Generic VNFM (which can manage multiple-types of VNFs) and Specific VNFM (which can manage only a specific type of VNF). Specific VNFMs are typically provided by network equipment vendors who supply the VNFs.

NFV Orchestrator (NFVO) – NFV Orchestrator is the controller of all the workflows in an NFV architecture. NFVO coordinates across multiple entities such as OSS/BSS, VNFM and VIM. For example, when there is a service creation request from the OSS/BSS, NFVO coordinates with VIM . NFVO often performs two distinct roles:

> **Resource Orchestration** – As a resource orchestrator, NFVO coordinates with VIM for tenant space creation, coordinates with VNFM for starting a VNF instance and loading it with appropriate

configuration. For example, a Virtual Evolved Packet Core (vEPC) function may have multiple Virtual Machines (VMs) to be started in a cloud environment. There can be one or more VM instances for each of the vEPC sub-systems such as PGW, SGW, PCRF and MME. NFVO coordinates with VIM to create a tenant space for each of those VMs. NFVO coordinates with VNFM to move the VM image and configuration files to the tenant space and start the VNF instances.

Service Orchestration – As a service orchestrator, NFVO is responsible for the creation of network services. NFVO coordinates with OSS/BSS and VNFMs for downloading service-related configuration to the VNFs. NFVO defines the Service Function Chains (SFC) by establishing the path or sequence in which the packets have to traverse the network through the different VNFs. For example, NFVO creates a network service by stitching the vEPC function with a Virtual Firewall (vFW) and a Virtual Deep Packet Inspection (vDPI) engine.

Service Catalogue – Service Catalogue includes all of the meta data and descriptors related to the VNFs. For example, service catalogue would include information such as CPU, memory and storage resource requirements of a VNF. Service Catalogue can be a standalone entity in the NFV architecture or it can be combined with other functions in the MANO stack, such as the NFVO

Element Management Systems (EMS) - EMS is provided by the VNF vendor to support FCAPS (Fault, Configuration, Accounting, Performance and Security management) functions. When a VNF instance is instantiated in the cloud environment, EMS is responsible for downloading the 'default' configuration supplied by the vendor to the VNFs. Subsequently, when a service gets activated using the VNF, the EMS downloads the service configuration to the VNF. For example, EMS would download Access Point Name (APN) related service configuration to the PGW VM in a vEPC.

Virtual Network Function (VNF) - VNF is the software implementation of the hardware-based network function. VNFs run on the NFVI, to deliver network services. Virtualized RAN, Virtualized Evolved Packet Core, Virtualized Firewalls, Virtualized Load Balancers, Virtualized Routers and Virtualized WAN Optimizers are some of the popular VNFs in the market, today.

They key VNFs in the 5G network, in a non-standalone architecture are:

- Virtualization of Radio Access network (vRAN)
- Virtualization of Evolved Packet Core (vEPC)

The virtualization of cloud-native 5G NG-Core functions are yet to be seen in the market.

Virtualized RAN (vRAN)

4G architecture sowed the seeds for virtualization of RAN functionality. Base station has two distinct functions called the Remote Radio Head (RRH) and the Baseband Unit (BBU). In a 5G network, BBU function is split further into Centralised unit (CU) and Distributed unit (DU). The service provider gets to choose whether to deploy the entire BBU or just the CU or DU at the network edge. 5G architecture supports virtualization of the BBU function. When multiple instances of BBUs are run in a cluster it is called as BBU pool. RRH function, which is now called as the Radio Unit (RU) in a 5G network, continues to reside in the cellsite.

The Virtualized BBU performs functions such as baseband processing, radio resource management and mobility management, in addition to providing application security.

RU is connected to Virtual BBUs using Optical Fibre Fronthaul links, for maximum performance. Each RU can either connect to a dedicated BBU or there can be a switch in the cloud that efficiently distributes RU connections across a pool of available BBUs. The latter approach helps in efficiently managing BBU resources.

The following are some advantages of hosting BBUs in a virtualized cloud environment:

1. Today, bulk of the cost involved in rolling out a wireless network, gets spent on commissioning cell towers, installing base stations and connecting the

infrastructure to the backhaul using transport links. Carving out the BBU functionality from the base station and moving it to the Central Office helps the service providers to reduce the cost of deploying the cell sites.

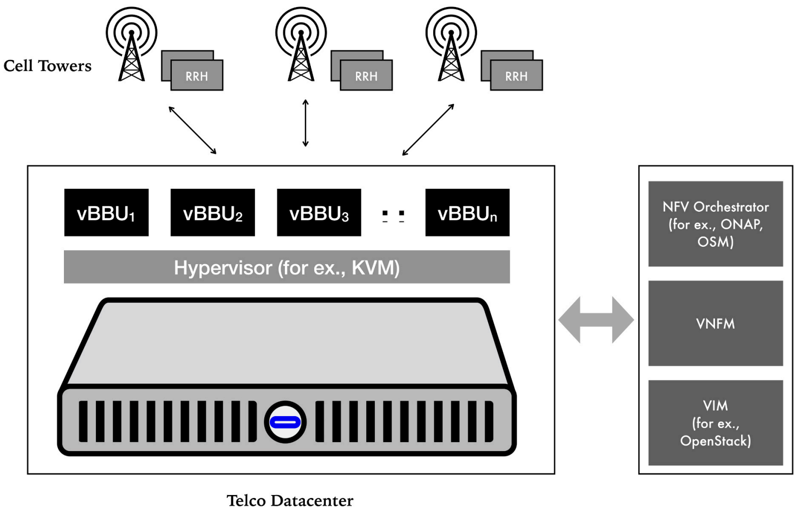

FIGURE 4.3 - VIRTUALIZED RAN

2. The cell site has limited power and processing capacity for the BBU. By moving the BBU function to Central office, service providers get access to extra power and processing capacity.

3. Resources can be allocated on-demand and can be shared across multiple RUs. This results in improved resource utilization and a reduction in power consumption.

4. In addition to running vBBUs, the same server(s) can also be used to host additional services such as content caching, deep packet inspection and analytics. This would increase the speed of application services, as they are hosted at the network edge and near the users.

5. When BBU function is virtualized, it reduces the downtime of network services when there are faults. In the past, a technician had to manually go to the cell site to fix any issues with the BBU/BTS. Now, with virtualization, a faulty instance of BBU can be terminated and a new instance of BBU can be spun instantly on the cloud.

Virtualized Evolved Packet Core (vEPC)

Virtual Evolved Packet Core (vEPC) is functionally similar to the physical EPC. However, the way in which the EPC is deployed and managed is different from physical EPC. There are two methods in which a Virtualized Evolved Packet Core (EPC) can be deployed:

1. An all-in-one Virtual EPC (vEPC)
2. Standalone instances of MME, PGW, SGW, HSS and PCRF.

There are some pros and cons for each of these approaches. In an all-in-one deployment model, it is easy to manage the vEPC instance as one entity. However, it lacks mechanisms to individually scale one or more services. For example, if the service provider wants to increase the number of PCRF instances, it can only be achieved by creating multiple instances of the all-in-one vEPC.

In a deployment with standalone instances of the vEPC components, the service provider can individually scale the components. For example, if there is a need to increase the number of PCRF instances, it can be achieved by spinning one or more instances of the PCRF application. This approach helps in optimizing the resource utilization on the telco cloud and brings-in agility. However, there will be an overhead involved in managing the standalone instances on the telco cloud. The network equipment vendors can help offset this management overhead, by providing a vEPC specific VNF manager along with the vEPC.

Architecturally, the vEPC will be different from that of a physical EPC. Following are some of the key architectural differences between a physical EPC and a Virtual EPC:

- A Virtual EPC may have one or more VMs for each of the components. For example, a PCRF service may have multiple micro-services. Each of these microservices may run on a separate VM or a Container, on the telco cloud.

- A subscriber's session state information in a physical EPC may be stored in RAM or transient memory in the hardware. A physical EPC achieves high-availability and reliability by deploying multiple physical instances of the EPC hardware. However, in a Virtual EPC deployment, the vEPC instance may store the session state information in a reliable database, for session continuity during fail-overs.

- A physical EPC relies on the underlying hardware for dataplane acceleration. A Virtual EPC relies on software based dataplane acceleration technologies. In a vEPC, the dataplane is scaled by using technologies such as SRIOV (Single Root – Input/ Output Virtualization). SRIOV partitions a physical network interface card into multiple virtual network interface cards (vNICs) and provides direct access to the physical NIC, bypassing the hypervisor layer. Virtual EPC also leverages several advancements in the data plane acceleration such as the Data Plane Development Kit (DPDK) and FD.io (fast data input/ output).

Benefits of NFV

NFV offers a number of benefits for the service providers:

- Increases the utilization of the hardware in the network, by eliminating special purpose physical network functions
- Reduces operational costs by standardizing the management of different network functions
- Provides flexibility to scale-in / scale-out the virtual network functions based on the network load and infrastructure demand

- Helps service providers to implement a Continuous Integration / Continuous Deployment (CI/CD) pipeline to rollout new updates / changes to the network - without a huge network down time.

Role of NFV in 5G networks

NFV plays a critical role in the building of 5G infrastructure. Some of the benefits of virtualizing the 5G network infrastructure are:

- Enables Virtualization of Cloud RAN
- Simplifies the creation of Network Slices
- Makes the 5G network elastic and scalable
- Enables the 5G network to support a “service-based” architecture
- Improves the agility and simplifies network upgrades

Enables Virtualization of Cloud RAN

One of the major changes in 5G is the changes to the radio specification (5G New Radio Specification). Unlike 4G, 5G towers (aka small cells) have to be installed almost in every street - to achieve coverage and speed. If service providers end up deploying hardware-based RAN (Radio Access Network), the Capital Expenses (CAPEX) would go up. Virtualizing RAN and migrating select RAN functions (for ex., Base Band Unit function) to the Cloud would help service providers to bring down the cost of the network infrastructure. Service providers have to just deploy antennas on the streets and handling the data workloads will be done in the telco cloud, deployed at the edge of the network.

Simplifies the creation of Network Slices

Network Slicing allows the same physical network infrastructure to be partitioned and made available as multiple logical or virtual network slices. Each of the network slices would have its own performance (speed or latency) and quality of service characteristics. A user-subscribed service such as Enhanced Mobile Broadband will get mapped to the network slice. NFV provides infrastructure for orchestration and automation of the life cycle management of network slices.

Makes the 5G network elastic and scalable

Given the dynamic nature of the bandwidth demands and the diversity of the 5G use-cases, it is important for service providers to build an elastic network that scales-in / scales-out based on demand. For example, there will be a number of mobile connections originating from the residential areas, during late evenings and early mornings. However, during the day, there will be more mobile connections originating from industrial / work locations. A static network will result in low utilization of the network infrastructure. 5G infrastructure services are cloud-native, thereby making the network more dynamic. If there are unused 5G core instances in the cloud, they can be temporarily shutdown to save power and cooling costs in the data center. An elastic 5G network will also improve the user experience - as the network adapts to the user's demand.

