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The Evolution of Wireless Mobile Communication from Pre-Cellular to 6G and the Effects of the Digital Divide and Digitization in Nigeria

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Abstract: Wireless technology is undergoing rapid evolution. Since the inception of radio telephony in the pre-cellular generation, the evolution of mobile communication has experienced exponential growth. This paper provides an overview of the evolution of mobile communication from the pre-cellular generation to the fifth generation (5G), including the history, technical features, capabilities, application areas, modulation techniques, and network architectures. Furthermore, it examines emerging technologies in the sixth generation (6G), its concepts, requirements, features, benefits, research challenges, and transformative potential. The paper also contributes significantly to discussions on the digital divide, using Nigeria as a case study, including the causes, impacts, and ways of bridging the gap, as well as the effects of digitization and improved connectivity and the impacts of emerging solutions.

Keywords: *1G, 2G, 3 G, 4G, 5G, 6G and Digital Divide.*

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I. INTRODUCTION

Wireless technology has undergone a remarkable evolution, fundamentally transforming global communication and information access. The journey from the first generation (1G) of mobile networks to the current fifth-generation (5G) and the anticipated sixth generation (6G) reflects significant technological advancements and societal impacts [1]. The evolution began with 1G in the late 1970s, introducing analog voice communication. This was succeeded by 2G in the early 1990s, which transitioned to digital voice and enabled basic data services like SMS [2]. The early 2000s saw the advent of 3G, offering enhanced data rates that facilitated mobile internet access [3]. The subsequent deployment of 4G networks provided high-speed internet, supporting a wide range of applications from streaming services to real-time gaming [4]. Currently, 5G technology is being rolled out globally, promising unprecedented data speeds, ultra-low latency, and massive connectivity, thereby enabling innovations such as the Internet of Things (IoT) and autonomous vehicles [5].

Each generation of wireless technology has introduced new capabilities and addressed the limitations of its predecessors [5] [6]. For instance, 5G not only aims to deliver higher data rates but also focuses on improving spectral efficiency, network reliability, and energy consumption. These enhancements are crucial for supporting the growing number of connected devices and the increasing demand for data-intensive applications [5] [6]. Further, the development of Wi-Fi technology has paralleled the evolution of cellular networks, playing a pivotal role in providing wireless internet access in local areas [7]. Since the introduction of the IEEE 802.11 standard, commercially known as Wi-Fi, there has been a significant expansion in its adoption, connecting billions of devices worldwide and enabling a multitude of applications [8].

Looking ahead, the research community is actively exploring the potential of 6G networks. The vision for 6G encompasses not only enhanced communication capabilities but also the seamless integration of the physical and digital worlds [9] [10]. Key technologies under consideration include terahertz communication, artificial intelligence integration, and reconfigurable intelligent surfaces, all aimed at creating a more connected and intelligent environment [10] [11]. The evolution of wireless technology from 1G to 5G and the ongoing research into 6G highlights a trajectory of continuous innovation [114]. Each generation has expanded the possibilities of wireless communication, contributing to the development of a more interconnected and technologically advanced society [114].

II. PRE-CELLULAR GENERATION

The military began using radio-telephony links during the Second World War (1939 to 1945). This radio-telephony was known as hand-held transceivers or walkie-talkies. Hand-held transceivers were developed by radio engineers, including Donald Hings, Alfred J. Gross, and Henryk Magnuski, as well as an engineering team from Galvin Manufacturing Company (now known as Motorola), which included Marion Bond, Lloyd Morris, Bill Vogel, and Dan Noble [12][13]. The device comprises a speaker at one end, a microphone at the other end, and an antenna mounted on top [13]. The transceiver is typically a half-duplex communication device, allowing communication between users, but not simultaneously [13]. The device worked on the principle of push-to-talk, with the default mode of the transceiver set to listen [13].

Wireless mobile communication became predominant after the Second World War; engineers from US-based Bell Labs started researching automobile systems to enable mobile users to transmit and receive telephone calls [14]. The design of the system was successfully achieved, and mobile users began using the service on June 17, 1946 [14]. Further research by AT&T in 1946 led to the advent of pre-cellular, with the development of Mobile Telephone Service (MTS) on October 2, 1946 [14]. The system included a mobile operator, the caller, and the receiver [14]. When a call was made, the call would be routed to a mobile operator, and the mobile operator would then route the call to the receiver [14].

The Pre-Cellular Generation used the frequency modulation (FM) technique to transfer signals, varying the frequency of the carrier wave according to the input voice signal [13].

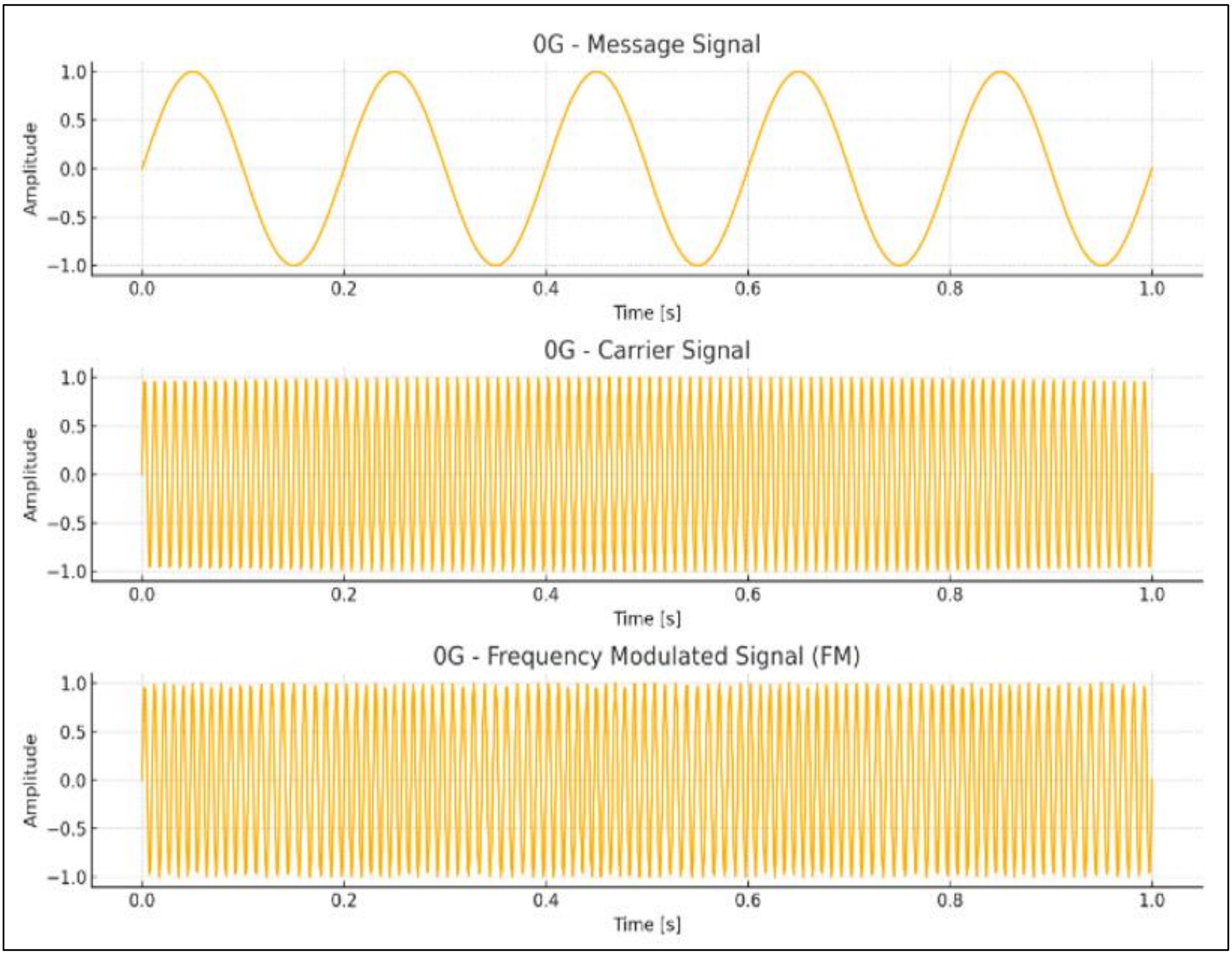


Fig 1 Modulation Technique in Pre-Cellular Generation

The transmitter and receiver in the designed walkie-talkie utilized the FM band of 40.0 to 48.0 megacycles, divided into 200 MHz segments, in order to yield a total of 41 channels [13]. The device covers an operational distance of three miles, with the appropriate noise-canceling circuits to facilitate clear reception [13].

The MTS used Very High Frequency (VHF - 30 to 300 MHz) radio systems linked to the public switched telephone network (PSTN) [14]. MTS used 25 VHF radio channels in the U.S. and Canada, as shown in the table below. The transmitting and receiving frequencies among the channels were very close, leading to network congestion and interference [14].

Table 1 MTS Frequency Band

12-Channel Mobile	**ID**	**24-Channel Mobile**	**Base Station (MHz)**	
			Transmit	**Receive**
	JJ		152.480	157.740
	XJ	1	152.495	157.755
1	JL	2	152.510	157.770
	XK	3	152.525	157.785
2	YL	4	152.540	157.800
	XL	5	152.555	157.815
3	JP	6	152.570	157.830
	XP	7	152.585	157.845
4	YP	8	152.600	157.860
	XR	9	152.615	157.875
5	YJ	10	152.630	157.890
	XS	11	152.645	157.905
6	YK	12	152.660	157.920
	XT	13	152.675	157.935
7	JS	14	152.690	157.950
	XU	15	152.705	157.965
8	YS	16	152.720	157.980
	XV	17	152.735	157.995
9	YR	18	152.750	158.010
	XW	19	152.765	158.025
10	JK	20	152.780	158.040
	XX	21	152.795	158.055
11	JR	22	152.810	158.070
	XY	23	152.825	158.085
12	JW	24	152.840	158.100

Subsequently, AT&T introduced the Improved Mobile Telephone System (IMTS) in 1964, which used VHF and Ultra High Frequency (UHF - 300 MHz to 3 GHz) [14]. IMTS used 10 low VHF radio channels, 13 high VHF radio channels, and 12 UHF radio channels, as shown in the table below [14].

Table 2 IMTS Frequency Band [14]

Channel	**Base frequency**	**Mobile frequency**
VHF Low Band		
ZO	35.26	43.26
ZF	35.30	43.30
ZH	35.34	43.34
ZM	35.38	43.38
ZA	35.42	43.32
ZY	36.46	43.46
ZR	35.50	43.50
ZB	35.54	43.54
ZW	35.62	43.62
ZL	35.66	43.66
VHF High Band		
JJ	152.48	157,74
JL	152.51	157.77
YL	152.54	157.80
JP	152.57	157.83
YP	152.60	157.86
YJ	152.63	157.89
YK	152.66	157.92

JS	152.69	157.95
YS	152.72	157.98
YR	152.75	158.01
JK	152.78	158.04
UHF Band		
QC	454.375	459.375
QJ	454.375	459.375
QD	454.425	459.425
QA	459.450	459.450
QE	454.475	459.475
QK	454.525	459.525
QB	454.550	459.55
QO	454.575	459.575
QR	454.6	459.6
QY	454.625	459.625
QF	454.65	459.65

IMTS had 25 watts of transmit power at the mobile station and 100-250 watts at the terminal, with base station sites covering an area of 40-60 miles in diameter due to high antenna placement at around 100-500 feet [14]. IMTS was typically a full-duplex communication device, enabling simultaneous communication between users. The device comprised a dialing keyboard and a telephone handset connected to a separate large radio transceiver chassis with a 0.5-inch multi-colored conductor cable [14]. The transceiver was placed about 1.6 feet high in the trunk or under the seat of an automobile [14]. However, new users were required to wait for up to three years before getting an IMTS because existing customers needed to disconnect subscriptions before new users could get a mobile telephone number. This resulted in low sales and production quality and high costs for intended users [14]. This limitation on IMTS drove the development of cellular networks, which started with 1G as the next generation of wireless evolution [14].

III. FIRST GENERATION

First Generation technology originated in Japan in 1979 as the first cellular network. Nippon Telegraph and Telephone (NTT) introduced the technology as an analog cellular system for car phones [15]. The technology was later released in Sweden (September 1981) by Comvik and in other Nordic countries (October 1981) by Nordic Mobile Telephone (NMT), supporting international roaming [15]. Further research by Bell Labs and Motorola introduced the Advanced Mobile Phone System (AMPS) in North America on October 13, 1983 [16], in Israel in 1986, in Australia in 1986, in Singapore in 1987, and in Argentina in 1989[17]. John F. Mitchell, Motorola's Chief Operating Officer, and Martin Cooper, the pioneer of the wireless communication industry and the inventor of the mobile phone, conducted this research [18]. AMPS in the First Generation is similar to the IMTS in the Pre-Cellular Generation as AMPS also used the frequency modulation (FM) technique to transfer signals, varying the frequency of the carrier wave according to the input voice signal at a peak derivative of 12kHz [19]. However, the transmitting and receiving frequencies among the channels needed considerable bandwidth for a large number of users to minimize network congestion and interference [19]. The call center was able to flexibly assign channels to handsets based on signal strength, allowing the reuse of a particular frequency [20].

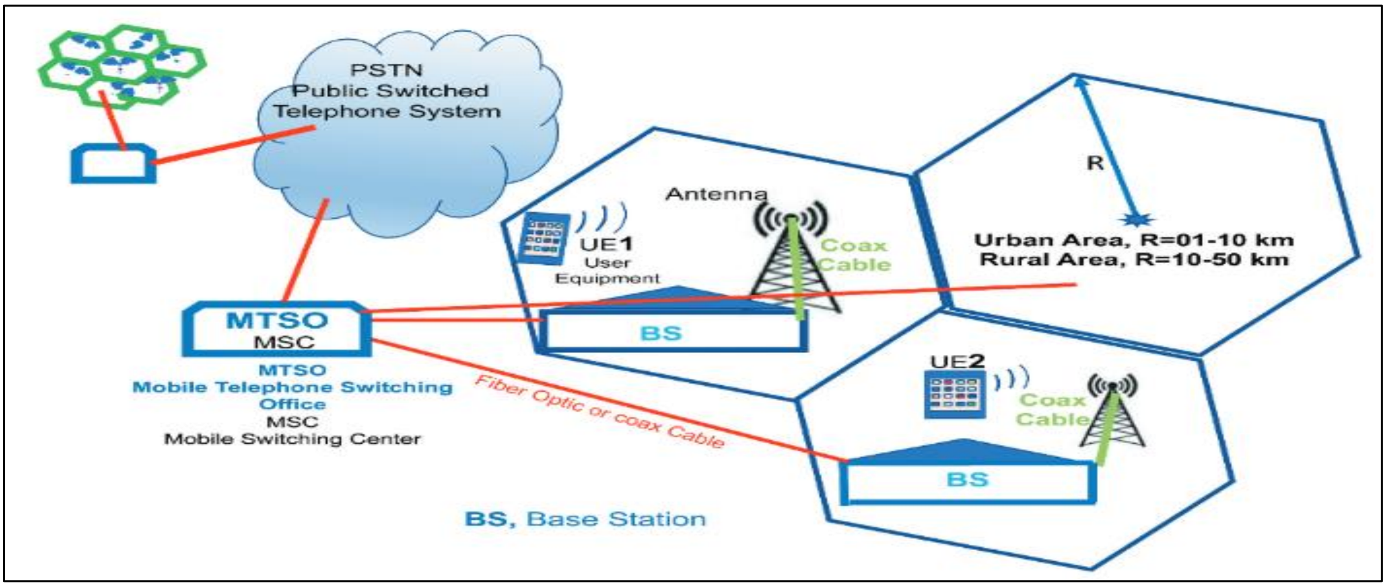


Fig 2 1G AMPS Network Architecture [21]

- *Modulation Techniques*

Modulation techniques are used to directly vary the characteristics of carrier signals with message signals [22]. The techniques are divided into analog and digital modulation, as indicated in Fig 1. Pre-cellular Generation and First Generation are analog systems utilizing analog modulation. Analog Modulation is further divided into Amplitude Modulation, Frequency Modulation (FM), and Phase Modulation. These generations specifically utilize Frequency Modulation techniques [22].