Enables 5G network to support a "Service-based" architecture

4G networks are connection based, whereas 5G network architecture is "service-based". In a service-based architecture, end-to-end services are provided by creating service chains that span across multiple network functions. For ex., a Live TV service may not just depend on video streaming servers running on the network edge, but may also have dependancies on other network functions such as firewalls, WAN optimizers, transcoding/transrating servers, and caching services. NFV allows service providers to dynamically create service chains in the network, linking all of these network services together.

Enables delivery of multi-site/multi-domain network services

In a 5G world, network services delivered to customers may span across one or more network sites (for ex., multiple MEC locations) or through different administrative domains (for ex., a user roaming from one service provider to another). This would require the establishment of virtual network connectivity between multiple sites and multiple domains, in real time. Network Virtualization helps service providers to provide virtual connectivity for services that span across multiple sites or multiple domains.

Improves the agility and simplifies network upgrades

Given the fact that 5G network is continuously evolving - network equipment vendors are continuously rolling out software upgrades / patches introducing newer functionalities in the network. When the 5G core infrastructure is virtualized and supports cloud-native services, a network equipment vendor can just roll out a patch for a specific network function (for example, Policy and Charging Rules Function (PCRF)), as opposed to the complete Evolved Packet Core. This simplifies the management of the network services, for the service providers.

Review Questions

1. What is NFV?

2. What is the role played by NFV in 5G networks?

3. What are the benefits of NFV?

4. What are the different components in the NFV architecture?

5. What is the role of NFVI in NFV architecture?

6. What are the different functions performed by the MANO components in the NFV architecture?

7. What are the building blocks of the Virtualized RAN ?

8. What is the difference between the Resource Orchestrator and the Service Orchestrator?

9. What is the role of a Virtual Infrastructure Manager (VIM) in a Virtualized Network?

10. What is the role of NFV in 5G Network?

5. Network Slicing

5G will enable new services and new business models that were not possible using older wireless technologies such as 4G. 5G technology is expected to provide a consistent and highly reliable user experience for a wide variety of use cases. For example, 5G infrastructure has to support a Smart Metering application, where several thousands of utility meter devices are continuously sending small chunks of information over a long period of time. This use case is not latency sensitive, but expects the network to scale to several thousands of devices. And, at the same time, 5G has to support a fast moving autonomous vehicle, that consumes lots of data and expects sub-millisecond response time. Building a network infrastructure that addresses the needs of a wide variety of use cases and at the same time, meeting the performance expectations is quite challenging. 5G architecture introduces a new concept called "Network Slicing", to meet the scalability and user experience demands of the wide variety of use cases.

What is Network Slicing?

Network Slicing allows 5G service providers to divide a single physical network (all the way from the radio to the core network) into multiple virtual networks. Each network slice can have different speed limits, different latencies and different quality of service configuration.

Network Slicing is an end-to-end feature offered by 5G infrastructure ranging from the Radio Access Network (RAN) to the 5G NG-Core. Each of the network slices will have its own configuration settings and performance characteristics. Each network slice is optimised to meet the needs of a given 5G use case. For example, smart meters will operate in a separate network slice when compared to autonomous vehicles.

Network Slicing is made possible by the advancements in Network Functions Virtualization, Software Defined Networks and Cloud. A network slicing implementation in the radio network as well as the core network, can be based on physical resources or virtualised / logical network resources. In the core network, a network slice can have its own dedicated virtual network functions instances running on the telco cloud. This allows the service providers to offer customised services to its customers and at the same time, optimise the infrastructure costs.

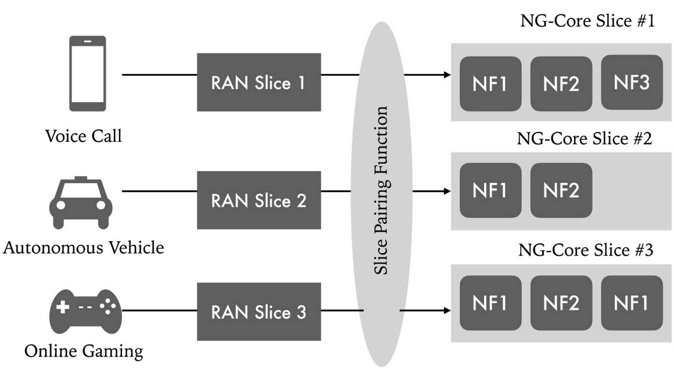

FIGURE 5.1 - NETWORK SLICING ARCHITECTURE

Each network slice provides a set of network capabilities, performance levels and specific Service Level Agreements (SLAs), to the services that run on top of the network. Services get mapped to network slice instances based on their capabilities, performance levels and SLAs. A network slice can be dedicated for a given service or may get shared across multiple services. For example, a network slice that supports online gaming service (high bandwidth and latency sensitive) can also support virtual reality service. A network slice that supports web browsing (low bandwidth and latency insensitive service) can also support IOT services that gather analytics. The mapping of RAN slice to the NG-Core Slice is done by the Slice Pairing function. The slice pairing function can reside in a network management system or as an application running on top of a SDN Controller.

Requirements for Network Slicing

The following are some of the requirements for the network slicing implementation in a 5G network:

- Service provider should be able to configure / manage a network slice dynamically based on the customer needs

- Service provides should be able to manage each network slice separately without impacting the performance characteristics of other network slices

- Provide security for the services that run on top of a network slice, including protection of the data that gets transferred over the network slice

- Service providers should be able to expose Application Programmers Interfaces (APIs) for its partners, vendors or customers to create and manage network slices

- Support end-to-end resource management from RAN all the way to the 5G NG-Core

Network Slice Management

Network Slicing architecture provides mechanisms for service providers to manage the end-to-end network slice infrastructure - both at the Radio Access Network (RAN) and the Core Network (5G NG-Core). The RAN in-turn may be divided into control plane and user plane. The configuration policies for a network slice will provision and activate services in both the control and user planes.

There are three distinct layers to be managed for a network slice:

- **Service instance layer** - This layer consists of instances of services that are either exposed to customers or business partners of the service provider. For ex., IOT services, Video streaming services and AR/VR services. The services can be created / managed by a network operator or a third party service provider.

- **Network Slice instance layer** - This layer consists of both the RAN slice instance and the Core Network slice instance. This layer provides the network characteristics required by a service instance. A network slice instance may get shared across one or more service instances.

- **Resource layer** - This layer consists of the actual physical or virtual network functions that are used for creating a network slice. There are scenarios where the resources for a network slice may span across multiple operator domains.

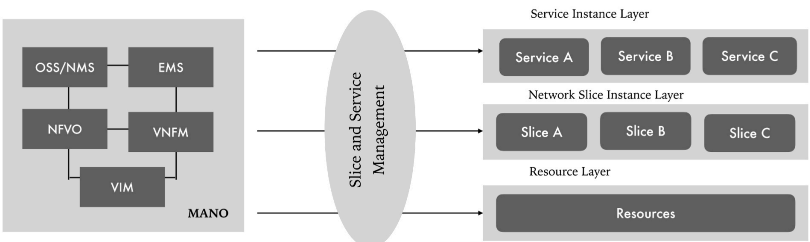

FIGURE 5.2 - NETWORK SLICE MANAGEMENT

Network slice life cycle management function would in-turn interact with the NFV Management and Orchestrator (MANO) function for managing the Virtualized Network Functions (VNFs) and would deal with other network managers that manage Physical Network Function (PNF).

MANO function consists of the NFV Orchestrator, VNF Manager and Virtual Infrastructure Manager (VIM).

Automation of the end-to-end network slice management is very critical to improve the user experience and operational cost reduction. It can be achieved by deploying a SDN Controller in the network. The SDN Controller exposes APIs for service providers to develop applications that can manage network slices in a wireless network.

Benefits of Network Slicing

Network slicing provides a number of benefits to both service providers and customers. Some of the benefits are:

- Reduces operational costs in managing / running the wireless networks - as the 5G network slicing exposes APIs for programmatically managing the network infrastructure.

- Today, Mobile Virtual Network Operator (MVNO) services (letting other wireless service providers share the network infrastructure) require complex manual pre-provisioning of network infrastructure. Network Slicing allows Service Providers to dynamically create, configure and manage MVNO services.

- Allows Service Providers to offer differentiated services to customers using the same network infrastructure, without impacting the performance of the services offered to other customers. For example, support Autonomous Cars and Smart Utility Meters on the same network infrastructure.

- Allows service providers to monetise the network infrastructure - not just based on bandwidth consumed, but also based on other parameters such as latency, quality of service, energy consumption and number of connections.

Review Questions

1. What is network slicing?

2. What is the need for network slicing in a 5G Network?

3. What are the various use-cases enabled by Network Slicing?

4. How is a network slice created in a 5G network?

5. What are the three different layers in network slice management?

6. Multi-access Edge Computing (MEC)

Multi-Access Edge Computing (MEC) is an integral part of the 5G ecosystem. MEC helps service providers to bring application oriented capabilities closer to the users and support several latency sensitive use cases from the edge. The MEC system brings networking and computing capabilities at the edge of the network to optimize the performance for ultra-low latency and high bandwidth services.

The initial use cases of MEC were very specific to mobile networks and hence it was called as Mobile Edge Computing (MEC). However, later on, the industry acknowledged the general applicability of MEC for both wireless and wired networks and hence renamed it to Multi-Access Edge Computing.

Need for MEC

Compute infrastructure for application services were existent in some form, even in 4G and 3G networks. For example, video transcoding, WAN optimization, Content Delivery Network (CDN) and transparent caching services were running previously in the service provider's core network in purpose built network equipment. However, with the growth in the number of mobile devices connecting to the network and the explosion of data consumption, it is impossible to offer such application services from a centralized location, without impacting the user experience. Hence, a mobile edge computing infrastructure was conceptualized.

Some of the key drivers for MEC in 5G Network are:

- Growth in the number of mobile devices connecting to the network (with IOT, it is expected to explode even further)

- Growth in the volume of data generated by the Over the Top (OTT) applications such as social media, video streaming and online gaming.

- Need for distributing the infrastructure where the application services are hosted in a service provider network, to improve the application performance and the user experience

- Need for running application services in multiple locations to increase the reliability of the services

- Need for virtualizing the application services and eliminate the dependancies with purpose-built hardware to simplify the management and orchestration of multi-vendor functions

- Dramatically reduce the network latency to support new use cases such as Autonomous Cars, Virtual Reality, Augmented Reality and Robotic Surgeries

MEC Architecture

MEC architecture resembles NFV architecture. The MEC architecture consists of the following functions:

- MEC Orchestrator
- MEC Platform
- MEC Platform Manager
- Virtualization Infrastructure
- MEC Application Services

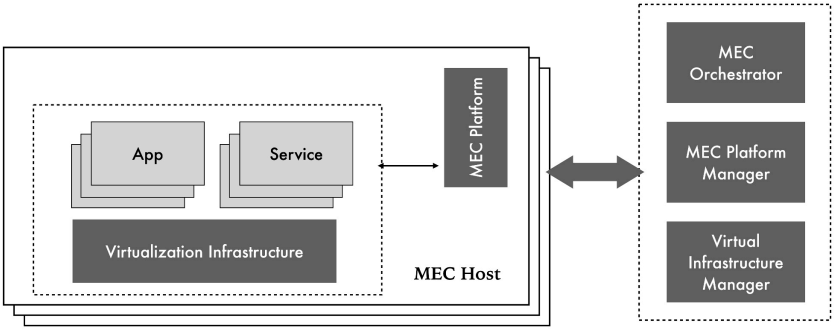

FIGURE 6.1 - MEC SYSTEM ARCHITECTURE

MEC Orchestrator

MEC Orchestrator is a centralized function and has the complete view of the multi-access edge systems including the topology, available resources in the virtualized infrastructure, available applications and services running on the virtualized infrastructure. MEC Orchestrator triggers the life cycle management of the applications and services running on the virtualized infrastructure, including service instantiation, service termination and service relocation. It also selects the right set of resources for running the applications and services, to meet the latency requirements.

MEC Platform

MEC platform provides an environment where applications can discover, advertise, consume and offer mobile edge services. It receives regular updates from the MEC platform manager and the various applications or services running in the virtualized infrastructure. Some of the updates received by the MEC Platform include activation and deactivation of traffic rules and DNS records. For example, MEC Platform would work with the data plane to establish the traffic path for the various applications. MEC Platform uses the DNS record updates to configure the DNS proxy or server in the network. Thus, DNS records can be used to redirect traffic to a specific application running on the MEC host.

MEC Platform Manager

MEC Platform manager provides the Fault, Configuration, Accounting, Performance and Security (FCAPS) management services. It periodically receives fault and performance related reports from the Virtual Infrastructure manager and notifies the MEC Orchestrator about the application and service specific events. MEC Platform manager also manages the application and service specific rules and policies for managing the traffic.

Virtualization Infrastructure

Virtualized infrastructure provides shared compute, storage and networking resources for hosting MEC related applications or Virtual Network Functions (VNFs). This infrastructure can also be shared with other non-MEC VNFs.

Virtualized Infrastructure Manager

Virtualized Infrastructure Manager manages the infrastructure resources required for the various applications and services hosted on the MEC host. It partitions the physical resources and make them available as multiple tenant spaces for hosting the MEC applications and services.

MEC Applications & Services

The service provider can run their own network applications or services in the MEC. The service provider can also run partner or customer applications on the MEC. A MEC application can belong to one or more network slices that have been configured in the 5G core network.

MEC Deployment modes

MEC can be deployed in one of the four deployment modes, as given below:

Breakout mode - The session connection is redirected to a MEC application which is either hosted locally on the MEC platform or on a remote server. Some examples of breakout applications are local Content Deliver Network (CDN) caches (for ex., Akamai caches), gaming services and media delivery services (for ex., Netflix streaming). Normally, you achieve this by defining forwarding policies

In-line mode - MEC is deployed transparently, in an in-line mode. The session connection is maintained with the original server, while all the traffic traverses and goes through the application running in the MEC. Examples of in-line MEC applications are transparent content caching and security applications.

Tap mode - In Tap mode, data exchanged in a session is selectively duplicated and and forwarded to the tap MEC application. Some examples of tap mode applications are virtual network probes, monitoring and security applications.

Independent mode - MEC application and services run independently, but still the MEC application is registered in the MEC platform and will receive other MEC services, such as DNS and radio network information (for ex., radio bearer statistics). Steering the traffic to the MEC is achieved by configuring local DNS or MEC host's data plane.

MEC Deployment scenarios in 5G Network

MEC can flexibly be deployed in different locations of the 5G network, from near the Base Station to the central Data Network. Irrespective of where the MEC is deployed, the User Plane Function (UPF) has to steer the traffic towards the MEC application and back to the network. UPF is responsible for traffic forwarding in a 5G network. 5G architecture provides the flexibility to deploy UPF instances at the network edge, as well as at the network core, for improving performance and reducing latency.

There are 4 possible deployment scenarios for the MEC system in a 5G network. The location in which the MEC is deployed is dependent on a number of factors such as the infrastructure availability (power, space and cooling), type of applications/services hosted in the MEC, network latency and bandwidth requirements.

1. MEC and the User Plane Function (UPF) can be co-located with the Base Station.
2. MEC co-located with a transmission node and possibly with a UPF
3. MEC and the UPF co-located with a network aggregation point
4. MEC co-located with the Core Network functions, in the same data centre

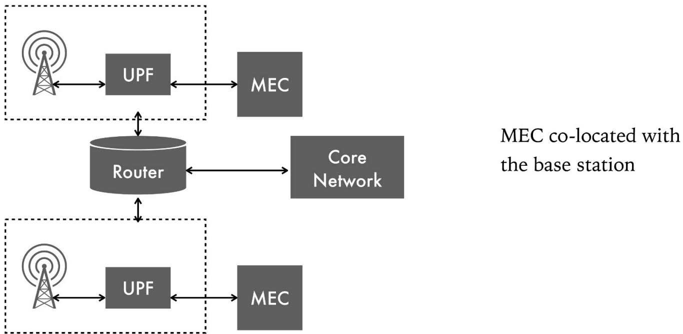

FIGURE 6.2 - MEC CO-LOCATED WITH BASE STATION

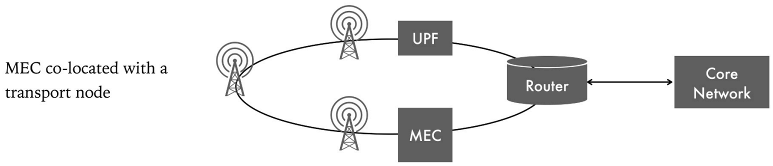

FIGURE 6.3 - MEC CO-LOCATED WITH TRANSPORT NODE

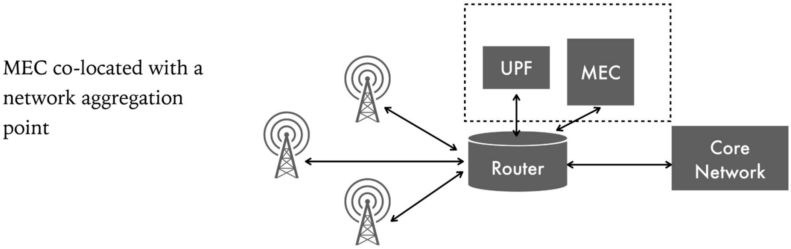

FIGURE 6.4 - MEC CO-LOCATED WITH NETWORK AGGREGATION POINT

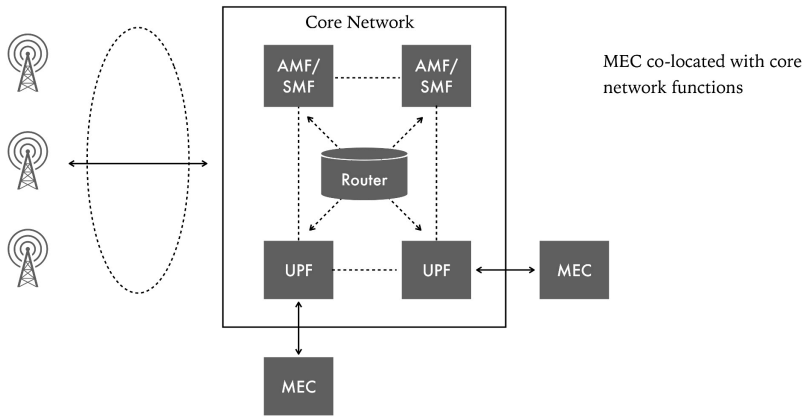

FIGURE 6.5 - MEC CO-LOCATED WITH CORE NETWORK FUNCTIONS

Integrating MEC with 5G Networks

5G architecture provides a number of ways to integrate MEC into the network.

- MEC Services and Applications can be mapped to the Application Functions (AFs) to allow the consumption of services and information exposed by the 5G network. For example, user's mobility and location related updates can be consumed by the MEC services.

- Supports local routing and traffic steering for selectively routing traffic to the applications running in the local data network.

- Application Functions (AFs) can influence the selection of User Plane Functions through the Policy Control Function (PCF) or via the Network Exposure Function (NEF). Administrators can define the forwarding rules and redirection policies in the PCF or define them via an API exposed by the NEF. NEF consolidates the APIs across different functions and provides a unified access to the 5G Core.

- MEC applications can connect to the Local Area Data Network (LADN) in the 5G Core Network. LADN is a new concept introduced in 5G, to provide localised services to users. For example, a video streaming application can be hosted near the RAN in a stadium, accessible through the LADN. Service providers can let users stream a replay of the last goal made by the players, in a football match. Only the people who are watching the sports in the stadium would be able to access those video feeds.

Deploying MEC system in 5G networks, brings in some complexities related to User Equipment (UE) and Application Mobility. For example, UEs such as autonomous cars will be continuously in motion. A session maintained between the UE and a MEC Application, running in a MEC host, may not provide the same level of response times, when the UE moves away from the MEC host. In such situations, the session has to be seamlessly moved to another MEC host or MEC application instance which is closer to the UE. If the application is stateful, it would require continuous synchronization of UE session data or state information across the MEC application instances. If the application is stateless, then there is no need for synchronizing the session data and the session can be easily migrated to the MEC application instance that is running closer to the UE.

MEC Use Cases

MEC supports multiple use cases enabling service providers to realize new revenue streams. Some of the potential use cases for MEC in a 5G network are:

MEC for Enterprise services: By deploying an MEC system within the Enterprise, service providers can let the Enterprise host some of its corporate applications locally, without having to compromise on the security requirements. When the corporate users move out of the Enterprise coverage zone, they'll also lose access to the applications hosted on the MEC system, unless they access those applications through a VPN connection. Enterprises such as healthcare providers, government institutions and industries can get benefited by the locally deployed MEC. Applications that require ultra-low latencies such as live streaming broadcasts and robotic surgeries can be hosted in the MEC system.