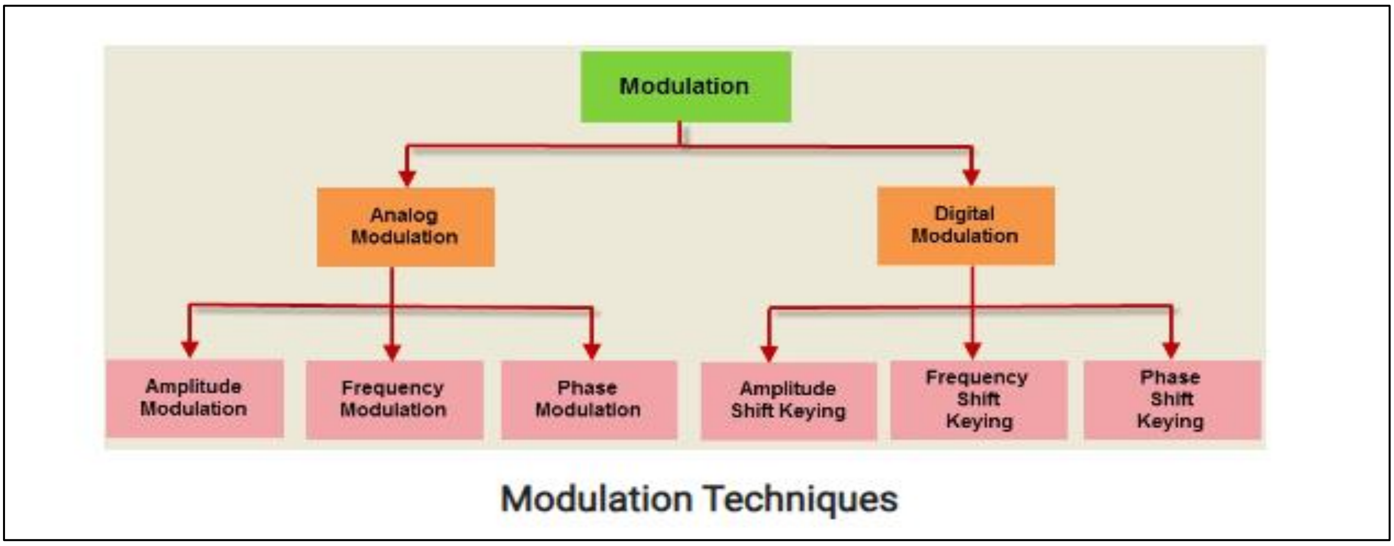


Fig 3 Modulation Techniques [22]

Frequency modulation is the process of encoding information in a carrier wave by changing the instantaneous frequency of the wave [19]. Analog FM deals with the modulation of audio signals, such as voice or music, in radio broadcasting [23]. Analog FM possesses an instantaneous frequency deviation, implying that the difference between the frequency of the carrier and the center frequency has a functional relation to the modulating signal amplitude [23], as indicated in Fig. 3 and Fig. 4. Digital Modulation is employed in subsequent technologies from second to the sixth generations of mobile networks.

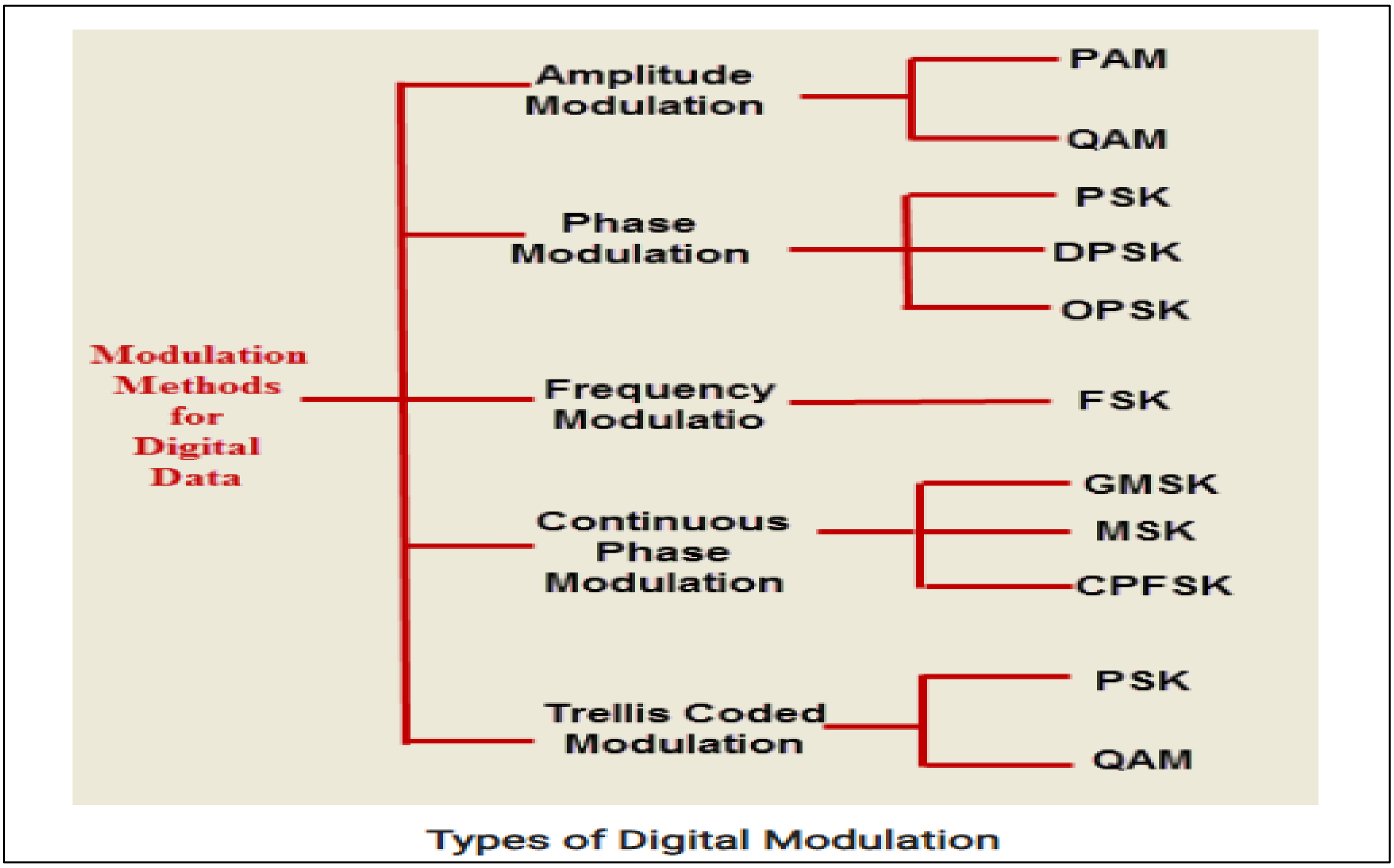


Fig 4 Types of Digital Modulation [22]

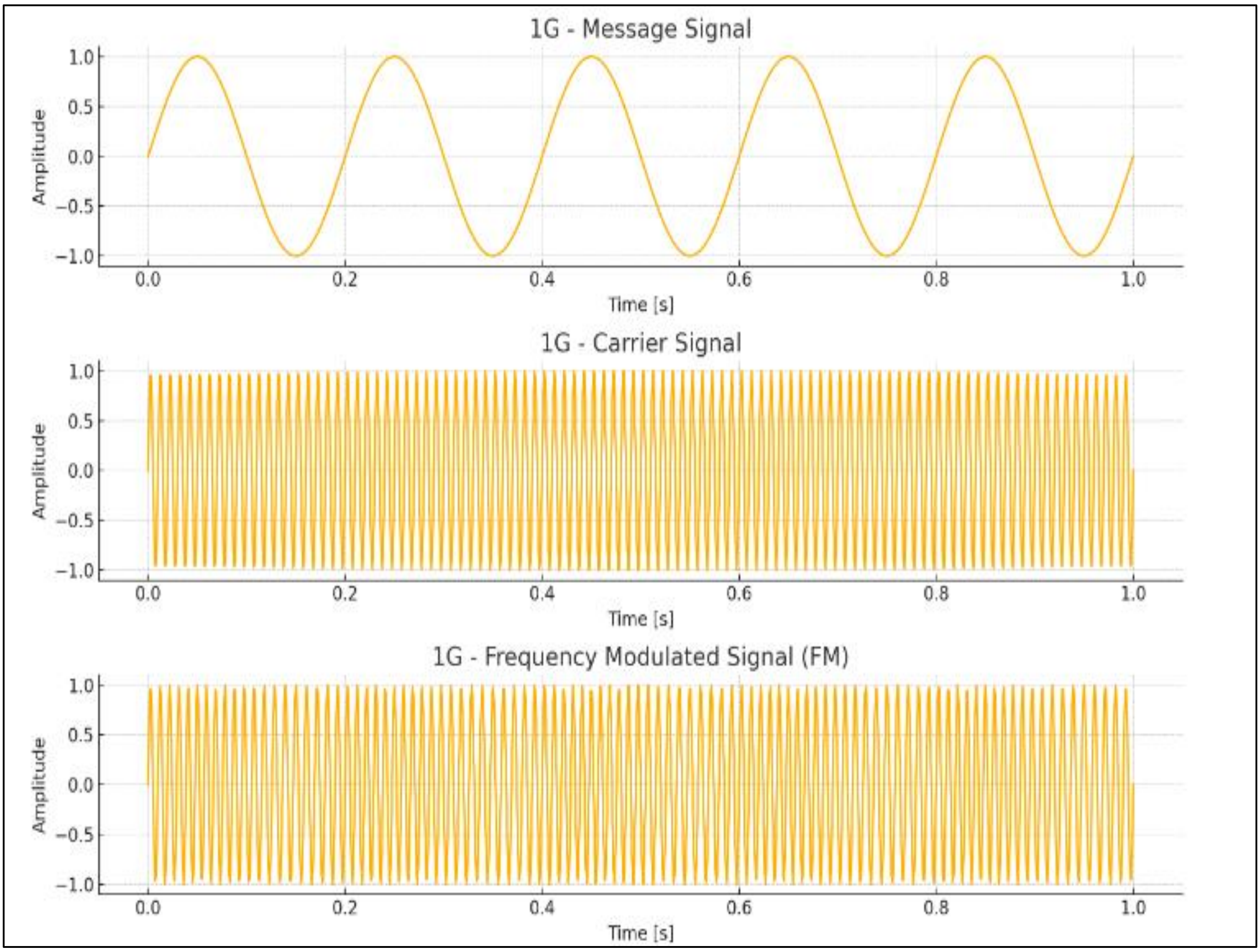


Fig 5 Modulation Technique in First Generation

The AMPS initially operated in the 850 MHz Cellular frequency band [20]. Cellular frequency bands are frequency ranges within the UHF assigned for cellular network purposes such as mobile phones [24]. In 1989, the U.S. Federal Communication Commission granted 832 channels for AMPS, with 416 channel pairs. Each of the duplex channels consisted of two different frequencies: the first 416 channels were 824 and 849 MHz, while the other channels were 869 and 894 MHz [25]. Just like IMTS, an improvement on AMPS was proposed in 1991 by Bells, called narrowband AMPS (NAMPS or N-AMPS) [26] [27]. AMPS suffered several limitations, such as static and noise and a lack of protection from 'eavesdropping' by a scanner or an older TV [20] [28]. Limitations occurred because the system was analog-based, which led to the development of Second-Generation technology as a digital cellular network [27].

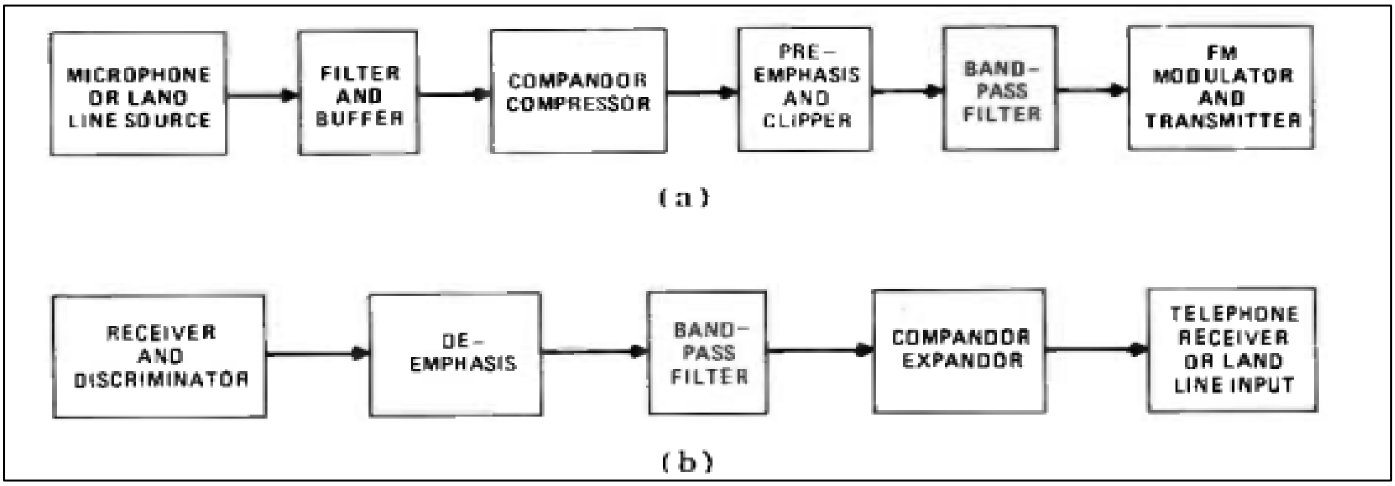


Fig 6 AMPS Audio Processor (a) Transmit Processor (b) Receive Processor [20]

IV. SECOND GENERATION

Digital Cellular was launched in 1991 as a second-generation technology. The development of second-generation technology was pioneered by Radiolinja, a Finnish telecommunications company [29]. This technology operated on the Global System for Mobile Communications (GSM), a standard developed by the European Telecommunications Standards Institute (ETSI) [30]. The system includes GSM900, operating mainly in the 900 MHz frequency band, with an uplink frequency of 880-890 MHz and a downlink frequency of 925-935 MHz during Phase 2 deployment (Phase 1 deployment used an uplink frequency of 890-915 MHz and a downlink frequency of 935-960 MHz) [31]. In the UK, a version of GSM called the Digital Cellular System (DCS1800) was launched, operating mainly at 1800 MHz, with an uplink frequency of 1710-1785 MHz and a downlink frequency of 1805-1880 MHz and a guard band/channel bandwidth of 200 kHz [31].

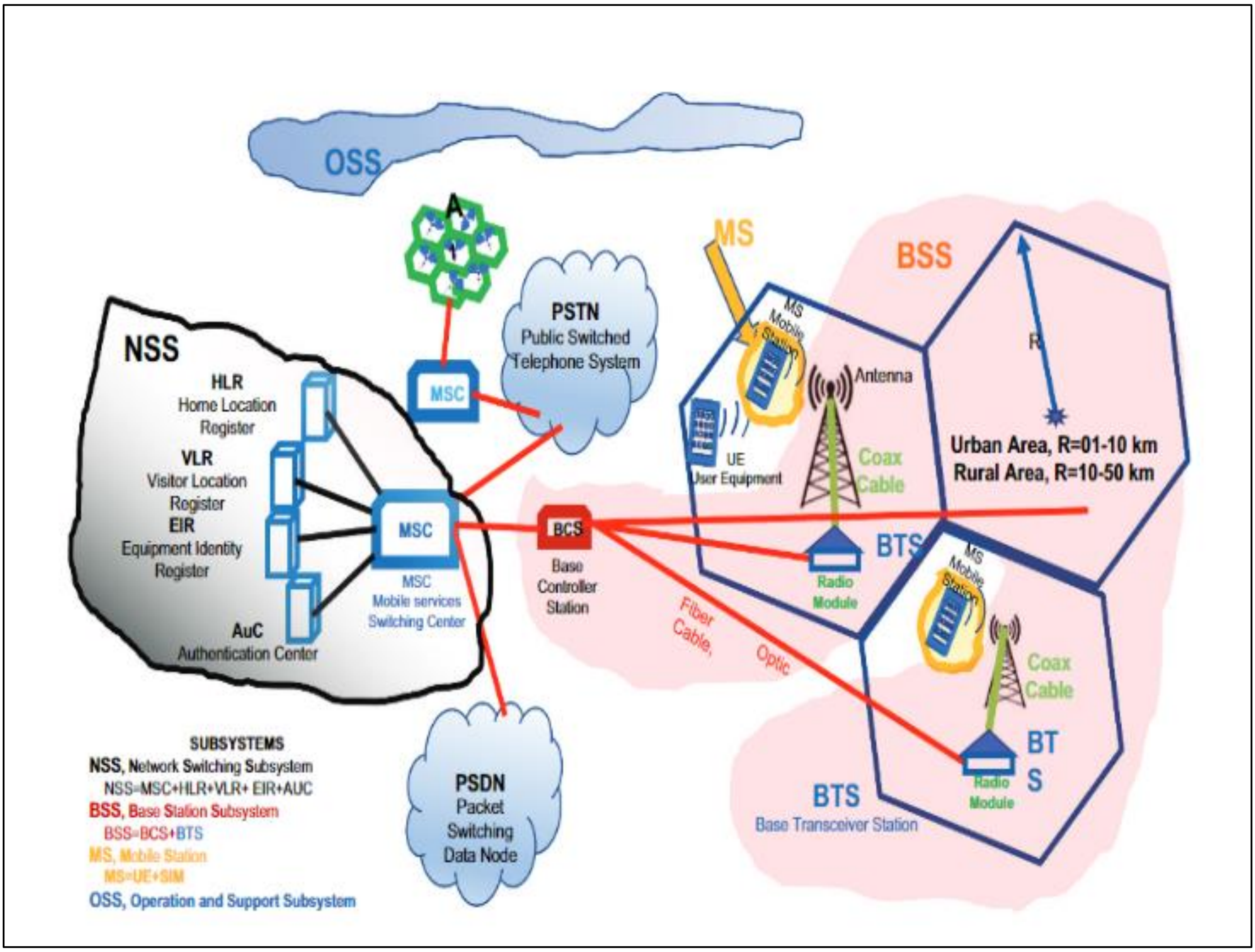


Fig 7 2G GSM Network Architecture [21]

In 1993, Bell Labs upgraded AMPS and N-AMPS to a second-generation digital version called Digital AMPS (D-AMPS – Interim Standard [IS]-54 and IS-136) [30][32]. GSM and D-AMPS technologies use TDMA signaling over Frequency Division Duplex Carriers [30][32]. D-AMPS operates mainly in the 800 MHz and 900 MHz frequency bands, with a 30 kHz channel bandwidth further divided into three TDMA channels, tripling the number of calls and channels available [29][33]. Further research by Qualcomm introduced cdmaOne (IS-95) in 1995, utilizing Code Division Multiple Access (CDMA) signaling over Frequency Division Duplex Carriers, allowing the sharing of the same frequencies across several radio networks [31]. cdmaOne offered increased network capacity, as the 30 kHz channel bandwidth in AMPS carriers was replaced with one or more 1.25 MHz cdmaOne carrier spacings and 45 MHz duplex separation [31]. cdmaOne transfers user data at bit rates of up to 9.6 kb/s for IS-95 and 14.4 kb/s for CDMA-PCS (an improved version of IS-95) [31].