MEC for Internet of Things (IOT) services: IOT is going to be one of the biggest beneficiaries of the MEC system in 5G networks. IOT services require the service providers to host and run many applications on the IOT edge. IOT Applications such as the ones used for data collection and analysis has a need to gather large amounts of data locally near the source. MEC system can provide the infrastructure for hosting such applications near the IOT edge. IOT service monitoring applications can also be hosted in the MEC, for improving the reliability of the IOT services provided by the service provider.

MEC for Thirdparty services: Traditionally, service providers were hosting thirdparty applications such as video optimization, WAN acceleration and CDN caches in the core of the network to improve the user experience for their customers. However, due to the speed and latency requirements of 5G networks, such services can no more be centrally deployed and managed. Such thirdparty applications can be now hosted on the MEC systems near the users. Opening up the service provider network for hosting thirdparty application services can also let the service provider to monetize their MEC infrastructure. For example, a cloud service provider can partner with the telco service provider to host their applications in the MEC system. Or, a video streaming solution provider can host their application on the MEC system. This would enable the telco service provider to get into a revenue sharing agreement with the OTT service provider.

Benefits of MEC

MEC provides the following benefits:

- Support low latencies in a 5G network. Low latencies improve application performance and user experiences, as applications are run in local compute infrastructure
- Provides a platform for service providers to experiment with new customer facing services, without disrupting their network architecture significantly
- Helps service providers to increase their monetization opportunities by rolling out new network services to customers, beyond the traditional connectivity services
- Provides an environment for Over the Top (OTT) applications to leverage wireless customer information to offer customized experience (for ex., services based on customer location)
- Provides security for IOT services, by distributing the attack surface
- Improves reliability of application and network services, by offering a distributed infrastructure for service failover

- Provides real time access to data locally, in an IOT environment
- Provides an environment for local policy management for enterprise customers
- Reduces operational costs, by avoiding the need to build costly data centres

Review Questions

1. What is the need for MEC in a 5G architecture?
2. What are the different components in a MEC Platform?
3. What are the different modes of deployment of a MEC infrastructure?
4. What are the different locations in which MEC infrastructure can be deployed in a 5G network?
5. What are the benefits of MEC?
6. What are the different use-cases of MEC?

7. Security in 5G Networks

5G supports a myriad use cases covering enterprises, consumers, communities, industries and government institutions. Considering the diverse set of users, devices and use cases that are riding on top of 5G network, providing secure connectivity services is very critical for the success of 5G.

Need for Security in 5G networks

Unlike the previous generation wireless technologies, 5G has native support for Massive IOT and Vehicle-to-Infrastructure services. Protecting these networks from Distributed Denial of Service (DDOS) attacks by hackers is very important.

- Massive IOT use cases will use 5G RAN and hackers could potentially overload the RAN through DDOS attacks, if the network is left unprotected.
- Introduction of MEC and Small Cells that get deployed closer to the subscribers and devices, create new attack vectors for hackers and they have to be protected
- 5G caters to mission critical use cases such as robotic surgeries and preventing hackers from exploiting the zero-day vulnerabilities is critical

Security features in 5G network

1. 5G uses licensed spectrum, which prevents hackers from eavesdropping into the network and getting access to sensitive data that gets exchanged over the network.
2. 5G achieves network segmentation through network slicing, by isolating each of the slices. Network slicing ensures that data exchanged by one customer or a service does not get shared with other customers or services riding on the network.
3. 5G supports "Home Control" features for preventing network spoofing attacks. Home Control feature authenticates the device location in roaming scenarios. When a device is roaming, the home network verifies if the device is actually present in the serving network, before allowing the user to roam in the visited network. This fixes a known vulnerability in the previous generation networks - 3G and 4G.
4. 5G provides native support for Extensible Authentication Protocol (EAP). It allows new authentication methods to be plugged into the network, by the service provider. It also homogenizes the authentication method for 3GPP and non-3GPP systems (for example, 5G and WiFi systems).
5. Security Anchor Function (SEAF) in 5G, allows for re-authentication of the device, when the device moves between different access networks without having to run the full authentication process. SEAF is now part of the Access and Mobility Management Function (AMF), in the 5G Core.

6. 5G network supports mutual authentication between the User Equipment (UE) and the network.
7. 5G supports Subscriber Identifier Privacy. In 3G and 4G networks, the IMSI (International Mobile Subscriber Identifier) is shared with the network during the connection establishment process. In 5G network, a globally unique Subscriber Permanent Identifier (SUPI) is allocated for each subscriber. The SUPI either follows the format of the IMSI or the Network Access Identifier (NAI). The SUPI is not shared during the connection establishment process. Instead, a temporary Subscriber Concealed Identifier (SUCI) is shared with the network, until the subscriber or device is authenticated. This feature protects the subscribers from rogue base stations in the network.

Mitigating the threats in the 5G Network

Protecting the MEC infrastructure

MEC is one of the vulnerable entities in a 5G network, as it gets deployed at the edge of the network. The risk can be minimized by deploying endpoint protection software in the MEC host. MEC applications and services can be protected and secured by configuring and enforcing application or service specific policies. For example, configuring role-based access control for administrators managing the MEC applications and services.

In addition, implement monitoring to provide enhanced visibility of the MEC applications, MEC services and the

MEC infrastructure components. For example, keeping track of activities of various logged-in administrators, collection of system resource utilization and system performance snapshots at various time intervals etc.,

As MEC is open to several third parties for running their own custom applications, it is better to deploy firewalls for DDOS protection, malware protection and API protection.

Protecting the Core Network

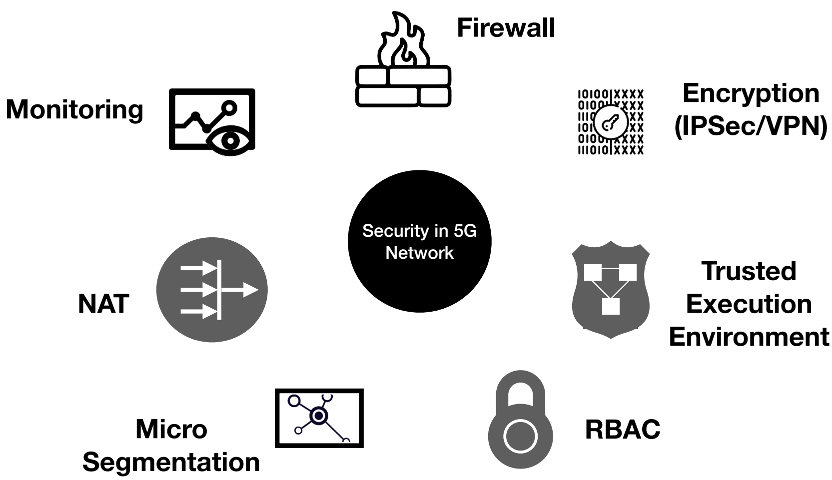

FIGURE 7.1 - PROTECTING THE CORE NETWORK

Core network can be protected by using several mechanisms. Micro segmentation is one of the emerging trends in the security landscape. Micro segmentation helps in protecting the core network, allowing administrators to control the communication between different components in the core network. Micro segmentation allows policies to be configured at different levels such as Virtual Machine (VM) level, Operating System (OS) level, application level and at the flow-level.

Data exchanged over the network can be protected by encrypting data using traditional methods such as IPSEC and VPN.

NAT allows network administrators to isolate select internal networks and prevents access to those networks from the external world. Network administrators can deploy CGNAT (Carrier Grade NAT) functions to isolate networks.

In addition, service providers can deploy firewalls to protect the network and implement monitoring of the end-to-end core network functions.

Protecting the Virtualized Infrastructure

5G brings-in additional complexity to the operations teams, in deploying, managing and securing the network infrastructure - as several 5G components are deployed in a virtualized infrastructure. In order to protect, the Virtualized Network Functions (VNFs), service providers have to turn-on DNS level security features to block bad domains and bad talkers from accessing the network.

Network operations teams must deploy security software that blocks compromised VNFs, prevents VM hopping and blocks container image packages with vulnerabilities. In addition, Virtualized Infrastructure components must be continuously monitored for added protection.

Protecting the CPE and Small Cell devices

In 5G, several equipment such as the Customer Premise Equipment (CPE) and Small Cells are deployed closer to the user or at the user premise. In such cases, encryption of sensitive data stored in non-secure physical locations is a must.

All the CPE or Small Cell devices connecting to the service provider’s 5G network should validate firmware and software packages cryptographically at the time of booting. When vulnerable software packages are detected, the security teams must be alerted, and the software must be rolled back to a trusted version. The devices can provide a Trusted Executive Environment (TEE) to isolate resident applications on the devices, by leveraging hardware capabilities. Each device connecting to the network should authenticate itself at the time of connecting to the network. This can be achieved through certificate-based authentication. Service providers can pre-provision device credentials in the certificate and install them on the device, before shipping the device to the field.

In addition, device location can be continuously tracked by embedding a GPS chipset in the device. The location of the device can be validated during the connection establishment process.

Review Questions

1. What is the need for security in 5G Networks?

2. What are some security features built into the 5G Network?

3. What are the different layers of protection available in a 5G Network?

4. How do you protect the MEC infrastructure in a 5G Network?

5. What is the role of micro segmentation in protecting the 5G Core Network?

6. How are the CPEs and Small Cell Devices protected in the 5G Network

8. 5G Use-cases

5G supports a wide variety of use cases covering residential customers, businesses, communities and government agencies. By supporting multiple use-cases, 5G provides additional monetization opportunities to service providers, beyond the traditional mobile phone services. Also, use cases such as Private Wireless, enables enterprises to deploy their own 5G based mobile wireless gear, making them a service provider. This chapter will cover the various use-cases supported by 5G wireless technology.