The modulation technique behind 2G, particularly GSM technologies, was Gaussian Minimum Shift Keying (GMSK) modulation, a variant of Phase Shift Keying (PSK) [34]. Phase Shift Keying (PSK) is the process of encoding information in a carrier wave by changing the phase of the wave [22]. In GMSK, a Gaussian filter of appropriate bandwidth is used before the phase of the carrier wave is varied by the message signal [35].

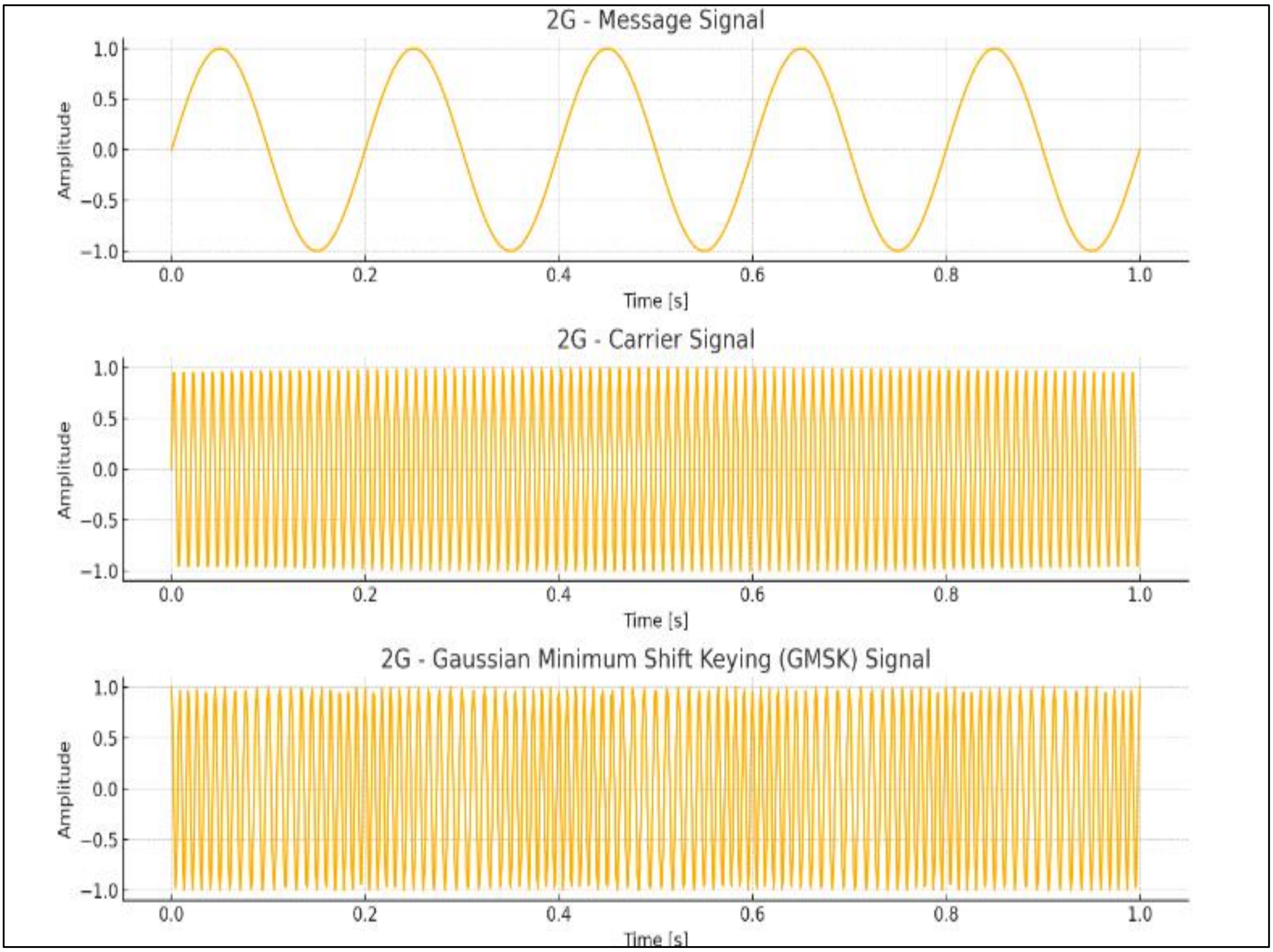


Fig 8 Modulation Technique in Second Generation

- *Stages of Second Generation*

- *G – High-Speed Circuit Switched Data (HSCSD)*

The technology uses four channels connected in a circuit-switched connection. Phone conversations are digitally encrypted between mobile phones and base stations [34]. This stage supports Short Message Service (SMS) text messages and Multimedia Messaging Services (MMS) [31] [34]. HSCSD technology allows for symmetric transmissions, where the same number of uplink and downlink timeslots are used, or asymmetric transmissions, where more timeslots are allocated in one direction. However, only downlink-biased asymmetry is permitted, and the number of uplink timeslots must be a subset of the downlink timeslots [31].

- *G -- General Packet Radio Service (GPRS)*

This stage added packet-switched connection to circuit-switched functions, allowing data connections for web browsing, Push-to-Talk over Cellular, SMS messaging and broadcasting, MMS, instant messaging, internet applications for smart devices through Wireless Application Protocol (WAP), Point-to-Point (P2P) service for inter-networking with the Internet Protocol (IP), and Point-to-Multipoint (P2M) service for point-to-multipoint multicast and point-to-multipoint group calls. The system supports Internet Protocols (IP) and Point-to-Point Protocols (PPP) [31]. GPRS operates on one or more frequencies within 850 MHz, 900 MHz, 1800 MHz, and 1900 MHz, with a maximum capability of 14 kbit/s uplink speed and 40 kbit/s downlink speed [34] [36]. User Equipment was also classified based on speed capabilities: Class A simultaneously supports GSM and GPRS connections; in Class B, the GPRS connection is interrupted during a GSM call and automatically resumes at the end of the call; and Class C allows manual switching between GSM and GPRS modes [34].

Table 3 GPRS Modulation Scheme [34] [113]

GPRS Coding Scheme (CS)	**Modulation**	**Code Rate**
CS-1	GMSK	1/2
CS-2	GMSK	~2/3
CS-3	GMSK	~3/4
CS-4	GMSK	1

- *5G -- Enhanced Data rates for Global Evolution (EDGE)*

In 2003, Cingular and AT&T deployed EDGE with a higher and faster bit rate in each radio channel for data transmission [37]. EDGE supports up to 236.8 kbit/s in data transfer rate and end-to-end latency below 150 ms for four timeslots in packet mode [36] [38]. The technology supports every function in 2G and 2.5G [34] [31]. To cater to increased noise sensitivity in marginal coverage areas, EDGE added 8PSK to the GMSK modulation technique, resulting in an enhancement in bit rate of up to threefold in capacity and performance of GSM under all radio conditions [31] [34]. EDGE was standardized by the 3rd Generation Partnership Project (3GPP) [34].

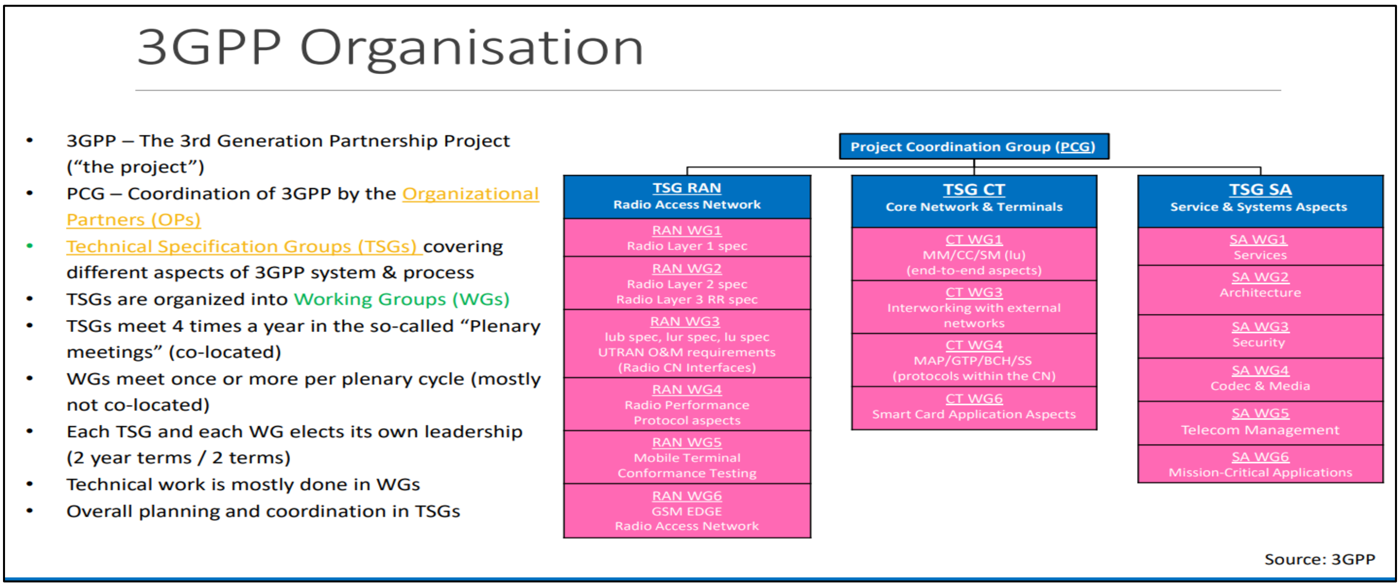
Table 4 Edge Modulation Scheme [34] [113]

EDGE Modulation and Coding Scheme (MCS)	Code rate (Note 1)	Header Code rate	PAN Code rate (if present)	Modulation	Data rate kb/s (Note 2)
MCS-9	1,0	0,36	n/a	8PSK	59,2
MCS-8	0,92 (0,98)	0,36	0,42		54,4
MCS-7	0,76 (0,81)	0,36	0,42		44,8
MCS-6	0,49 (0,52)	1/3	0,39		29,6 27,2
MCS-5	0,37 (0,40)	1/3	0,39		22,4
MCS-4	1,0	0,53	n/a	GMSK	17,6
MCS-3	0,85 (0,96)	0,53	0,63		14,8 13,6
MCS-2	0,66 (0,75)	0,53	0,63		11,2
MCS-1	0,53 (0,60)	0,53	0,63		8,8

Note 1: The number in bracket indicates the coding rate for transmission using FANR (Fast Ack/Nack Reporting), when the PAN (Piggy-backed Ack/Nack) is present.
MSC- Modulation and Coding Scheme.
Note 2: These data rates are applicable for BTTI (Basic Transmission Time Interval) configuration. The data rates are doubled in case of RTTI (Reduced Transmission Time Interval) configuration.

V. THIRD GENERATION PARTNERSHIP PROJECT (3GPP)

In 1998, seven telecommunications standard development organizational partners (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, and TTC) collaborated to form the 3rd Generation Partnership Project (3GPP) [39]. 3GPP is responsible for the development and standardization of mobile communication technologies of 3G to 5G networks as well as next-generation 6G technologies [39]. The main technical specifications include Radio Access Networks (RAN), Services and systems Aspects (SA), Core Networks, and terminals (CT) [39].



3GPP Organisation

- 3GPP – The 3rd Generation Partnership Project ("the project")
- PCG – Coordination of 3GPP by the Organizational Partners (OPs)
- Technical Specification Groups (TSGs) covering different aspects of 3GPP system & process
- TSGs are organized into Working Groups (WGs)
- TSGs meet 4 times a year in the so-called "Plenary meetings" (co-located)
- WGs meet once or more per plenary cycle (mostly not co-located)
- Each TSG and each WG elects its own leadership (2 year terms / 2 terms)
- Technical work is mostly done in WGs
- Overall planning and coordination in TSGs

Project Coordination Group (PCG)

TSG RAN
Radio Access Network
RAN WG1
Radio Layer 1 spec
RAN WG2
Radio Layer 2 spec
Radio Layer 3 RR spec
RAN WG3
Iub spec, Iur spec, Iu spec
UTRAN O&M requirements
(Radio CN Interfaces)
RAN WG4
Radio Performance
Protocol aspects
RAN WG5
Mobile Terminal
Conformance Testing
RAN WG6
GSM EDGE
Radio Access Network

TSG CT
Core Network & Terminals
CT WG1
MM/CC/SM (Iu)
(end-to-end aspects)
CT WG3
Interworking with external networks
CT WG4
MAP/GTP/BCH/SS
(protocols within the CN)
CT WG6
Smart Card Application Aspects

TSG SA
Service & Systems Aspects
SA WG1
Services
SA WG2
Architecture
SA WG3
Security
SA WG4
Codec & Media
SA WG5
Telecom Management
SA WG6
Mission-Critical Applications

Source: 3GPP

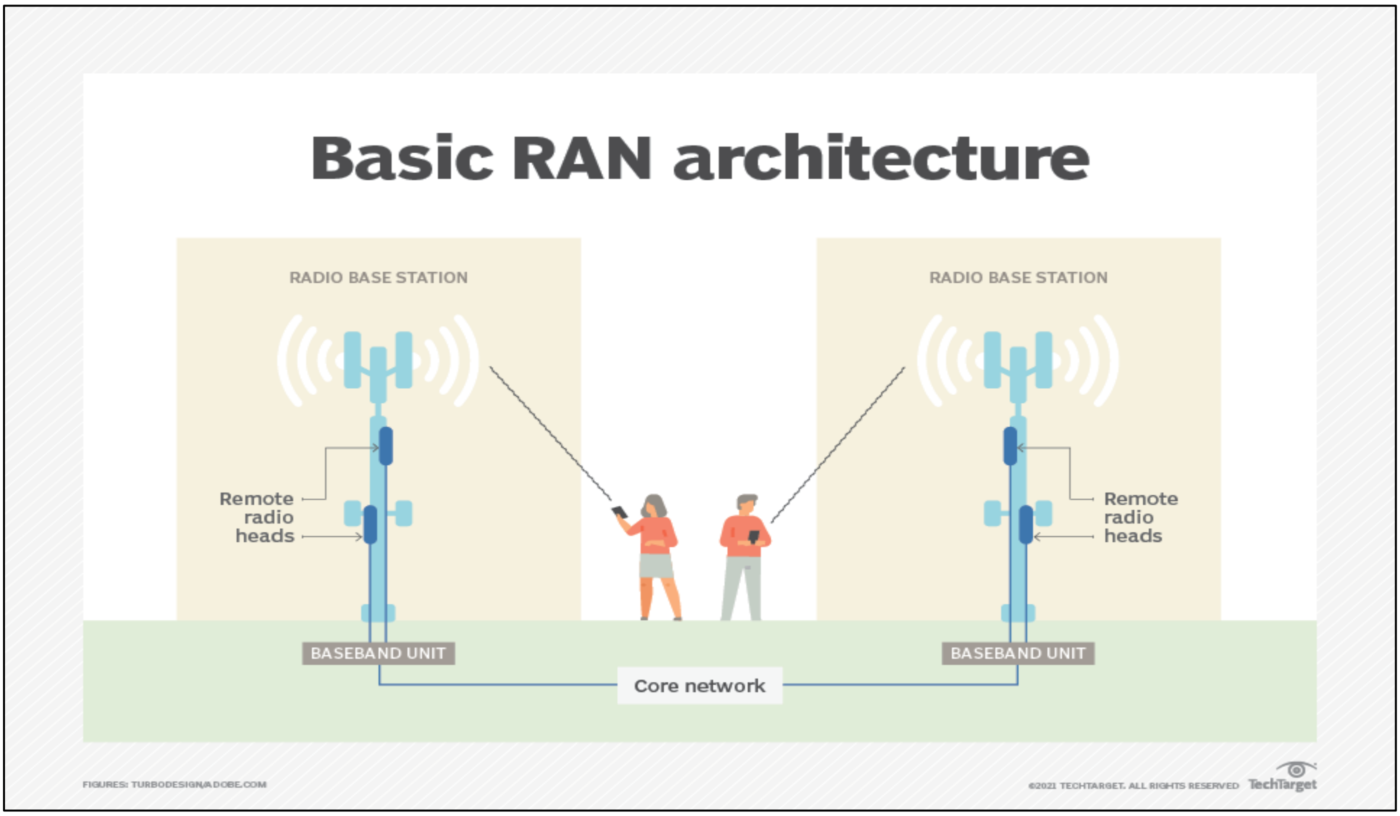
Fig 9 3GPP Organization

- *Radio Access Network (RAN):*

RAN uses a radio link to connect devices over a fiber or wireless backhaul connection [40]. Components of RAN include base stations and antennas that cover a particular area based on capacity [40]. The antenna converts electrical signals to radio waves, while the base station contains radios that digitally transform information for wireless transmission, ensuring correct frequency bands and power levels are used [40]. The base station also includes the Base Band Unit (BBU), which processes signals based on licensed or unlicensed radio spectrum, aiding proper wireless communication [40].