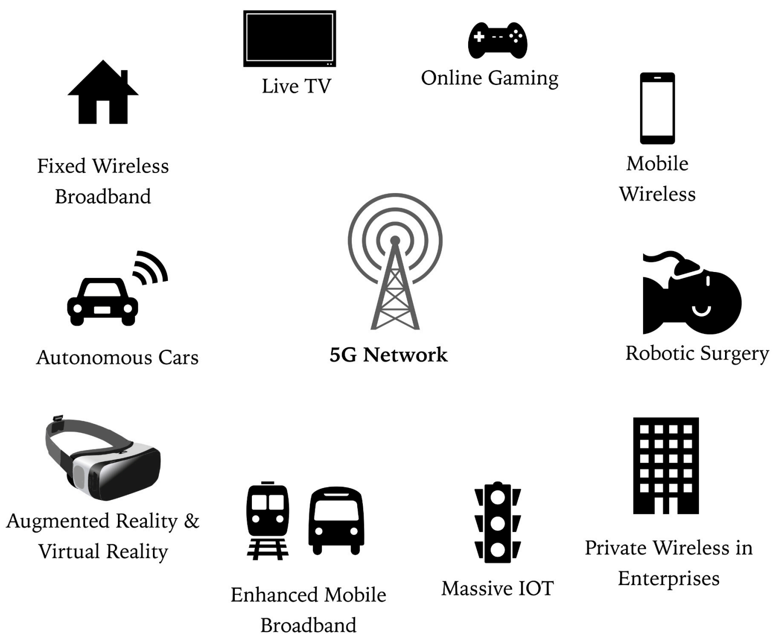

FIGURE 8.1 - 5G USE CASES

Enhanced Mobile Broadband (eMBB)

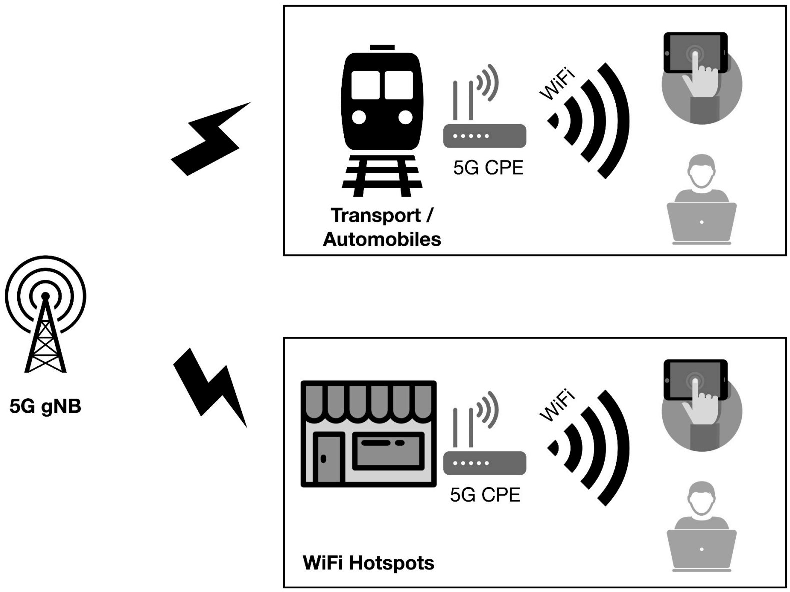

FIGURE 8.2 - ENHANCED MOBILE BROADBAND

With data speeds of 1Gbps, 5G is well suited for Enhanced Mobile Broadband (eMBB) services. In eMBB deployments, routers or Customer Premise Equipment (CPE) devices with 5G modems connect to the 5G network for Internet access. In turn, they use WiFi to provide network connectivity locally to the users or devices. eMBB services are typically deployed in places such as trains, public transport systems, shopping malls and airports.

In addition, eMBB solutions are used to provide broadband access to users through hotspots in dense areas or during special events, such as sports events in stadiums or concerts, where there is large gathering of users. The hotspot service providers can charge their customers for the usage of broadband service or make it available as a free service, to attract and retain customers. For example, a coffee shop or a diner with free high-speed WiFi access would attract more foot falls.

Fixed Wireless

Fixed wireless deployments provide broadband access to residential or small enterprise customers through wireless networks. Verizon is the first 5G wireless service provider in the world to offer Fixed Wireless services to customers. Fixed Wireless services eliminate the need to dig the road and lay cables in the last mile to provide Internet connectivity to homes. The service provider ships a CPE device to the customer. The customer receives the shipment and powers up the CPE device. The CPE device automatically connects to the nearest 5G tower or Small Cell. The service provider authenticates the CPE device, before granting the device, access to the Internet. The customer can connect their Television, VoIP phone and other devices such as tablets, mobile phones and laptops to the CPE. Most of these CPE installs are ‘self-installs’ for the customer. Hence it reduces the cost of dispatching a technician to customer’s home, for the service provider.

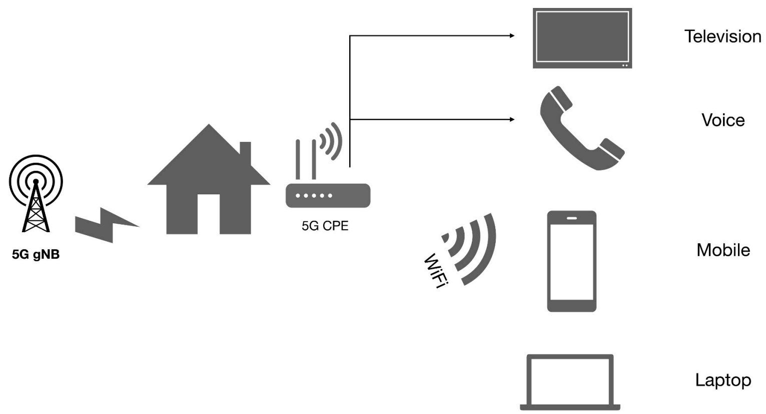

FIGURE 8.3 - FIXED WIRELESS

Live TV

The increase in the bandwidth and the reduction in latency allows service providers to stream Live Television on top of 5G network. South Korean (SK) Telecom is one the leading service providers to demonstrate broadcasting of live TV over a 5G network. Live Over the Top (OTT) TV services will help the consumers to cut cords from the cable service providers. Most 5G service providers would bundle their 5G services with either their home-grown OTT services or with third-party OTT services such as Apple TV or YouTube TV. Live TV services can be offered to residential customers or to enterprises such as Airports and Hotels.

Robotic Surgery

5G supports ultra-low latencies (1ms or less), which makes it ideal for latency sensitive use cases such as Robotic Surgery. Robotic Surgery allows a doctor to remotely diagnose a patient and perform surgery. This allows hospitals to provide quick treatment to patients, saving lives and money.

Post Covid-19 era, market analysts are expecting a spike in Telemedicine services, as people would be hesitant to go to hospitals for an in-person consultation. 5G can enable the growth in Telemedicine services across the globe, as it saves time for the patient and reduces the health risk of getting exposed to sick people at the hospital.

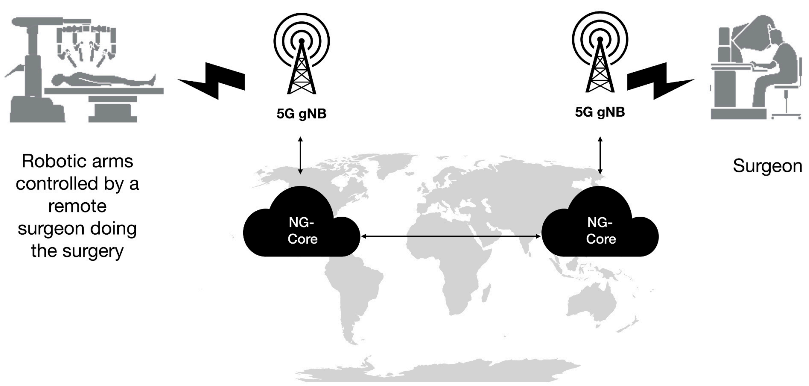

FIGURE 8.4 - ROBOTIC SURGERY

Autonomous Cars

Autonomous / Self-Driving Cars consume a lot of bandwidth and at the same time, require quicker responses from the network. A fast-moving autonomous car cannot wait for seconds to decide whether the object crossing the road is a vehicle or a human. Most of the intelligence of autonomous Cars reside in the cloud and the car requires continuous connectivity to the network. 5G supports higher bandwidth and lower latencies which enables use cases such as autonomous cars. The Multi-access Edge Computing (MEC) infrastructure helps the autonomous car manufacturers to host their applications and make their services available from the edge of the network. The autonomous car can continuously push analytics and other vital statistics about the health of the car to the applications hosted on the network edge.

Massive IOT

Several countries and communities are pursuing their mission of Smart Cities by deploying Internet of Things (IOT) solutions. In a digitised world, almost anything and everything can be categorised as an IOT application. IOT solutions would connect utility meters, traffic lights, surveillance cameras, light poles, temperature monitoring devices etc., to the Internet. This category of use cases that connect a massive number of devices is called as Massive IOT. 5G enables industries and societies to rollout Massive IOT solutions. Depending upon the IOT use-case, the sensors and devices in IOT can either directly connect to the

5G network or connect to a local IOT gateway using protocols such as Zigbee/LoRA and then, the IOT gateway connects to the 5G tower.

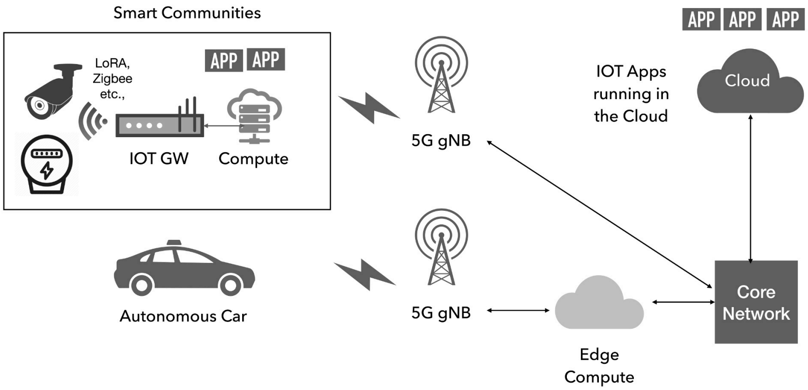

FIGURE 8.5 - MASSIVE IOT

Some of the popular IOT use-cases enabled by 5G are:

- Smart Community
- Industrial IOT
- Autonomous Cars
- Smart Home
- Remote Health monitoring
- Robotic surgeries
- Surveillance
- Predictive Maintenance of equipment

Connectivity needs of an IOT network

An IOT network imposes a lot of demands from the network due to the wide variety of use-cases that are supported. Some of the connectivity related requirements from an IOT network are:

- Need for a standard and consistent mechanism for wirelessly connecting different types of devices to the network.
- Need for ubiquitous availability of network coverage, for moving vehicles such as autonomous cars and driverless trucks.
- Support for uniform network speed and high uplink speed for use-cases such as live video streaming, gaming and surveillance.
- Network should not drain the battery on the devices. For example, Smart Utility meters may be deployed in remote locations and should not require a person to frequently change the batteries.
- Network should scale to support several thousands of devices in a given geographical location.
- Network should support low latencies for applications such as Augmented Reality and Virtual Reality.

5G capabilities for IOT

Wireless technologies of the past such as 3G and 4G had focused on improving the speed of the networks and the network throughput. However, 5G is not only focusing on improving the speed of the networks, but is also focusing on improving the network latency and in scaling the network for several thousands of connections.

5G's capabilities that enable IOT use-cases:

- **High Speed Broadband** – 5G network supports 1 Gbps+ network speed, making it an ideal wireless technology to offer high speed broadband services. With such high broadband speeds, surveillance cameras from the community can stream video feeds to an edge cloud location.