Types of RAN include GSMRAN (GRAN) developed for 2G, GSM EDGE RAN, or GERAN, which includes Enhanced Data GSM Environment packet radio services, Universal Mobile Telecommunications System (UMTS) Terrestrial RAN, or UTRAN, developed for 3G, and Evolved Universal Terrestrial RAN, or E-UTRAN, developed for LTE, and Next Generation RAN, or NG-RAN for 5G[40].

Recent trends in RAN include Open RAN, which involves developing interoperable open hardware, software, and interfaces for cellular wireless networks that use white box servers and other standard equipment rather than the custom-made hardware typically used in base stations [40]. Cloud-RAN involves separating the radio elements in a base station into remote radio heads (RRHs) used on cell towers for efficient radio coverage [40]. Artificial Intelligence (AI)-RAN utilizes AI algorithms trained to govern most networking processes, from the physical layer to radio resource management (RRM) [41]. The radio link in RAN connects to the core network to manage subscriber information, location, and other functions [40].



FIGURES: TURBODESIGN/ADOBE.COM

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Fig 10 Basic RAN Architecture [40]

- *Service and System Aspect*

Service and System Aspects refer to the different elements and considerations involved in the development, deployment, and management of a software system or application [42]. This aspect considers architectural design, performance, scalability, reliability, security, and maintainability [42].

- *Core Network Terminals*

A Core Network is the central part of a network, performing critical operations such as authentication, policy enforcement, billing, and data routing for customers connected to the RAN [43]. The terminals provide a path for exchanging information between LANs, WANs, and other subnetworks [43] [44].

VI. THIRD GENERATION

The third generation (3G) technology represents a pivotal milestone in the evolution of mobile communication, bridging the gap between basic voice services and comprehensive multimedia capabilities [3] [45]. Following the development of first- and second-generation systems, 3G was conceived to provide significantly higher data transmission rates, enabling the proliferation of mobile internet and data-driven services [46] [47]. The formal introduction of 3G technology occurred in the early 2000s under the International Telecommunication Union's (ITU) IMT-2000 initiative [48]. This global framework aimed to standardize mobile communication protocols and ensure interoperability across regions [45] [48]. Japan played a key role in the early deployment of 3G, with

NTT DoCoMo launching the first commercial 3G network in 2001 based on Wideband Code Division Multiple Access (WCDMA) [1] [46]. Following this, countries like South Korea and several European nations swiftly adopted the technology [3] [48].

One of the defining features of 3G was its use of packet-switched data transmission, a departure from the circuit-switched systems of previous generations [45] [47]. This innovation allowed simultaneous voice and data communication, paving the way for applications such as video conferencing, web browsing, and multimedia messaging [3] [47]. The theoretical data rates for 3G ranged from 384 kbps for mobile environments to up to 2 Mbps for stationary users, facilitating streaming and other bandwidth-intensive activities [46] [49]. Technologically, 3G networks employ the Universal Mobile Telecommunications System (UMTS) architecture built on WCDMA [48] [49]. This architecture was designed to enhance spectral efficiency, support more users per cell, and provide robust coverage [46] [49]. Core components of the 3G system included the Radio Access Network (RAN), Core Network, and User Equipment (UE) [1] [47]. The RAN managed the wireless communication link, while the Core Network ensured seamless service delivery and mobility management [3] [47].

The adoption of 3G marked the beginning of a mobile internet revolution [46]. Social media platforms, mobile applications, and real-time communication tools flourished, reshaping the way individuals and businesses interacted globally [1] [49]. However, despite its widespread success, 3G faced limitations in meeting the exponential growth of data demands, leading to the development of fourth-generation (4G) systems [47].

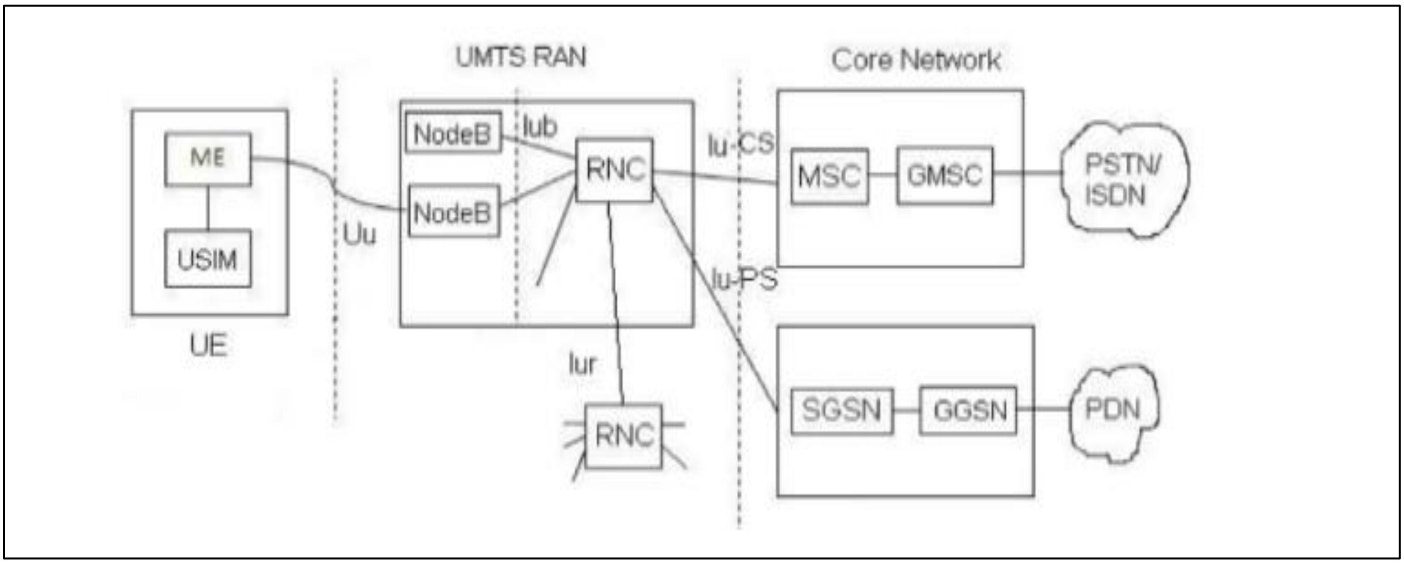

Fig 11 The Universal Mobile Telecommunications System (UMTS) architecture [50]

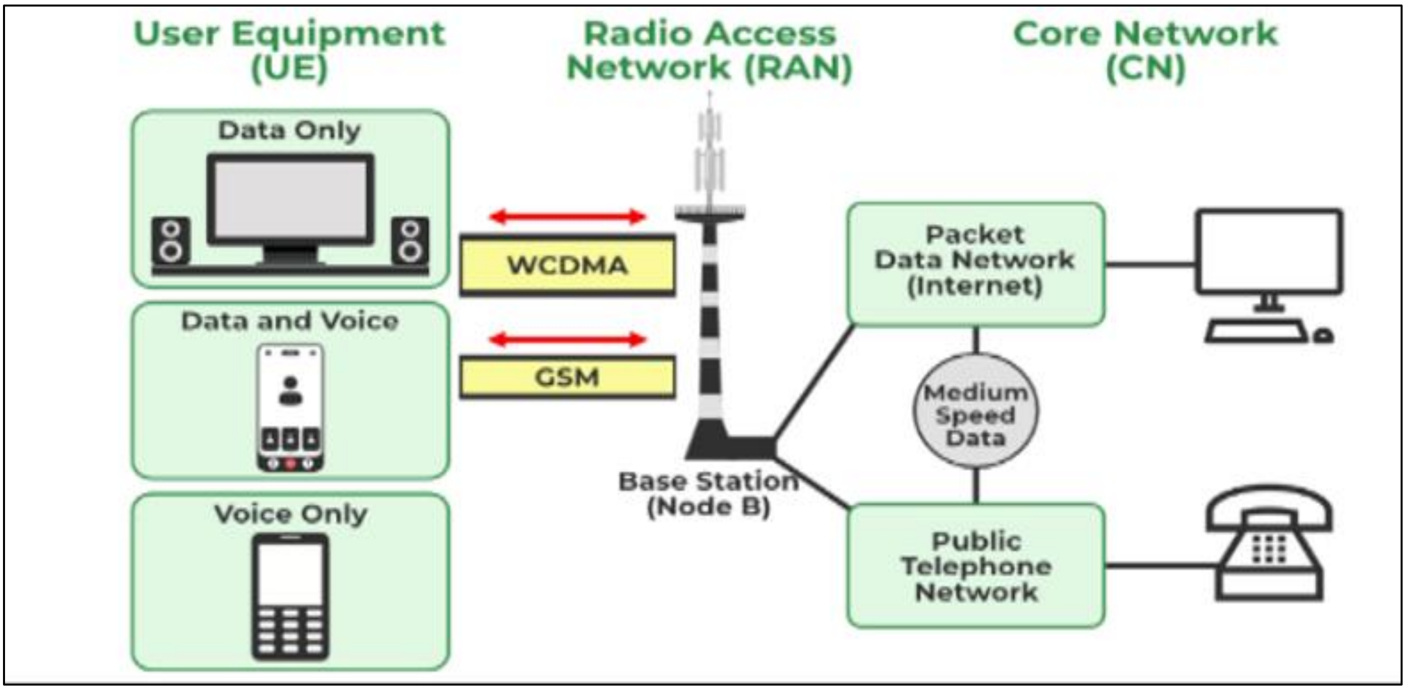

Fig 12 The Wideband Code Division Multiple Access (WCDMA) [51]

The modulation technique behind 3G, particularly UMTS technologies, was Quadratic Phase Shift Keying (QPSK) modulation, another variant of Phase Shift Keying (PSK) [38] [52]. In QPSK, the carrier wave is modulated by two bits simultaneously while selecting one of the four possible carrier phase shifts. The modulation technique allows the signal to transmit twice as much information as ordinary PSK 'or BPSK' using the same bandwidth [52].

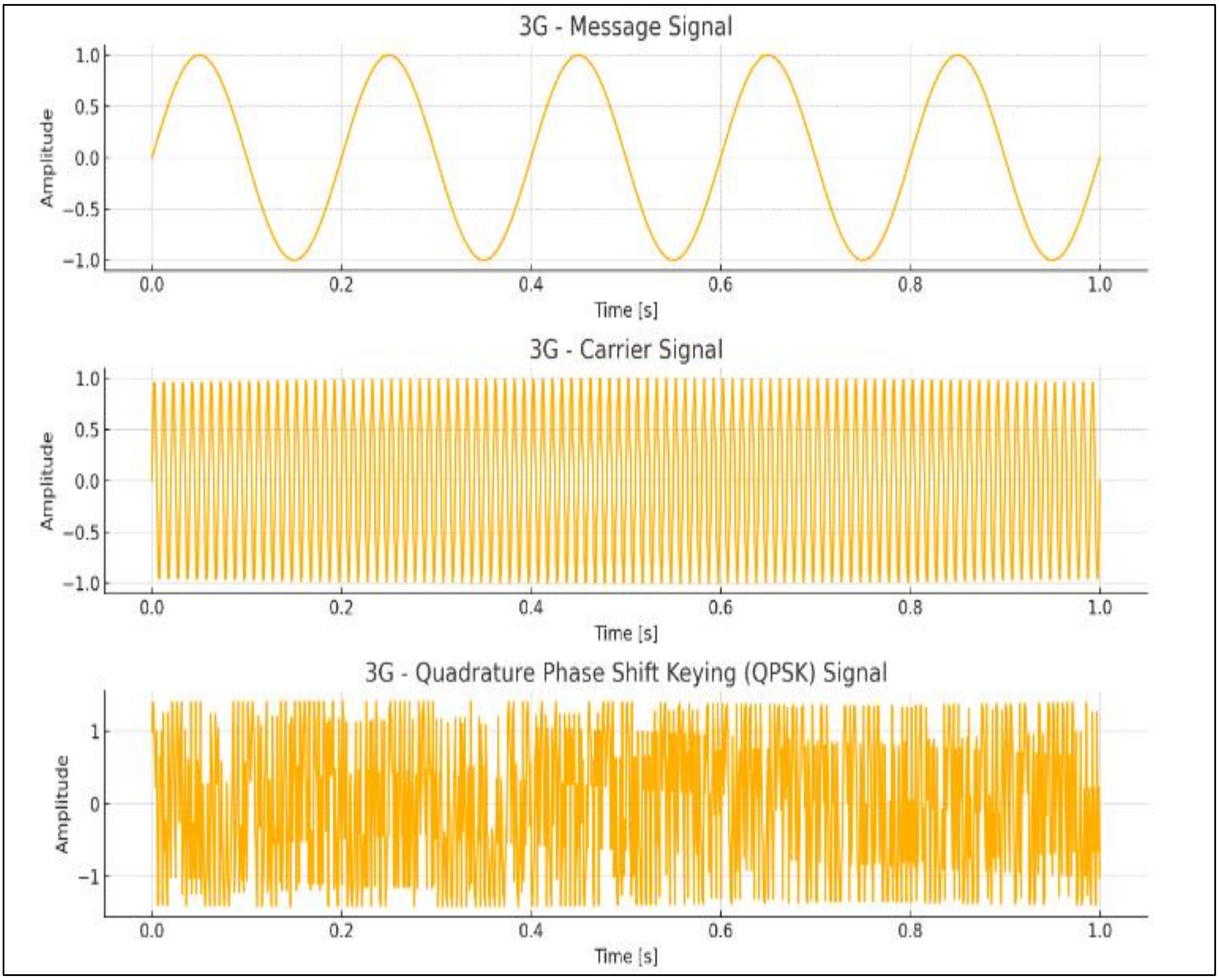

Fig 13 Modulation Technique in Third Generation

- ➢ *Stages of Third Generation*

- *G -- High-Speed Packet Access (HSPA) and 3.75G -- Evolved High-Speed Packet Access (HSPA+)*

The technology builds on UMTS to combine uplink (HSUPA) and downlink (HSDPA) protocols, resulting in higher data rates and capacity [38]. This stage supports shared channel and multi-code transmission, higher-order modulation, QPSK, 16-quadrature amplitude modulation (16QAM), short transmission time interval (TTI), fast link adaptation and scheduling, and fast hybrid automatic repeat request (HARQ) with incremental redundancy [38]. 3.75 G utilizes a 5 MHz carrier frequency, enabling data rates up to 42 Mbps in the downlink and 28 Mbps in the uplink, which can be doubled by using a dual carrier or dual cell [38]. This stage added 64QAM modulation and 2×2 multiple input multiple output (MIMO) technology [38].

VII. FOURTH GENERATION

The ITU laid down the vision for 4G in 2002, modified in November 2008 by the ITU-Radiocommunication sector (ITU-R) [53][54]. This specification was called IMT (International Mobile Telecommunications) – Advanced [53]. During the same period, HTC launched the "Max 4G" smartphone, the first WiMAX-enabled mobile phone [55]. 4G became commercially available in December 2009, mainly in Oslo, Norway, and Stockholm, Sweden [56][57]. The technology branded as "4G" was first commercially deployed by TeliaSonera, a Swedish telecommunication company [57][58]. TeliaSonera relied on modem devices from Samsung and network infrastructures by Huawei in Oslo and Ericsson in Stockholm [58].

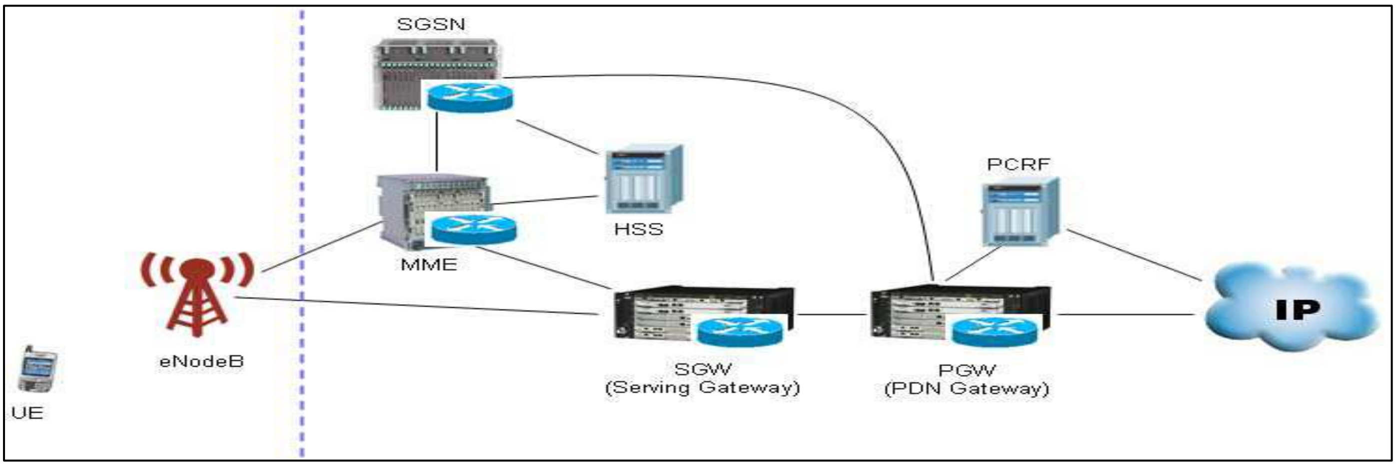

Fig 14 4G LTE Network Architecture [59] [60]

MME: Mobility Management Entity, PDN: Public Data Network, HSS: Home Subscriber Server, PCRF: Policy and Charging Rules Function, and e-Node B: 4G site that the UE connects to providing radio interface to the UE.

In 2010, the ITU defined 4G to include Long Term Evolution (LTE), Worldwide Interoperability for Microwave Access (WiMAX) and Evolved High-Speed Packet Access (HSPA+) [57] [61]. In 2011, the standard was upgraded to Mobile WiMAX Release 2 (also known as WirelessMAN-Advanced or IEEE 802.16m) and LTE Advanced (LTE-A) [38][57][62]. 4G technology supports Internet Protocol-based communication, such as IP telephony, but does not support traditional circuit-switched telephony services, unlike previous generations [57]. The technology offers 100 megabits per second (Mbit/s) for high-mobility communication and 1 gigabit per second (Gbit/s) for stationary users, along with advanced antenna techniques, including the use of MIMO (Multiple Input Multiple Output) and beamforming for improved signal quality and spectral efficiency [57].

In 2014, Huawei launched LTE-Advanced Pro (LTE-AP), also known as 4.5G [63]. This technology supported a data rate of 3 Gbps using 32-carrier aggregation, with bandwidth increasing from 20 MHz in LTE to 100 MHz in LTE-A and 640 MHz in LTE-AP [38]. LTE-AP enabled the sharing of licensed and unlicensed spectrum and introduced Massive MIMO antenna technology [38].

Though 4.5G utilized 256-QAM, the modulation technology was also employed in 5G [63]. The modulation technique in 4G was Orthogonal Frequency Division Multiplexing (OFDM), also known as multicarrier modulation [64]. OFDM is similar to the Frequency Division Multiplexing method, where several messages are sent through one radio channel in an associated unionized manner [64]. In OFDM, the carrier frequencies are similar, with a small number of bits transmitted on each channel [64].

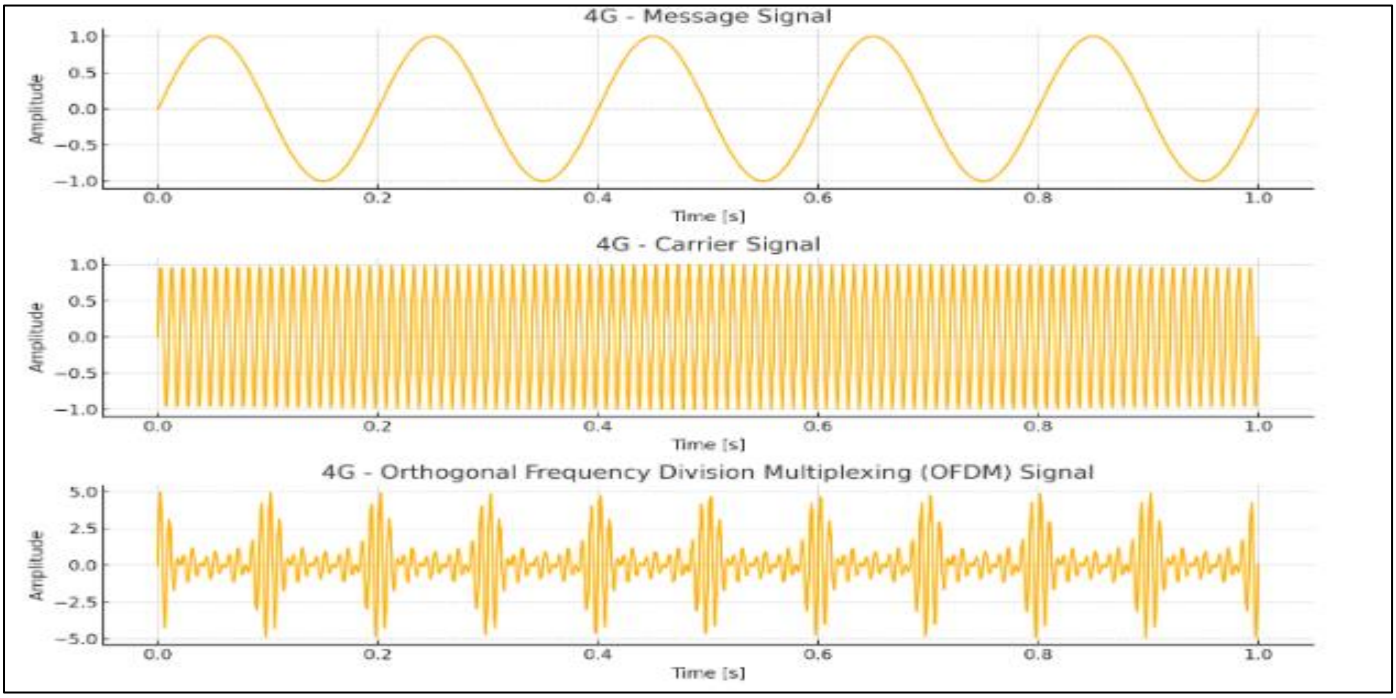

Fig 15 Modulation Technique in Fourth Generation

The Evolved UMTS Terrestrial Radio Access (E-UTRA) is the primary radio access technology for 4G LTE and LTE Advanced, enabling wireless connectivity between user equipment and 4G core networks [65]. The operating bands for E-UTRAN were released by 3GPP on September 26, 2024 [66].

Table 5 E-UTRA Operating Bands [66] [115]

E-UTRA Operating Band	**Uplink (UL) operating band BS receive UE transmit**			**Downlink (DL) operating band BS transmit UE receive**			**Duplex Mode**
	F_{UL_low}	**–**	**F_{UL_high}**	**F_{DL_low}**	**–**	**F_{DL_high}**	
1	1920 MHz	–	1980 MHz	2110 MHz	–	2170 MHz	FDD
2	1850 MHz	–	1910 MHz	1930 MHz	–	1990 MHz	FDD
3	1710 MHz	–	1785 MHz	1805 MHz	–	1880 MHz	FDD
4	1710 MHz	–	1755 MHz	2110 MHz	–	2155 MHz	FDD
5	824 MHz	–	849 MHz	869 MHz	–	894MHz	FDD
6[1]	830 MHz	–	840 MHz	875 MHz	–	885 MHz	FDD
7	2500 MHz	–	2570 MHz	2620 MHz	–	2690 MHz	FDD
8	880 MHz	–	915 MHz	925 MHz	–	960 MHz	FDD
9	1749.9 MHz	–	1784.9 MHz	1844.9 MHz	–	1879.9 MHz	FDD
10	1710 MHz	–	1770 MHz	2110 MHz	–	2170 MHz	FDD
11	1427.9 MHz	–	1447.9 MHz	1475.9 MHz	–	1495.9 MHz	FDD
12	699 MHz	–	716 MHz	729 MHz	–	746 MHz	FDD
13	777 MHz	–	787 MHz	746 MHz	–	756 MHz	FDD
14	788 MHz	–	798 MHz	758 MHz	–	768 MHz	FDD
15	Reserved			Reserved			FDD
16	Reserved			Reserved			FDD
17	704 MHz	–	716 MHz	734 MHz	–	746 MHz	FDD
18	815 MHz	–	830 MHz	860 MHz	–	875 MHz	FDD
19	830 MHz	–	845 MHz	875 MHz	–	890 MHz	FDD
20	832 MHz	–	862 MHz	791 MHz	–	821 MHz	FDD
21	1447.9 MHz	–	1462.9 MHz	1495.9 MHz	–	1510.9 MHz	FDD
22	3410 MHz	–	3490 MHz	3510 MHz	–	3590 MHz	FDD
23[1]	2000 MHz	–	2020 MHz	2180 MHz	–	2200 MHz	FDD
24[17]	1626.5 MHz	–	1660.5 MHz	1525 MHz	–	1559 MHz	FDD
25	1850 MHz	–	1915 MHz	1930 MHz	–	1995 MHz	FDD
26	814 MHz	–	849 MHz	859 MHz	–	894 MHz	FDD
27	807 MHz	–	824 MHz	852 MHz	–	869 MHz	FDD
28	703 MHz	–	748 MHz	758 MHz	–	803 MHz	FDD
29	N/A			717 MHz	–	728 MHz	FDD[2]
30[15]	2305 MHz	–	2315 MHz	2350 MHz	–	2360 MHz	FDD
31	452.5 MHz	–	457.5 MHz	462.5 MHz	–	467.5 MHz	FDD
32		N/A		1452 MHz	–	1496 MHz	FDD[2]
33	1900 MHz	–	1920 MHz	1900 MHz	–	1920 MHz	TDD
34	2010 MHz	–	2025 MHz	2010 MHz	–	2025 MHz	TDD
35	1850 MHz	–	1910 MHz	1850 MHz	–	1910 MHz	TDD
36	1930 MHz	–	1990 MHz	1930 MHz	–	1990 MHz	TDD
37	1910 MHz	–	1930 MHz	1910 MHz	–	1930 MHz	TDD
38	2570 MHz	–	2620 MHz	2570 MHz	–	2620 MHz	TDD
39	1880 MHz	–	1920 MHz	1880 MHz	–	1920 MHz	TDD
40	2300 MHz	–	2400 MHz	2300 MHz	–	2400 MHz	TDD
41	2496 MHz		2690 MHz	2496 MHz		2690 MHz	TDD
42	3400 MHz	–	3600 MHz	3400 MHz	–	3600 MHz	TDD
43	3600 MHz	–	3800 MHz	3600 MHz	–	3800 MHz	TDD
44	703 MHz	–	803 MHz	703 MHz	–	803 MHz	TDD
45	1447 MHz	–	1467 MHz	1447 MHz	–	1467 MHz	TDD
46	5150 MHz	–	5925 MHz	5150 MHz	–	5925 MHz	TDD[8]
47	5855 MHz	–	5925 MHz	5855 MHz	–	5925 MHz	TDD[11]

48	3550 MHz	–	3700 MHz	3550 MHz	–	3700 MHz	TDD
49	3550 MHz	–	3700 MHz	3550 MHz	–	3700 MHz	TDD[16]
50	1432 MHz	-	1517 MHz	1432 MHz	-	1517 MHz	TDD[13]
51	1427 MHz	-	1432 MHz	1427 MHz	-	1432 MHz	TDD[13]
52	3300 MHz	-	3400 MHz	3300 MHz	-	3400 MHz	TDD
53	2483.5 MHz	-	2495 MHz	2483.5 MHz	-	2495 MHz	TDD
54	1670 MHz	-	1675 MHz	1670 MHz	-	1675 MHz	TDD
…							
64	Reserved						
65	1920 MHz	–	2010 MHz	2110 MHz	–	2200 MHz	FDD
66	1710 MHz	–	1780 MHz	2110 MHz	–	2200 MHz	FDD[4]
67		N/A		738 MHz	–	758 MHz	FDD[2]
68	698 MHz	–	728 MHz	753 MHz	–	783 MHz	FDD
69	N/A			2570 MHz	–	2620 MHz	FDD[2]
70	1695 MHz	–	1710 MHz	1995 MHz	–	2020 MHz	FDD[10]
71	663 MHz	–	698 MHz	617 MHz	–	652 MHz	FDD
72	451 MHz	–	456 MHz	461 MHz	–	466 MHz	FDD
73	450 MHz	–	455 MHz	460 MHz	–	465 MHz	FDD
74	1427 MHz	–	1470 MHz	1475 MHz	–	1518 MHz	FDD
75		N/A		1432 MHz	–	1517 MHz	FDD[2]
76		N/A		1427 MHz	–	1432 MHz	FDD[2]
85	698 MHz	–	716 MHz	728 MHz	–	746 MHz	FDD
87	410 MHz	–	415 MHz	420 MHz	–	425 MHz	FDD
88	412 MHz	–	417 MHz	422 MHz	–	427 MHz	FDD
103[18]	787 MHz	–	788 MHz	757 MHz	–	758 MHz	FDD
106	896 MHz	–	901 MHz	935 MHz	–	940 MHz	FDD

NOTE 1: Band 6, 23 is not applicable

NOTE 2: Restricted to E-UTRA operation when carrier aggregation is configured. The downlink operating band is paired with the uplink operating band (external) of the carrier aggregation configuration that is supporting the configured cell.

NOTE 3: A UE that complies with the E-UTRA Band 65 minimum requirements in this specification shall also comply with the E-UTRA Band 1 minimum requirements.

NOTE 4: The range 2180-2200 MHz of the DL operating band is restricted to E-UTRA operation when carrier aggregation is configured.

NOTE 5: A UE that supports E-UTRA Band 66 shall receive in the entire DL operating band

NOTE 6: A UE that supports E-UTRA Band 66 and CA operation in any CA band shall also comply with the minimum requirements specified for the DL CA configurations CA_66B, CA_66C and CA_66A-66A.

NOTE 7: A UE that complies with the E-UTRA Band 66 minimum requirements in this specification shall also comply with the E-UTRA Band 4 minimum requirements.

NOTE 8: This band is an unlicensed band restricted to licensed-assisted operation using Frame Structure Type 3

NOTE 9: In this version of the specification, restricted to E-UTRA DL operation when carrier aggregation is configured.

NOTE 10: The range 2010-2020 MHz of the DL operating band is restricted to E-UTRA operation when carrier aggregation is configured and TX-RX separation is 300 MHz The range 2005-2020 MHz of the DL operating band is restricted to E-UTRA operation when carrier aggregation is configured and TX-RX separation is 295 MHz.

NOTE 11: This band is unlicensed band used for V2X communication. There is no expected network deployment in this band so Frame Structure Type 1 is used.

NOTE 12: A UE that complies with the E-UTRA Band 74 minimum requirements in this specification shall also comply with the E-UTRA Band 11 and Band 21 minimum requirements.