- **Massive Machine Type Communications (mMTC)** – 5G network supports scaling of the wireless network to interconnect several thousands of network devices to mobile towers, enabling IOT use-cases such as smart utility meters, smart street lights and health gadgets.

- **Ultra-Reliable Low Latency Communications (URLLC)** - 5G network supports sub-milli-second network latency with error rates that are lower than 1 packet loss in 100,000 packets. IOT services such as autonomous cars rely on the URLLC capability of 5G. For example, an autonomous car can wirelessly connect with the control applications running on the edge cloud, to make quick decisions, as it moves from one location to another.

5G supports the varying data transfer needs of the different types of IOT devices:

- **Periodic Chunks:** Some IOT devices send small chunks of information in synchronous batches (such as the smart utility meters that send meter readings to the cloud once every hour or once every day)

- **Continuous Streaming:** Some IOT devices continuously stream data to the cloud (such as the surveillance cameras that send video feeds to the cloud)

- **Asynchronous Notification:** some IOT devices asynchronously send data to the cloud, triggered by an event (such as the sensors that monitor the health of the industrial equipment. They send notifications to the monitoring application running on the cloud, when there is an equipment failure).

Virtual Reality (VR) / Augmented Reality (AR)

Imagine visiting a zoo from your living room or playing a game like Pokeman – these are use cases for Virtual Reality and Augmented Reality, respectively. 5G supports both VR and AR use cases enabling consumers to play high definition games or consume high quality entertainment, from anywhere.

AR combines both the real and virtual worlds together, by creating an overlay on top of the real-world video capture. The overlay can be an imaginary character or an object, in case of a gaming application. The overlay can also be step-by-step instructions for technicians to assemble a product or troubleshoot an equipment in an industry. AR requires low latency access to the network, as the mobile device captures live video streams and sends them continuously to applications running on the edge cloud. In turn, the applications hosted on the edge cloud, analyze the data, generate overlay images and send them back to the mobile device. Such high bandwidth and low latency conversations between the mobile device and the edge cloud can be powered by 5G network.

Virtual Reality creates a simulated experience which is closer to or completely different from the real world. For example, you can visit your favourite zoo or museum from the comfort of your living room, without having to waste your time in travel. A VR experience would involve streaming several 10s or even 100s of live video feeds continuously to the mobile device that provides the virtual reality experience. 5G can cater to the bandwidth needs of a VR application.

Private Wireless Network

Today, Enterprises rely heavily on WiFi for ubiquitous access to Internet and Intranet, from within the campus. 5G, with the support for unlicensed spectrum, allows Enterprises to install and manage a secure Private Wireless Network for its users. Private Wireless Networks lower the latency of wireless services and increase the security, as it is a dedicated infrastructure for the Enterprise. Potential Enterprises who would be interested in the Private Wireless Network solution are factories having automated machinery, airports, defence/ army and IOT enabled industries.

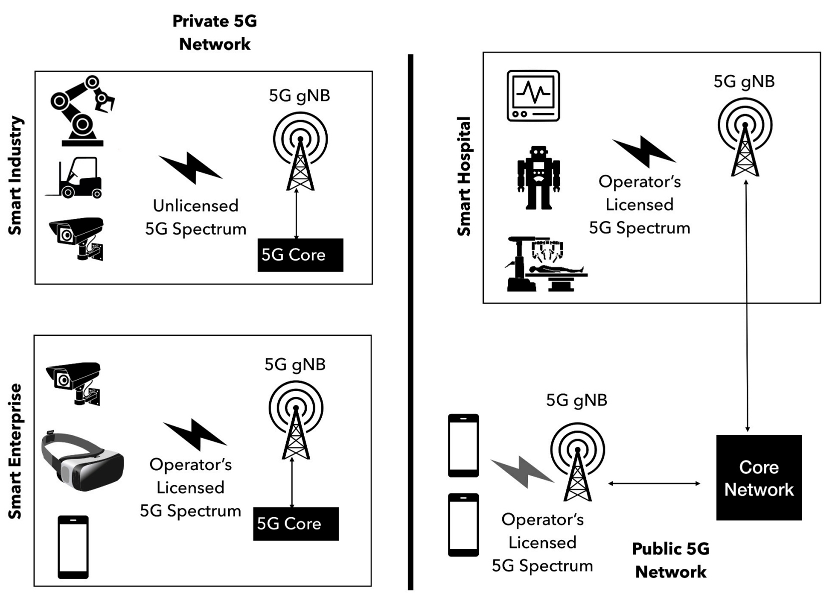

FIGURE 8.6 - PRIVATE WIRELESS NETWORK

There are multiple types of Private Wireless Network deployments supported in 5G:

- The enterprise deploys its own Private Wireless Network, operating using an unlicensed spectrum. In this deployment, the end-to-end solution (5G radio and 5G core) would be deployed and managed by the enterprise's network administrators.
- Service provider deploys the 5G network in the enterprise and operates/manages the end-to-end solution. The 5G network would use the operator's licensed spectrum for its communication.
- Service provider deploys dedicated 5G radio in the enterprise for enhanced coverage. The 5G radio is connected to the centralized 5G core, deployed and operated by the service provider. The 5G core network infrastructure is shared by other 5G towers in the region. The service provider may choose to place the enterprise on a dedicated network slice – for improved quality of service.

Mobile Services

5G would continue to provide mobile data, voice and video services, like the older generation wireless technologies. However, most of the initial use cases that are getting rolled out by service providers are for use cases other than providing mobile connectivity services. LTE-advanced provides up to 400 Mbps speed in 4G. Hence, there is little to no incentive for customers to upgrade to a 5G based mobile service.

Holographic Call

Vodafone UK demonstrated the first live holographic call using 5G. Holographic call allows you to create live interactions with someone who is geographically miles apart. It saves travel costs and time for Enterprises and Consumers. Imagine a corporate executive team doing their quarterly all-hands / townhall meeting using a Holographic Call. Hologram provides equivalent of a live viewing experience for the audience. As 5G supports high bandwidth and low latencies, hologram services can be offered on top of a 5G network.

Review Questions

1. What are the different 5G use cases?

2. What is a Private Wireless Network?

3. What are the different modes of deployment of a 5G network in a Private Wireless Network?

4. What is Massive IOT? How does 5G help with Massive IOT?

5. What are the IOT use cases enabled by 5G?

6. What are the requirements of IOT from the network?

7. How does 5G help in enabling Augmented Reality and Virtual Reality use cases?

9. 5G Marketplace

5G marketplace includes several stakeholders and entities such as the service providers, standard bodies, open source software communities and network equipment vendors. Collectively, they contribute to the growth and adoption of 5G technology by defining standards, identifying use cases,

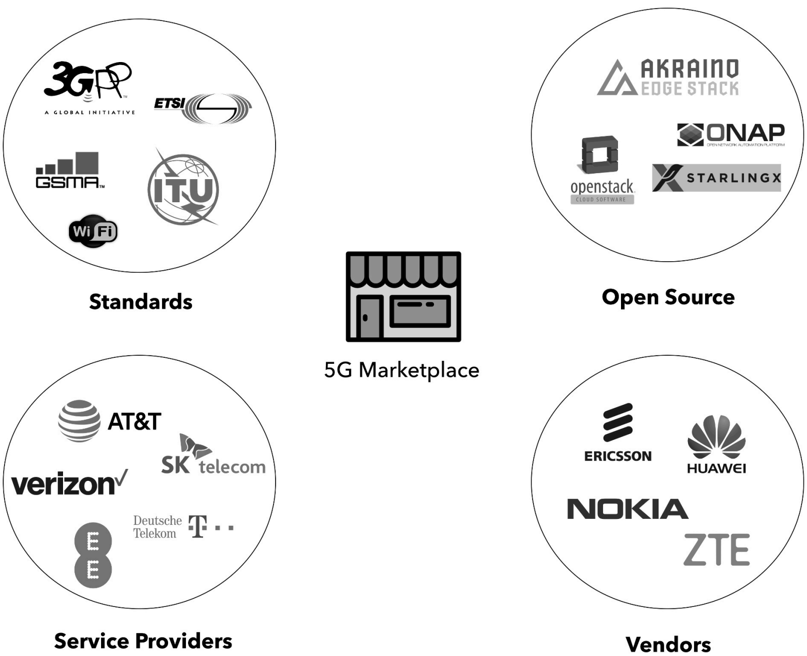

FIGURE 9.1 - 5G MARKETPLACE

developing prototypes, building network equipment and developing software frameworks. This chapter will cover the status of 5G deployments across the world and the role played by various standard bodies, network equipment vendors and the open source software communities in accelerating the adoption of 5G.

5G Vendors

Ericsson, Huawei, Samsung, Nokia and ZTE are the leading 5G equipment vendors. All the 5G buildouts done today, are based on the Non-Standalone architecture – where the 5G radio infrastructure is connected to the 4G LTE Core. The service providers across the globe are deploying 5G radios – in the form of cell towers or using small cells. Network equipment vendors are selling Radio Access Network (RAN) infrastructure to the service providers, including Virtualized Baseband Units (vBBUs). Many service providers are upgrading their core network with Virtualized Evolved Packet Core (vEPC) and Virtualized IP Multimedia Subsystem (vIMS) network functions. This enables them to dynamically scale their network when there is a need.

There is only a handful of vendors developing 5G compatible smartphones such as Samsung (Samsung Galaxy S10/S20, Note 10 Plus, Fold), Oppo (Reno 5G), OnePlus (8 Pro) and Xiaomi (Mi Mix 3 5G0). Apple is expected to launch a 5G ready iPhone in 2020.

Several start-ups are developing applications in the areas of online gaming, Augmented Reality / Virtual Reality (AR/VR), Internet of Things (IOT), 3D video streaming and healthcare for leveraging the capabilities of the 5G network.

5G Standard Bodies

Multiple standard bodies are collaborating to define 5G related standards, specifications, prototypes and APIs. The standard bodies collaborating to come up with 5G standards span across multiple geographies, multiple technology areas, multiple projects. 3GPP is leading all the 5G related standards definition activities.

- **3GPP** (3rd Generation Partnership Project) - Develops standards and protocols for mobile telecommunications.

- **GSMA** (Global System for Mobile Communications Association) - Develops frameworks and requirements for operational matters as well as influences mobile industry standardization and solutions development.

- **ETSI** (European Telecommunication Standards Institute) - Drives standards for network infrastructure and network functions virtualization

- **ITU** (International Telecommunications Union) - Coordinates standards for Telecommunications and Information communication technology.

- **IETF** (Internet Engineering Task Force) - Drives standards around the evolution of the Internet architecture and operation of the Internet (including the 5G networks)

- **5G PPP** (5G Infrastructure Public Private Partnership) - Drives 5G related prototypes, standards and solution development.