NOTE 13: UE that complies with the E-UTRA Band 50 minimum requirements in this specification shall also comply with the E-UTRA Band 51 minimum requirements.

NOTE 14: A UE that complies with the E-UTRA Band 75 minimum requirements in this specification shall also comply with the E-UTRA Band 76 minimum requirements.

NOTE 15: Uplink transmission is not allowed at this band for UE with external vehicle-mounted antennas.

NOTE 16: This band is restricted to licensed-assisted operation using Frame Structure Type 3

NOTE 17: DL operation in this band is restricted to 1526 – 1536 MHz and UL operation is restricted to 1627.5 – 1637.5 MHz and 1646.5 – 1656.5 MHz.

NOTE 18: This band is restricted to NB-IoT operation only

VIII. FIFTH GENERATION

The development of 5G technology began in 2015 with the 3GPP standardization body [67]. The first specification was released in 2017, followed by the commercial release in 2019 [67]. No company or research group single-handedly invented 5G [68]. However, major players in the telecommunications industry, including Ericsson, Nokia, Qualcomm, Samsung, Huawei, and ZTE, played significant roles in innovating critical components of the 5G network [68]. According to a report titled "The State of 5G" by Viavi Solutions, 5G was available in 2,497 cities across 92 countries as of April 2023 [69]. In February 2024, Huawei launched the first 5.5G intelligent core network, incorporating service intelligence, network intelligence, and Operation and maintenance intelligence, thereby improving business value and development potential [70].

The modulation technique behind 5G in its early stage was 256-quadrature Amplitude Modulation (QAM), while in the present stage, it is 1024-quadrature Amplitude Modulation (QAM) [71]. QAM is an advanced modulation scheme that combines phase modulation and amplitude modulation [72][73]. The amplitude modulation differentiates digital signals (0s and 1s) by changing the carrier amplitude, while phase modulation does so by changing the carrier phase [72][73]. QAM loads signals onto sine and cosine orthogonal carriers, adjusts their amplitudes, and superimposes them to generate signals modulated by both phase and amplitude [72][73]. QAM is also known as IQ modulation because the two carriers are referred to as I and Q signals [72][73]. QAM enables a higher data rate within the same bandwidth [74]. The 256-QAM transmits 8 bits per symbol within the same bandwidth, while 1024-QAM transmits 10 bits per symbol [74].

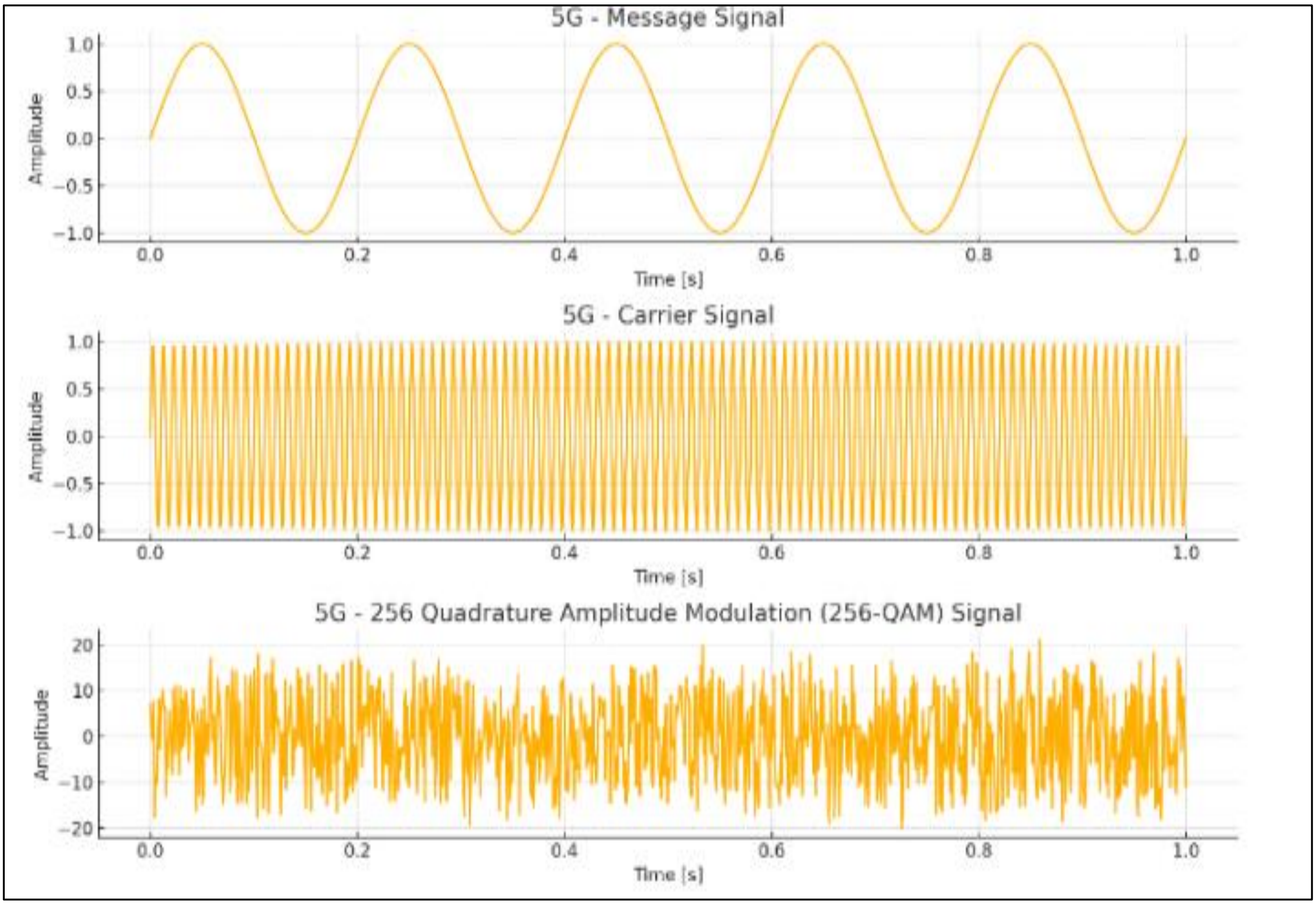

Fig 16 Modulation Technique in Fifth Generation

- *5G Use Cases*

The three 5G use cases include Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC), and Massive Machine Type Communications (mMTC) [75].

- Enhanced Mobile Broadband (eMBB) is an advanced version of conventional MBB, providing faster data transmission through higher frequency bandwidth, shorter latency, and an increased number of antennas, offering about a 10 to 100 times improvement over 4 G's data rates, capacity, and coverage [75][76]. eMBB offers a high data rate—a minimum user data rate of 100 Mbps and a peak data rate of 20 Gbps—along with high spectrum efficiency, with a peak of 15 bps/Hz in uplink and 30 bps/Hz in downlink [77].
- Ultra-Reliable Low Latency Communications (uRLLC) addresses throughput, latency (around 1 ms), and availability in sensitive applications requiring real-time response, round-trip time (RTT), and reliability, including

automated driving, telemedicine, smart grids, and other industrial applications [75][76]. URLLC offers extreme mobility of up to 500 km/h and a minimum reliability of 99.99%, with a success probability for up to 32 bytes within 1 ms [77].

- Massive Machine Type Communications (mMTC) involves large-scale communication for low-cost devices such as 5G Internet of Things (IoT), which require low data rates for large numbers of connected devices, including independent sensors or Single Board Devices (SBD) in a small area, based on high reliability and low latency [75][76]. mMTC offers low complexity, energy efficiency that improves as traffic increases, and a high connection density of up to 106/km2 [77].

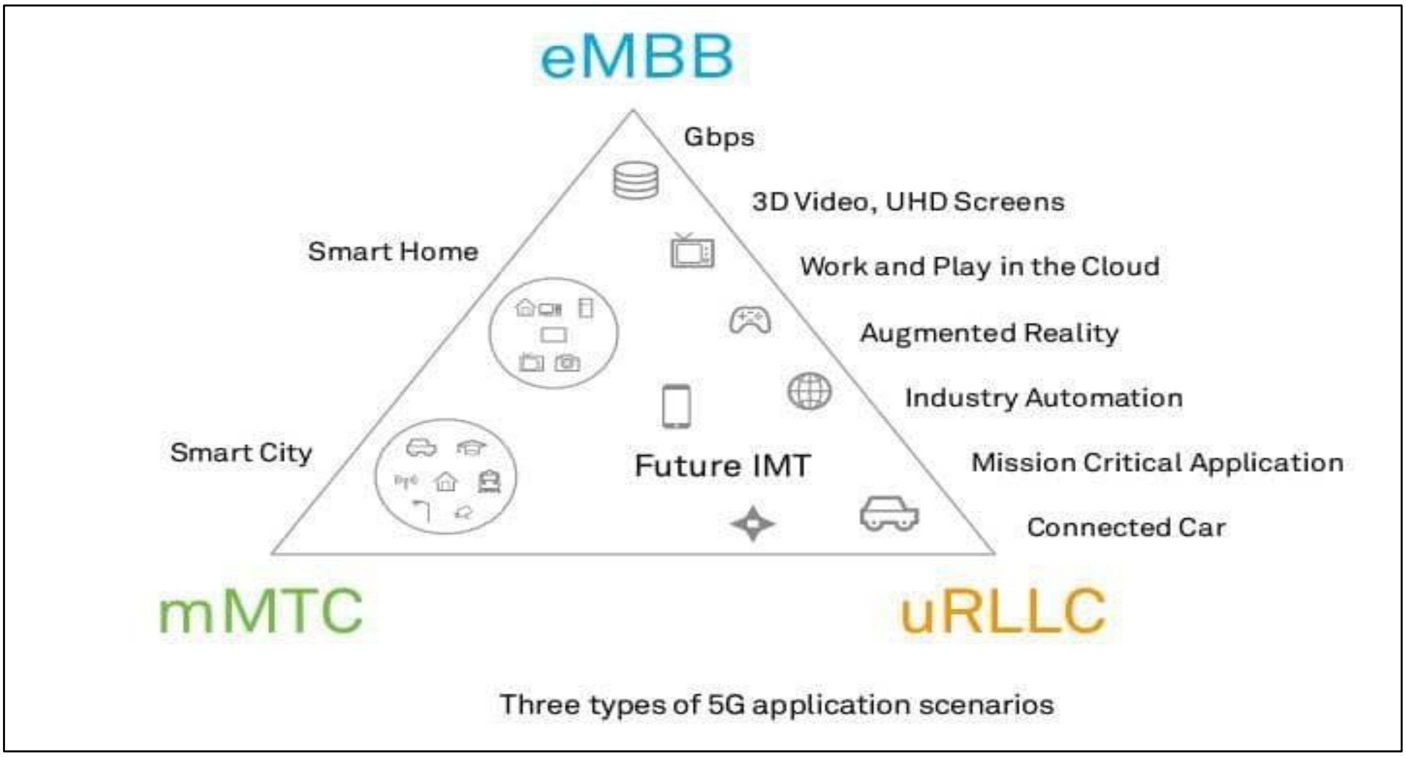

Fig 17 5G Use Cases. [77]

➤ *5G System/Network Architecture*

5G network architecture describes how the 5G cellular network is organized. (5G SYSTEM = UE + 5G ACCESS NETWORK + 5G CORE NETWORK) [77] [78].

➤ *The Key Elements Include [78]:*

- User Equipment (UE): UE refers to devices such as smartphones, tablets, laptops, IoT devices, and other wireless devices used to connect to the 5G network [78].
- RAN: In 5G, the Radio Access Network (RAN) consists of gNB (Next-Generation NodeB), which improves network capacity and coverage by supporting technologies like carrier aggregation, massive MIMO (Multiple-Input Multiple-Output), and beamforming. The NG-RAN represents the overall RAN architecture, including gNBs and other supporting elements [78].
- Core Network: The 5G Core network interfaces with data networks such as the internet, allowing UE to access data networks through the 5G Core and Access Networks [77][78].

Table 6 Core Network in 5G Performs the Following Network Functions [77]

Network Functions	**Expansion and Key Function**
5G-EIR	5G–Equipment Identity Register: Records blacklisted device IDs
AF	Application Function: Influences traffic routing and facilitates QoS control
AMF	Access and Mobility Management Function: Exchanges NAS signaling with the UE and manages registration, connection, reachability, and mobility
AUSF	Authentication Server Function: Authenticates the UE
LMF	Location Management Function: Helps determine the UE location
N3IWF	Non-3GPP Interworking Function: Supports an IPSec tunnel towards the UE through a non-3GPP access network
NRP	Network Repository Function: Supports discovery of NFs/services
NSSAAF	Network Slice-Specific Authentication and Authorization Function: Provides Network Slice-specific authentication and authorization by relaying Extensible Authentication Protocol (EAP) messages
NSSF	Network Slice Selection Function: Determines allowed Network Slices

NWDAF	Network Data Analytics Function: Provides network slice-specific analytics to an NF
PCF	Policy Control Function: Creates policy rules (e.g., to support QoS control)
SCP	Service Communication Proxy: Facilitates indirection communication between NFs and NF services
SEPP	Security Edge Protection Proxy: Secures inter-PLMN Control Plane interfaces
SMF	Session Management Function: Manages UE sessions and allocates an IP address to the UE
SMSF	Short Message Service (SMS) Function: Supports SMS over NAS
UDM	Unified Data Management: Manages subscriptions and generates authentication credentials
UDR	Unified Data Repository: Stores subscription data and policy data and structured data for exposure
UDSF	Unstructured Data Storage Function: Supports storage, modification, and retrieval of unstructured data
UPF	User Plane Function: Acts as a mobility anchor for user traffic
NEF	Network Exposure Function: provides interfaces for third-party applications and services to interact with the 5G network.

5G Service-Based Architecture refers to how the 5G network architecture utilizes a service-based approach by decoupling and organizing network functions as modular services [78]. The native capabilities of 5G networks include [79]:

- Network Slicing: Network slicing allows 5G networks to be divided into multiple virtual logical networks (network slices) based on physical infrastructures [78][80]. Each virtual network created is tailored to specific use cases from other components of a system model [80]. Network slicing depends on the 5G system (UE + 5G ACCESS NETWORK + 5G CORE NETWORK) [80]. Implementing network slicing can be done on the RAN alone, the core network alone, or both [80].
- Edge Computing/Multi-Access Edge Computing: Edge computing is a computational model that enables edge servers or networks using cloud functions in mini clouds to perform intensive computational tasks and store large amounts of data close to the user equipment [81][82]. Some of these computationally intensive tasks include augmented reality and virtual reality, which have high Quality of Service (QoS) requirements, including low latency and high throughput [81].

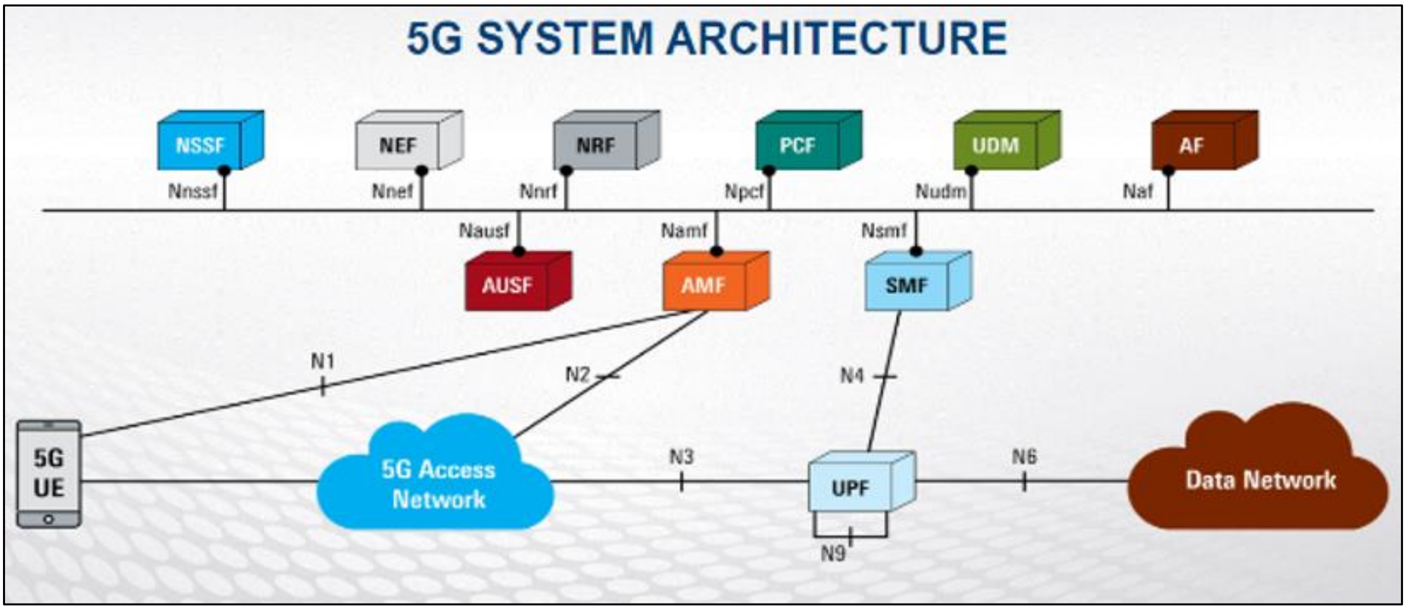

Fig 18 5G System Architecture. [77]

➢ *Evolution of 5G Release 15 To 20*

- Release 15 was launched in June 2019 [77][83]
- Release 16 was launched in July 2020 [77][84]
- Release 17 was launched in June 2022 [77][86]
- Release 18 was launched in June 2024 [77] [88]
- Release 19 is expected to be finalized by December 2024 [90]
- 5G release 20 is yet to be launched with stage 1 studies expected to begin by June 2025 [92].

IX. SIXTH GENERATION

The 6G technology initiative began in October 2020 with the Alliance for Telecommunications Industry Solutions (ATIS) [93]. The standardization organization launched the "Next G Alliance" in partnership with top communication companies, including Samsung, AT&T, Ericsson, Verizon, T-Mobile, and others [93]. However, the 6G breakthrough occurred in January 2022 from Purple Mountain Laboratories in China [94]. The research laboratory achieved the proposed base data rate for 6G cellular technology: a data rate of 206.25 gigabits per second (Gbit/s) in the terahertz frequency band, a rate 20 times that of 5G [94].

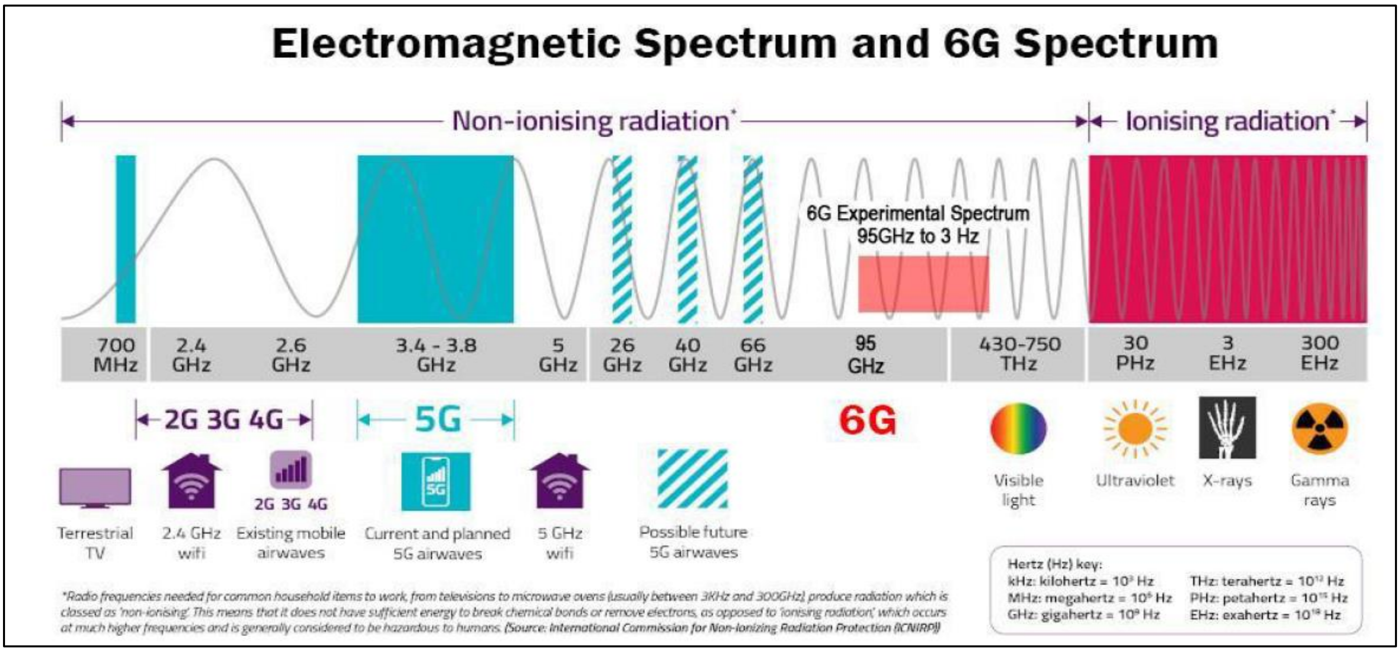

Fig 19 6G Spectrum [95]

According to a survey by Nikkei and the Cyber Creative Institute, based on 20,000 patent applications and participants for nine core 6G technologies, China leads the world in 6G patents, with 40.3% of 6G patent filings mostly related to mobile infrastructure as of 2021. The U.S. follows with 35.2%, Japan holds 9.9%, Europe accounts for 8.9%, and South Korea represents 4.2% [96]. See the figure below:

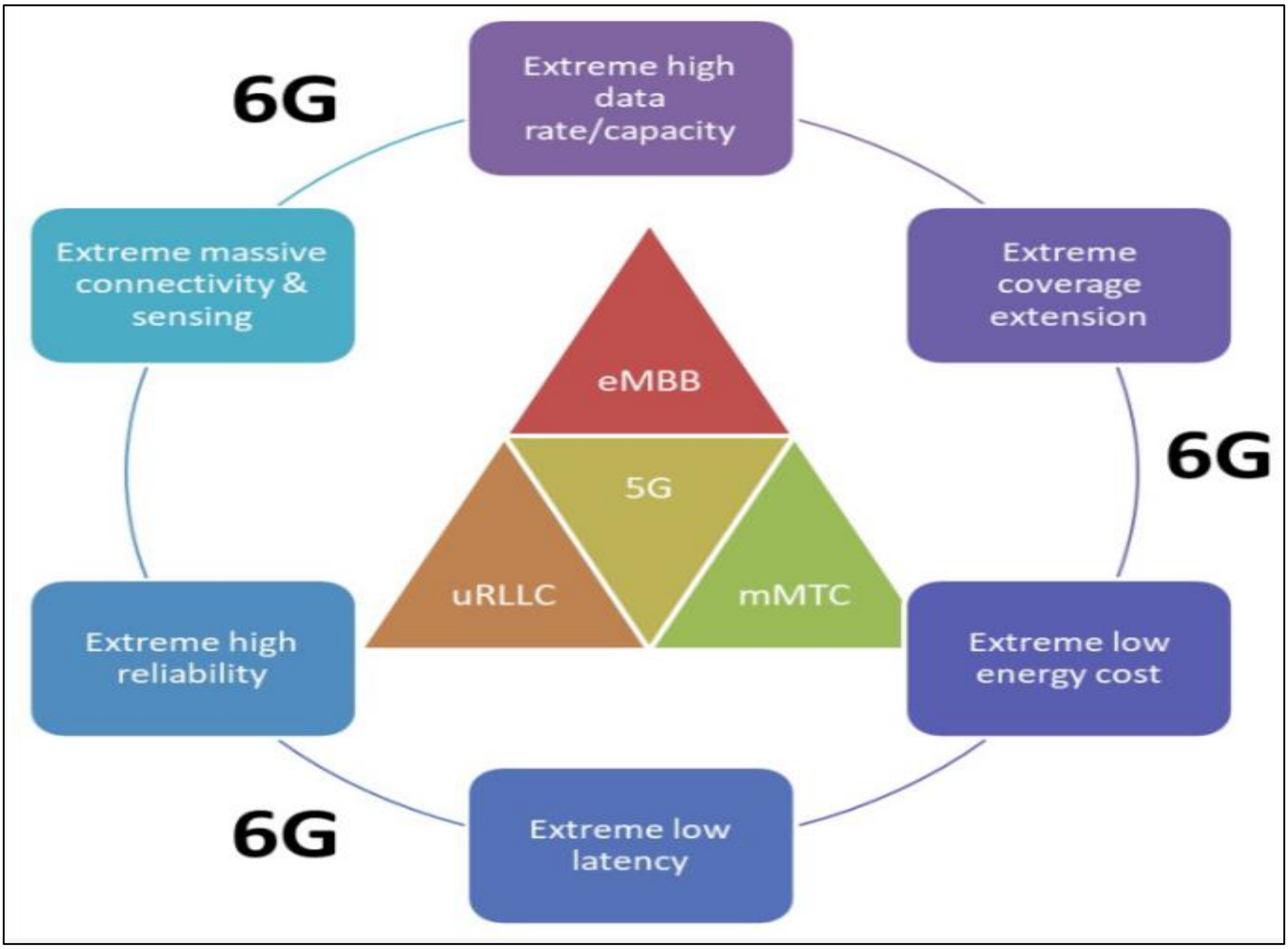

Fig 20 Comparison of 6G Features with Respect to 5G [96]

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6G would also incorporate O-RAN, which aids mobility management, traffic steering, QoE optimization, resource allocation, energy saving, MIMO beam-forming optimization, and automated RAN operations; network slicing to construct different "logically isolated" virtual networks (slices), thereby allocating different resources to different wireless services; and x-haul architecture (a combination of front haul (FH) and backhaul (BH)), enabling software-defined and adaptable reconfiguration of integrated network components for 6G[96].

- *Sixth Generation Enabling Technologies, Application Areas, and Research Challenges*

The major enabling technologies in 6G communication include Visible Light Communication, terahertz frequencies, Molecular Communication, Bio-Signal Processing, Blockchain, and Energy harvesting [96]. In addition, Quantum communication, Machine Learning, Big Data, and Deep Learning are future 6G enabling technologies [96]. The major application areas of 6G include Personal Edge Intelligence, Wireless Communication for the Automotive Sector, Internet of Things (IoT)-supported Smart City Services, Autonomous Ports and Autonomous Manufacturing, and Bio-Cybernetic-Based Identity [96]. However, there are major challenges in 6G research areas, including Data Security and User Privacy Challenges, Hybrid Radio Networks (RN) and Visible Light Communication (VLC), Wireless Networking for Cyber-Physical Systems (CPS), Quantum-Based Wireless Systems Design, Multiple Access and Modulation Techniques, Processing of Sensor Data at High Speed, Satellite Communication, RF Exposure and Related Human Health Concerns, Electromagnetic Compatibility, Reshaping the Developing Economies, and Ethical Responsibilities and User Awareness Programs [96].

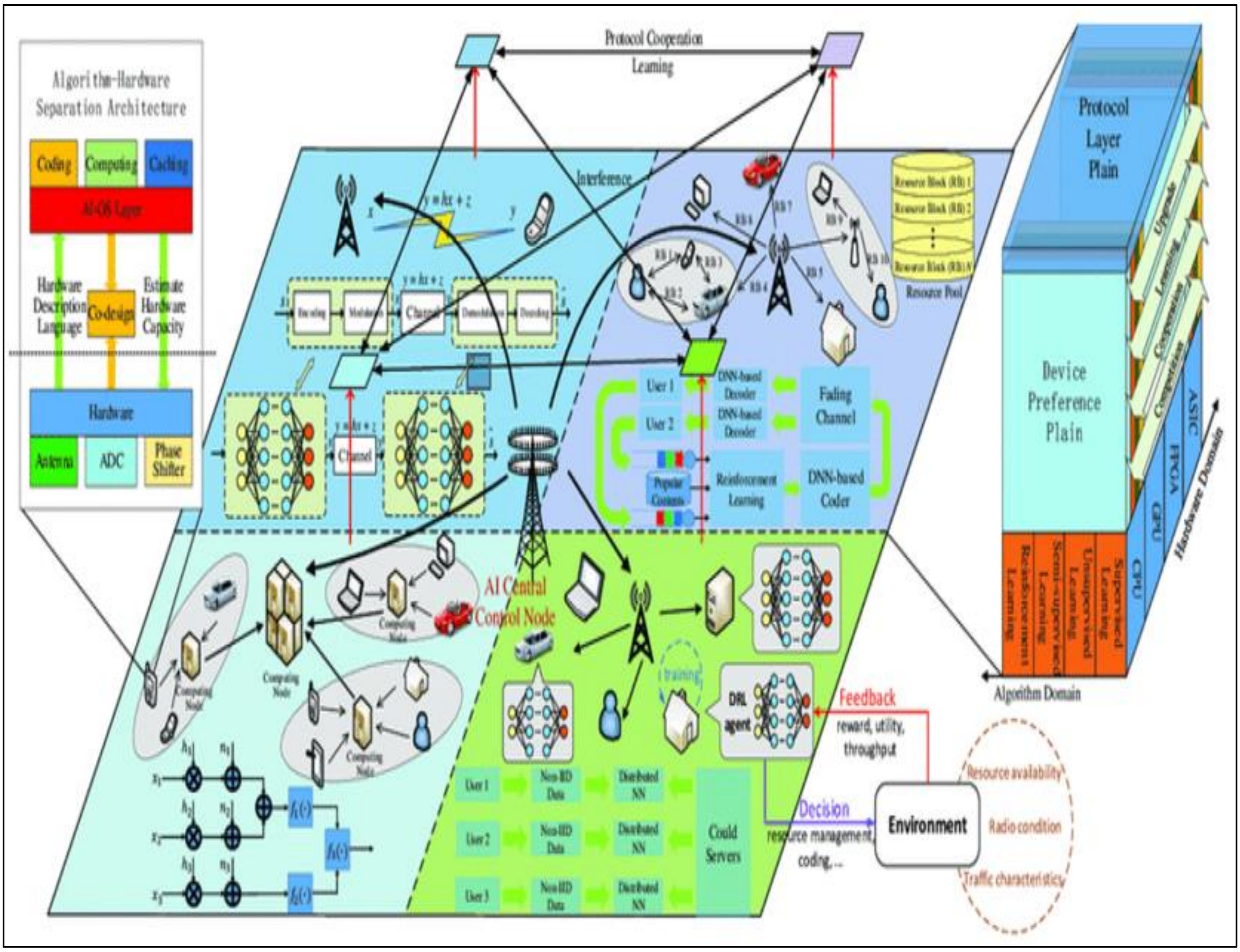


Fig 21 The architecture of 6G [97]

X. DIGITAL DIVIDE

Digital divide is used to describe unequal access and use of telecommunication infrastructures among a group of people [98][99]. The digital divide occurs globally, internationally, and nationally [98][99]. At the global level, the digital divide is the difference in telecommunication infrastructure access between industrialized and developing countries [99]. However, nations with an edge in modern science and technology and stable governments have more access to the internet than poor countries with emerging democracies [98]. The digital divide at the country level differs in gender, wealth, education, race, and minority designation [98]. This paper will consider Nigeria as a case study.

- *Digital Divide in Nigeria*

As of 2024, Nigeria has the fourth highest GDP in Africa but still faces problems of digital divide [100].

Table 7 Access to High-Quality Internet Service by Geopolitical Zones in Nigeria [99]

Geographical Zones	Internet Users	Year	Quarter
Eastern Region	13.7 million	2021	Fourth Quarter
Southwest	41.7 million	2021	Fourth Quarter
North Central	26.6 million	2021	Fourth Quarter
North West	25.4 million	2021	Fourth Quarter
South-South	20.8 million	2021	Fourth Quarter
North East	13.8 million	2021	Fourth Quarter

Nigeria is a country with a population of 226.48 million as of 2023, with rural populations accounting for 46% [101]. The country has 5,700 $PPP GNI per capita, 91% Mobile Connections, 86% Mobile Broadband Coverage, and 83% Mobile Broadband Connections [101].