- **TMForum** (Telecommunications Management Forum) - Drives network management related standards (including 5G networks)

- **IEEE** (Institute of Electrical and Electronics Engineers) - Enables the development of new, innovative use cases and standards for 5G.

5G Deployments

5G trials have been going on since 2015. However, there were no commercial deployments until late 2018. The momentum of 5G rollouts have picked up pace since late 2018. Several service providers in USA, EMEA and APAC announced the launch of 5G services, in 2018.

Unlike 4G, the initial launch of 5G services were not targeted at mobile phones. The initial set of 5G services were targeted mostly at enterprise and business customers. Later-on, the 5G services were expanded to the mobile phones and retail customers.

Verizon is the world's first service provider to launch a non-standard version of 5G in US. They launched their first 5G service called 5G Home, a residential broadband service to their customers. 5G Home is a fixed wireless use case. Customer would receive a 5G compatible Customer Premise Equipment (CPE). They can connect their television, VOIP phone, and WiFi router to the CPE device. The CPE device would connect to the 5G tower to provide broadband services to the customer. The initial speeds offered by Verizon for 5G Home service was 300 Mbps. In 2019, Verizon launched 5G based mobile services in US and started expanding their footprint.

AT&T, another leading service provider in USA, launched standards based 5G services in late 2018, targeting select business and retail customers. The solution includes a Netgear based 5G Mobile hotspot, which would connect to the 5G tower to provide broadband services to the customer. Later-on, AT&T expanded the 5G services to other mobile 5G devices.

Several other service providers such as EE in UK, Deutsche Telecom in Germany and A1 in Austria, SK Telecom in South Korea, China Mobile in China launched 5G services in the year 2019.

2020 turned out to be a bad year for 5G launches. Due to the impact of Covid-19 pandemic across the globe, several countries have put their 5G spectrum auction on hold. Service providers, who already had a well-defined 5G roadmap are taking a relook at the investments going into building their 5G infrastructure.

5G Pricing

Though Service providers are spending several billions of dollars to build the 5G network, many of them are still in the learning phase, trying to understand how to monetize their 5G investments. "How is 5G going to be priced?" - is still a million dollar question for many in the industry. In fact, 5G pricing is still a puzzle for even the service providers.

Traditionally, service providers charged their wireless customers based on the amount of bandwidth they consumed. For example, a customer using 2GB of data a day is priced higher than the customer who is using 400 MB of data, a day. But, that pricing model is not going to be relevant for 5G, as 5G caters to a variety of use cases such as IOT and Autonomous Cars. For example, in an IOT deployment, several 1000s of sensors / devices are going to push small chunks of data at periodic intervals to the network or to the cloud. The aggregate volume of data pushed to the network is not going to be as high as 2GB a day. However, the network must support all the active IOT sensors/devices. So, service providers cannot make a lot of money if they charge customers just based on the bandwidth consumed. They'll have to be more creative at charging the customer, month-on-month basis.

US has been leading the 5G wave. So, let us investigate how the major service providers in US are pricing their 5G services. Verizon charges $70 per month for new customers signing up for Verizon 5G Home services. They are charging

$50 per month for existing wireless customers who sign up for Verizon 5G Home services. The good news is, there is no data cap/limit for 5G Home customers. So, they can do unlimited data downloads/uploads.

For 5G mobile services, Verizon is charging an additional $10 per month, when compared to the 4G customer. AT&T's initial launch of 5G services comes with a $70 per month plan and with a 15GB data cap / limit.

How can Service Providers price their 5G services?

There are a few indications from leading service providers on how they are planning to price their 5G services. Hans Vestberg, the CEO of Verizon, in his keynote address at the 2019 Consumer Electronics Show (CES), talked about the 8 currencies of 5G. He talked about 8 key parameters, that make 5G services unique. His speech gives an indication on how the 5G services can be priced such as the Peak Data Rate, Mobile data volume, Rate of Mobility of the device/ user, number of Connected Devices, Service Deployment time, Service Reliability, Energy Efficiency and end-to-end Latency.

1. **Pricing based on Bandwidth consumed** - This is the traditional pricing strategy and some service providers would continue to provide 5G wireless plans based on customer's bandwidth consumption. Once the customer reaches their maximum upload/download limits, the service provider would

switch the customer to a slower tier of service. This would be apt for mobile broadband services.

2. **Pricing based on network latency** - There are services such as Autonomous Cars and Robotic Surgeries that are latency sensitive. Customers and Enterprises using such services would avail plans that support different latency tiers. For example, a customer signing up for 1 millisecond latency would be charged higher than the customer who signs up for 5 milliseconds or more latencies.

3. **Pricing based on number of devices** - In an IOT deployment, pricing of the 5G services is going to be based on the number of devices that connect to the network. For example, a farm land would have several 10s or 100s of sensors / devices actively monitoring parameters like weather, water levels, soil quality, pesticide levels etc., and pushing such data to the cloud. In such deployments, access to 5G services will be charged based on the number of devices that connect to the 5G network.

4. **Pricing based on network speed** - Services such as online gaming, Augmented Reality / Virtual Reality (AR/VR) would require a network that performs well and can support higher data speeds. Customers who use AR/VR or online gaming services can sign up for a pricing plan that offers higher network speeds. For example, customers who are availing a 1 Gbps 5G service would be charged higher than customers who are availing just 50 Mbps service.

5. **Pricing based on Network Slice** - Network slicing is a new technique introduced in 5G, to partition the physical

network into multiple virtual network slices, based on parameters such as speed, latency and security. An Enterprise customer can avail a dedicated network slice that offers a secure SD-WAN connectivity between its branch offices. This would improve the quality of the SD-WAN service for the customer..

6. **Pricing based on tenant space in the MEC infrastructure** - Multi-access Edge Cloud (MEC) infrastructure opens up the service provider edge for hosting a variety of MEC applications such as video streaming, video surveillance, IOT and AR/VR applications. Service providers can charge their partners and customers for the MEC tenant space. The various MEC use-cases would enable service providers to create additional revenue streams.

7. **Free 5G service (subsidised by OTT players)** - Considering the growth of OTT (Over-The-Top) services, online service providers are even ready to subsidize the connectivity to Internet for their customers. Google today is rolling out free WiFi services in railway stations, in countries like India. In the future, online service providers like Google may partner with telecom service providers to offer free 5G services to their customers.

8. **Pay using Bitcoins** - Imagine a day where you'll have to play online games and earn bitcoins that you can use for paying your monthly 5G services bill. Not sure whether we'll ever get to this. However, considering the amount of time subscribers spend in online gaming applications (and in earning bitcoins), this could also be a reality.

In the next few years, we would have more clarity on how service providers are going to monetize their 5G investments.

Is 5G Harmful?

In USA alone, close to 800,000 small cells are going to be deployed to support the various 5G services. It is nearly four times higher than the number of 4G towers already deployed in USA. When 5G is fully deployed, users should be able to see a small cell tower in almost every street corner. Considering the large number of small cells that are getting deployed, 5G rollout is going to increase the exposure to the radiations emitted from the mobile towers. There are at least two dozen lawsuits filed against Federal Communications Commission (FCC)'s ruling to accelerate 5G deployments in US.

So far, research does not provide any conclusive evidence related to the harmful impacts of 5G radiations on life.

In 2010, a study funded by World Health Organization (WHO) reported that "Our review does not indicate an association between any health outcome and radio frequency electromagnetic field exposure from mobile phone base stations at levels typically encountered in people's everyday environment"

In 2015, European Commission Scientific Community, published its findings on the impacts of RF radiation on humans. They said "Overall, the epidemiological studies on mobile phone RF Electromagnetic Field exposure do not show an increased risk of brain tumors. Furthermore, they do not indicate an increased risk for other cancers of the head and neck region."

In 2018, National Toxicology Program did a research and published their findings. They reported that "High exposure to radio frequency radiation (RFR) in rodents resulted in tumors in tissues surrounding nerves in the hearts of male rats, but not female rats or any mice". However, a senior scientist from National Toxicology Program added a disclaimer "The levels and duration of exposure to RFR were much greater than what people experience with even the highest level of cell phone use, and exposed the rodents' whole bodies. So, these findings should not be directly extrapolated to human cell phone usage".

In addition to the research done by independent entities such as WHO and European Commission, technology vendors and service providers are also analysing the impacts of the 5G radiations.

Hans Vestberg, the CEO of Verizon, when responding to an interviewer, confidently said that he has not seen any impacts of radiations, so far. He also mentioned that his previous employer did a lot of research in this area and has not found any impacts due to radiations emitted by the mobile towers.

Hans Vestberg's previous employer, Ericsson, is one of the leading vendors - carrying 40% of mobile traffic across the globe. Ericsson is also a key player in developing 5G radio technology. Ericsson claims to have done over 100 studies on the impacts of radiations. They published a report sharing details from the research done on 5G radiations. The report says, "The power levels of the radio signals transmitted by 5G radio equipment will be of similar or lower magnitude as those used in previous networks." Ericsson also says "5G devices will be designed and tested to comply with established radio wave exposure limits".

Recently, media speculated about 297 birds getting killed due to 5G tests in Netherlands. However, subsequently the news was reported as false.

The Covid-19 pandemic, triggered speculations that 5G radiations lowered the immune system of humans and made them vulnerable to the virus. The speculation started because Wuhan, the city where the first case of Coronavirus got reported, is a 5G city. Soon, the news got widely spread over the globe, creating citizens' uproar in social media. However, the Public Health Department of England dismissed the rumours and said "It is possible that there may be a small increase in overall exposure to radio waves when 5G is added to an existing network or in a new area. However, the overall exposure is expected to remain low relative to guidelines and, as such, there should be no consequences for public health".

So far, no study has clearly established a direct correlation between the radiations emitted by mobile towers and the health impacts on humans. However, in pockets research confirmed that excessive exposure to radiation is not good for human health. So, it is recommended to be farther from the antennas (cell phone towers, small cells and mobile devices). Unfortunately, 5G's reliance on milli-meter wave requires the small cell towers to be deployed closer to the users. Only time can answer the real health hazards caused by the 5G deployments.

Will 5G replace WiFi?

If 5G is expected to be ubiquitous, will WiFi then get killed by 5G? This is a common question or debate going around. We can safely assume that WiFi will not get killed by 5G, at least in the next 10 years.

Here are the reasons why WiFi technology is going to last longer:

WiFi is a growing industry: According to a study commissioned by WiFi Alliance®, the economic value provided by Wi-Fi is nearly $2 trillion in 2018, and is expected to grow to almost $3.5 trillion by 2023. This valuation is equivalent of the combined valuation of the two large companies in the world Apple and Amazon. So, WiFi is not shrinking and continuing to be a growing industry.

Technology Penetration: WiFi, as we know it today, got introduced in the year 1997 and it provided up to 2 Mbps speeds. In 1999, WiFi 802.11b standard was published, upgrading the WiFi speeds to 11 Mbps. WiFi has a wider foot print today - with deep penetration into our homes, enterprises, residential communities and in commercial establishments. WiFi has already reached the "ubiquitous" status. 5G is still in its nascent stages, with several operators focusing on doing trials and testing the waters with initial 5G deployments. It would take at least another 5 years for 5G to reach the current stage of 4G deployments, let alone matching the penetration of WiFi deployments.

Cost of Deployment: WiFi technology uses "unlicensed spectrum" (2.4Ghz or 5 Ghz) versus 5G, which uses "licensed spectrum". 5G spectrum is going to be costly because of the need for the broad range of spectrum, to support speed as well as coverage. Service providers would have to cough several billions of dollars to get the 5G spectrum. So, WiFi will be lot cheaper when compared to 5G. However, when 5G starts supporting the unlicensed spectrum bands, we have to look at “How much cost savings will be produced by 5G, when compared to WiFi?”

Speed and Customer Experience: 5G speeds are going to be significantly higher (1 Gbps+), when compared to 4G (40 - 600 Mbps). However, it cannot still beat the great speeds offered by WiFi. The theoretical maximum speed of 802.11ac, the latest WiFi standard, is roughly 7 Gbps. In real world situations, you may see somewhere around 1.7 Gbps and 2.5 Gbps, with 802.11ac WiFi. An 802.11ac WiFi router, connected to a Fiber network may offer a higher speed, when compared to 5G network.

Devices Support: WiFi is supported today by most devices that connect to Internet. Moreover, there are some devices (such as iPods and Chromecast) that connect only to the WiFi network. These devices are not going to vanish overnight from the world. It is going to take at least a decade to slowly phase out these WiFi only devices.

WiFi may get replaced by 5G in Enterprises use cases for multiple reasons:

- Enterprises can afford to buy a 5G small cell device (small cell tower) and deploy it in house to offer 5G coverage to its employees, slowly replacing WiFi with 5G. Service providers can themselves deploy 5G in Enterprises for cell densification and Enterprises can reuse that infrastructure to avail Private Wireless network services. Service Providers can carve out a 5G network slice for the Enterprise related services.
- Today, WiFi networks are deployed and managed separately by the IT administrators in Enterprises. Reusing 5G infrastructure, instead of corporate WiFi would reduce the administrative overhead for the Enterprises.
- Today, WiFi provides more security for Enterprises as they have complete control over what is going on over their private WiFi network. With 5G, because of the Service Based Architecture (SBA), Enterprises can manage their 5G based Private Wireless Network, through APIs - providing the same levels of controls they had on their WiFi network.
- Because of the evolution of the WiFi standards, Enterprises have to continuously upgrade their WiFi gear, once every 3 - 5 years. With 5G, that overhead can be outsourced to the Service Providers. Service Providers will take care of upgrading their wireless infrastructure periodically.

- The desk phones providing VOIP services can potentially vanish with Enterprises rolling out 5G based Private Wireless Network. Each employee becomes accessible through their wireless mobile phones, wherever they are - instead of having to be glued to their desks.

5G can complement WiFi, in some use cases:

- In Enhanced Mobile Broadband (eMBB) use cases, the customer premise equipment (CPE) can connect to the 5G network for Internet connectivity and can locally offer connectivity services through WiFi. Considering the huge bandwidth offered by 5G (1 Gbps), it can potentially serve a large number of WiFi users or WiFi enabled devices. 5G may increase the penetration of eMBB in public places and residential communities.
- 5G can complement WiFi in Fixed Wireless use cases (such as the 5G Home service launched by Verizon, recently). 5G would eliminate the need for service providers to dig the lawns of their customers to provide broadband services. With 5G, service providers can reduce the cost of their dispatch operations and enable customers to activate their Internet connectivity services through self-serve mechanisms.

Both the technologies 5G and WiFi are going to thrive together for a long time to come.

5G Open Source Communities

With IBM buying Redhat and Microsoft buying companies like Github, it is becoming very clear that open source software has strategic importance for leading players in the industry. Both service providers and technology solution providers are embracing open source, for accelerating growth and reducing the time to market. 5G involves a lot of network infrastructure upgrades. So, the open source communities are gearing up to solve the challenges in the areas of 5G Radio management, 5G NG Core infrastructure orchestration/management and Multi-Access Edge Cloud (MEC). Some of the communities are new, and many existing communities have reincarnated to solve 5G related challenges.

Community Name: Open AirInterface (OAI)
Started in: 2014
Description: OpenAirInterface Software Alliance (OSA), is a consortium funded by service providers, network equipment vendors and universities to accelerate the research and development activities in 5G. OpenAirInterface (OAI) provides open-source hardware and software wireless technology platforms (simulation, emulation, and realtime) for deployment of mock 5G networks. Some of the strategic areas of focus for the community include 5G Modem, Software-defined 5G system, Heterogeneous 5G Network, Large-scale Emulation, Internet of Things (IoT), Test and Measurement. OpenAirInterface implements 3GPP compliant radio access network (eNB, gNB and 4G, 5G UE) as well as the core network (EPC and 5G-CN).

Key Drivers: Eurecom, Orange, Nokia Bell Labs, Platforms for Advanced Wireless Research, TCL and Fujitsu

Community Name: 5G PPP (Private Public Partnership) Projects
Started in: 2013
Description: The 5G Public Private Partnership (5G PPP) is a joint initiative between the European Commission and European ICT industry (Information and Communication Technology manufacturers, telecommunications operators, service providers, SMEs and researcher Institutions). The 5G-PPP's charter is to deliver solutions, architectures, technologies and standards for the ubiquitous 5G communication infrastructures of the next decade. 5G PPP consortium is backed by a 1.4 billion Euro fund from the Horizon 2020 initiative. 5G PPP group has spun off 50+ projects focused on different verticals such as automative, manufacturing, media, energy, health and public safety and smart cities. These projects look at everything from soup to nuts in the area of 5G.
Key Drivers: European Commission, Universities, R&D organizations, Network Equipment vendors.

Community Name: M-CORD
Started in: 2013
Description: M-CORD is an open source reference solution for carriers deploying 5G mobile wireless networks. It is a cloud-native solution built on SDN, NFV and cloud technologies. It includes both virtualized RAN functions and a virtualized mobile core (vEPC) to enable mobile edge applications and innovative services using a micro-services architecture. M-CORD is one of the projects under the

CORD (Central Office Rearchitected as Data Center) project. It is driven by the Open Network Foundation (ONF)
Key Drivers: AT&T, Google, China Unicom, Juniper, NTT Group, Ciena, Radisys and several Network Equipment vendors / Service providers.

Community Name: Open Network Automation Platform (ONAP)
Started in: 2017
Description: ONAP Platform provides capabilities for design, creation and lifecycle management of network services - both physical and virtual. It was formed by integrating the ECOMP framework opensourced by AT&T and the Open-O open source community. ONAP community is customizing the orchestrator to support use cases such as 5G Network Deployment, Network Slicing, Optimization and Automation
Key Drivers: Amdocs, AT&T, China Mobile, Bell Canada and a bunch of service providers / network equipment vendors.

MEC Open Source Communities

When a new technology change happens, several open source communities would rise up to the challenge and try to come up with solutions through software. Multi-access Edge Computing (MEC) is not an exception. Acknowledging the importance of edge computing infrastructure, Linux Foundation (LF) created an umbrella organization called LF Edge to host edge computing open source projects such as Akraino Edge Stack, EdgeX Foundry and Project EVE. In addition, consortiums such as OpenFog and Cloud Native

Compute Foundation (CNCF) are creating reference framework and software stack for MEC deployments.

Community Name: Akraino Edge Stack
Started in: 2018
Description: Akraino Edge Stack aims to create an open source software stack that supports high-availability cloud services optimized for edge computing systems and applications. The Akraino Edge Stack is designed to improve the state of edge cloud infrastructure for enterprise edge, OTT edge, and carrier edge networks. It will offer users new levels of flexibility to scale edge cloud services quickly, to maximize the applications and functions supported at the edge, and to help ensure the reliability of systems that must be up at all times.
Key Drivers: ARM, AT&T, Baidu, Dell EMC, Ericsson, HP, Huawei, IBM, Intel, Juniper, Nokia, NTT, Qualcomm, Radisys, Redhat, Samsung.

Community Name: EdgeX Foundry
Started in: 2018
Description: EdgeX Foundry is an open source project that is building a common open platform for IoT edge computing. The interoperable platform enables an ecosystem of plug-and-play components that unifies the marketplace and accelerates the deployment of IoT solutions across a wide variety of industrial and enterprise use cases.
Key Drivers: Analog Devices, Dell EMC and Samsung.

Community Name: Project EVE
Started in: 2018
Description: Project EVE (Edge Virtualization Engine) provides a cloud-native based virtualization engine for developing and deploying containers for industrial edge computers. Project EVE is based on Zededa's EVx edge virtualization engine, which currently runs on edge hardware from partners including Advantech, Lanner, SuperMicro, and Scalys.
Key Drivers: Zededa.

Community Name: StarlingX
Started in: 2018
Description: StarlingX is a complete cloud infrastructure software stack for the edge used by the most demanding applications in industrial IOT, telecom, video delivery and other ultra-low latency use cases. It is supported by the Openstack Foundation.
Key Drivers: Intel and Windriver.

Community Name: ioFog
Started in: 2018
Description: ioFog makes it simple to deploy and manage any application or containerized microservices at the edge. ioFog allows users to "bring their own edge" by enabling any device or hardware to become a secure software platform.
Key Drivers: Edgeworx

Community Name: openVolcano
Started in: 2017
Description: The openVolcano platform aims at supporting mobile edge and fog computing services in 5G-ready infrastructures. It is part of Europe's 2020 5G-PPP projects. OpenVolcano platform provides in-network programmability capabilities for off-loading, virtualization and monitoring of services in a fog environment.
Key Drivers: European Commission and European ICT industry (ICT manufacturers, telecommunications operators, service providers, SMEs and researcher Institutions). Horizon 2020 & 5G-PPP members (https://5g-ppp.eu).

In addition to the above open source communities for MEC, existing open source communities focusing on network virtualization such as OpenStack, M-CORD, OpenShift, ONAP and OPNFV are also competing to solve the MEC deployment, management and orchestration challenges.

Review Questions

1. Who are the leading vendors developing 5G related networking equipment and software?

2. What are the various open source communities contributing to 5G efforts?

3. How can the service providers monetise their investments on 5G technology?

4. Can 5G technology replace WiFi?

5. Is 5G harmful? Does 5G radiation introduce new health hazards?

6. What are the standard bodies that deal with standardization of 5G technology?

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