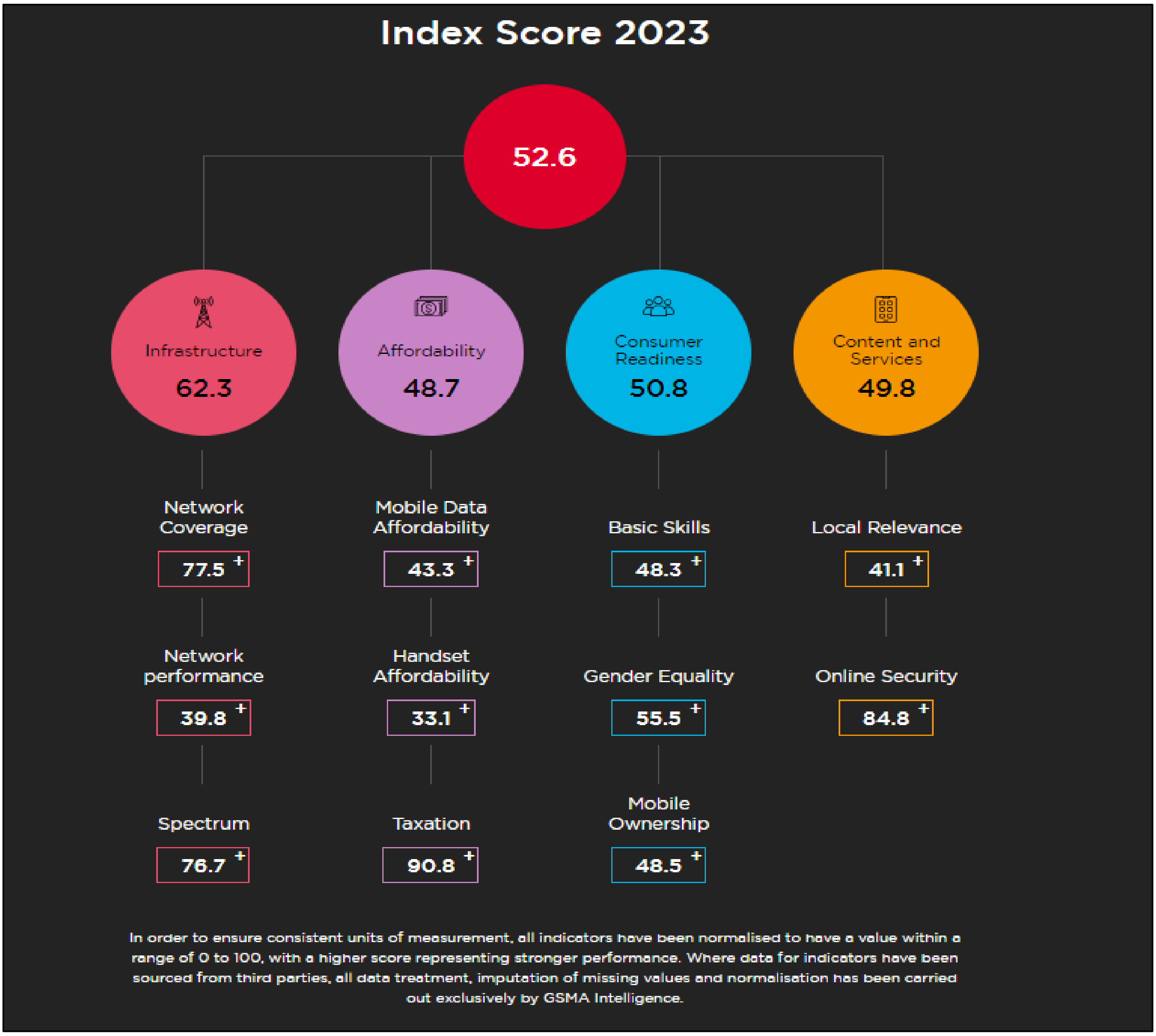


Fig 22 Nigeria's Mobile Connectivity Index Score as of 2023 [101]

Nigeria is a country in the sub-Saharan part of Africa [102]. Despite still being low, the coverage gap, usage gap, and number of connected people have improved as of 2022 compared to 2015, as indicated in the Figure below [103].

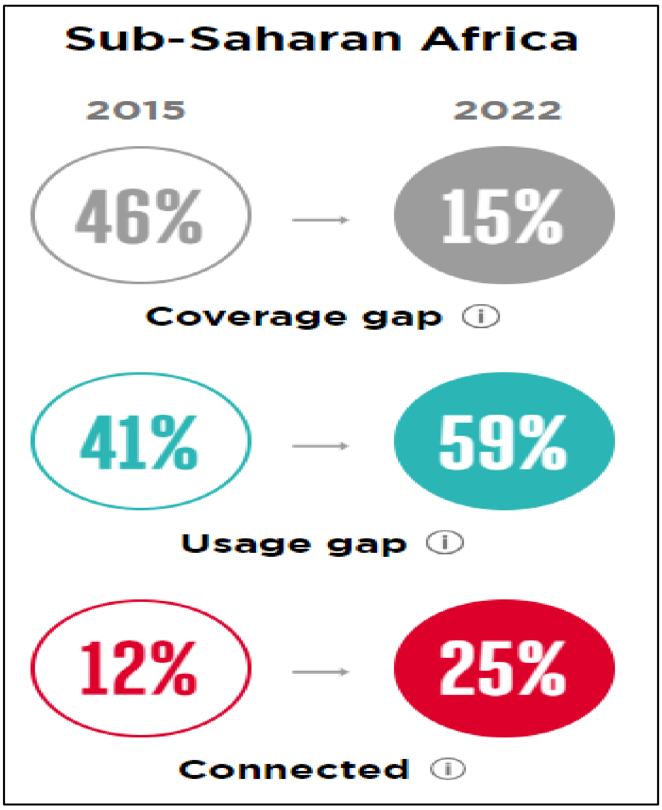
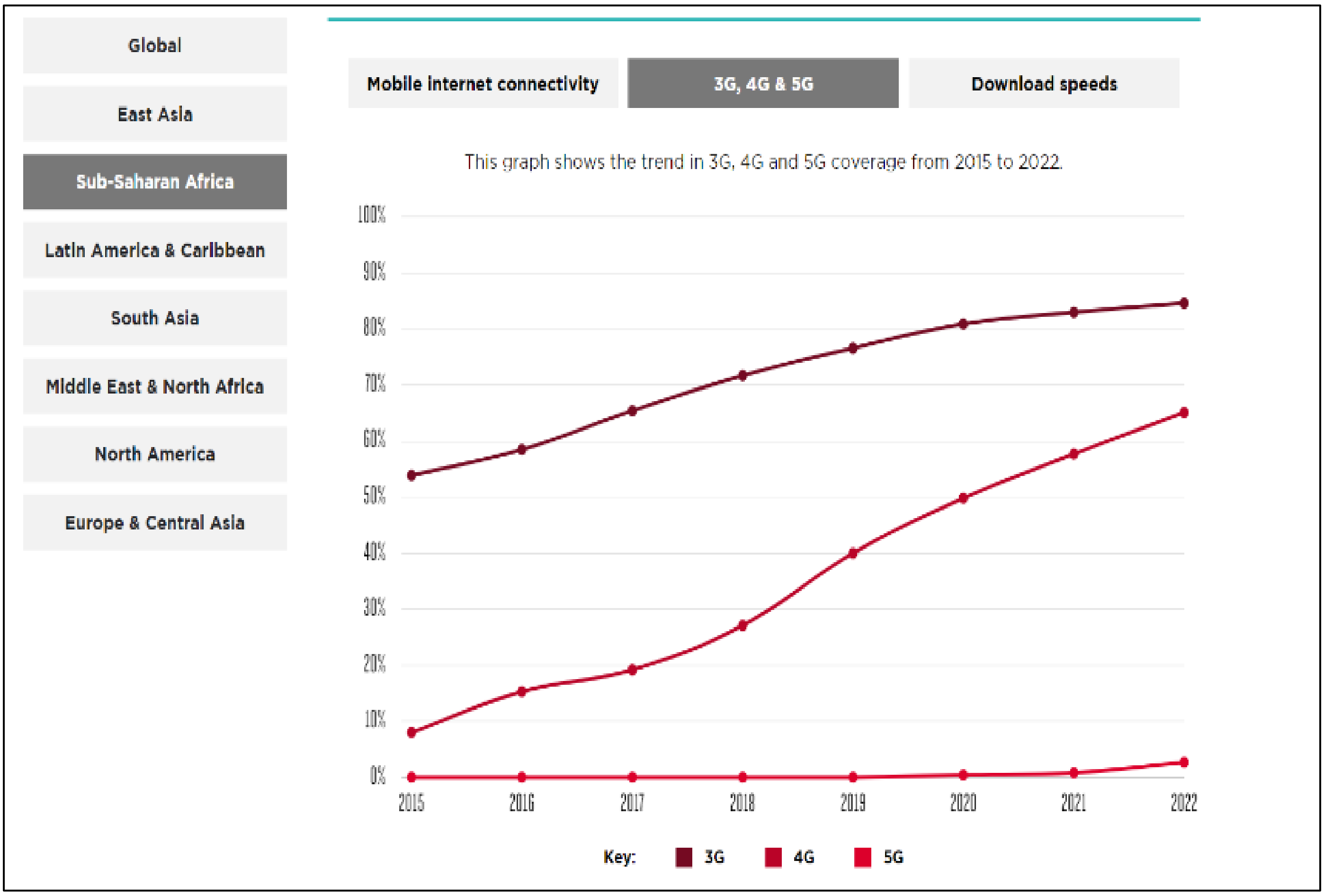


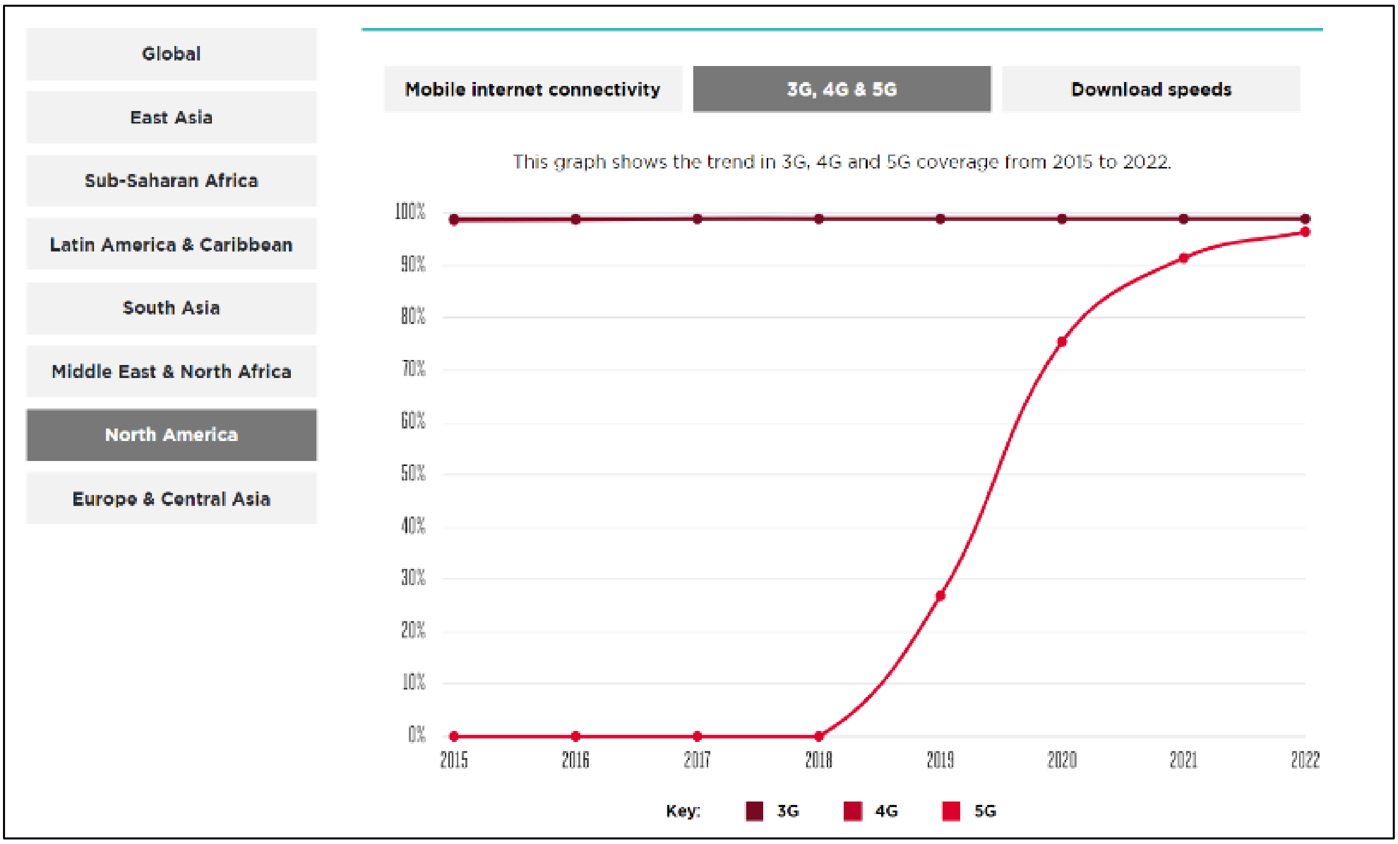
Fig 23 Sub-Saharan Africa's State of Mobile Internet Connectivity Gap from 2015 to 2022 [103]

However, sub–Saharan Africa still mainly uses 3G and 4G technology with minimal adoption of the latest 5G technology compared to regions like North America where 3G, 4G and 5G technology coverage are in similar coverage proportions as of 2022 as shown in the Figures below [103]. The average download speed in sub-Saharan Africa as 2022 is 11.1 Mbps compared to 96.4 Mbps in North America [103].



This graph shows the trend in 3G, 4G and 5G coverage from 2015 to 2022.

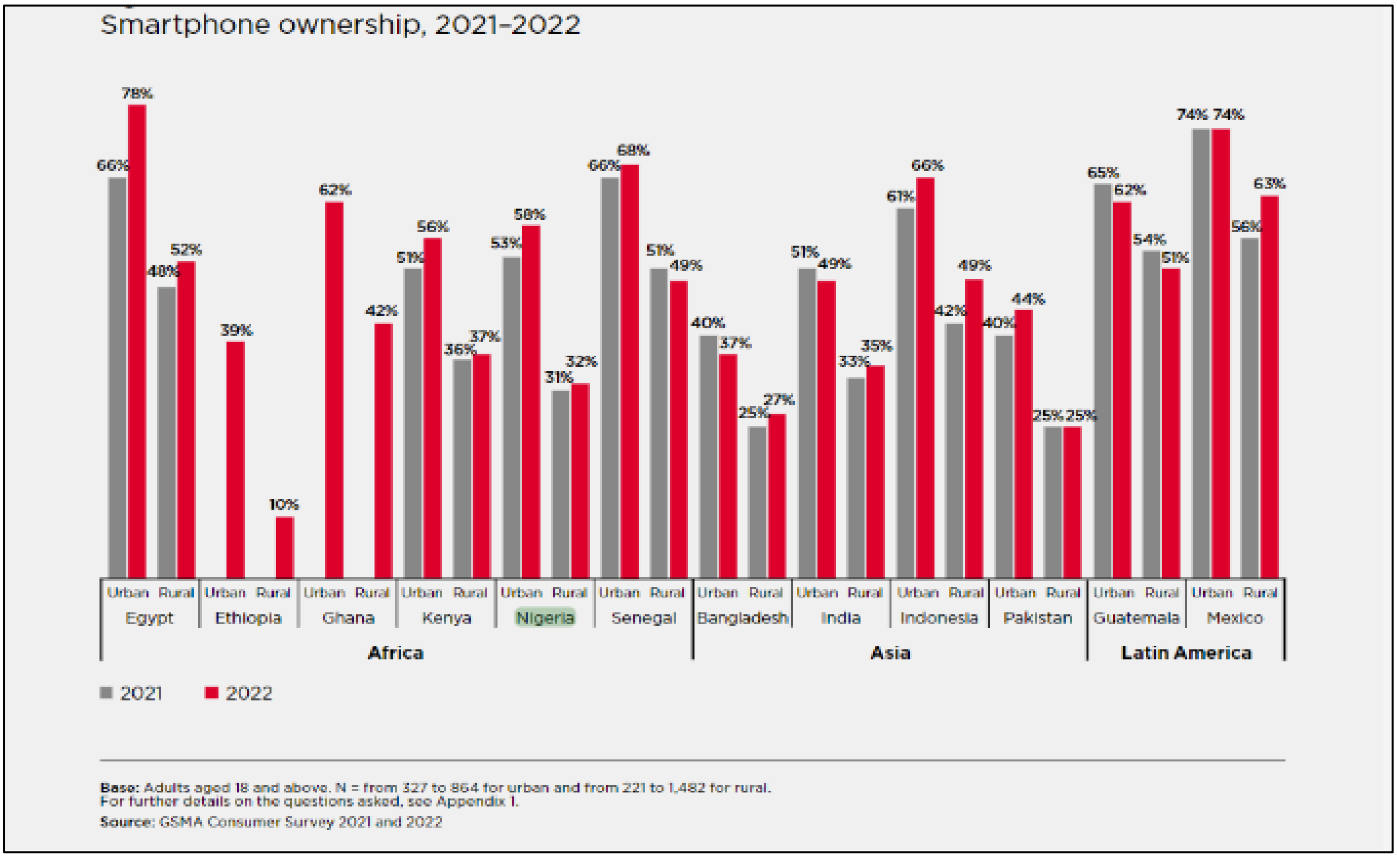
Fig 24 Sub-Saharan Africa's 3G, 4G, and 5G coverage trend from 2015 to 2022 [103]



This graph shows the trend in 3G, 4G and 5G coverage from 2015 to 2022.

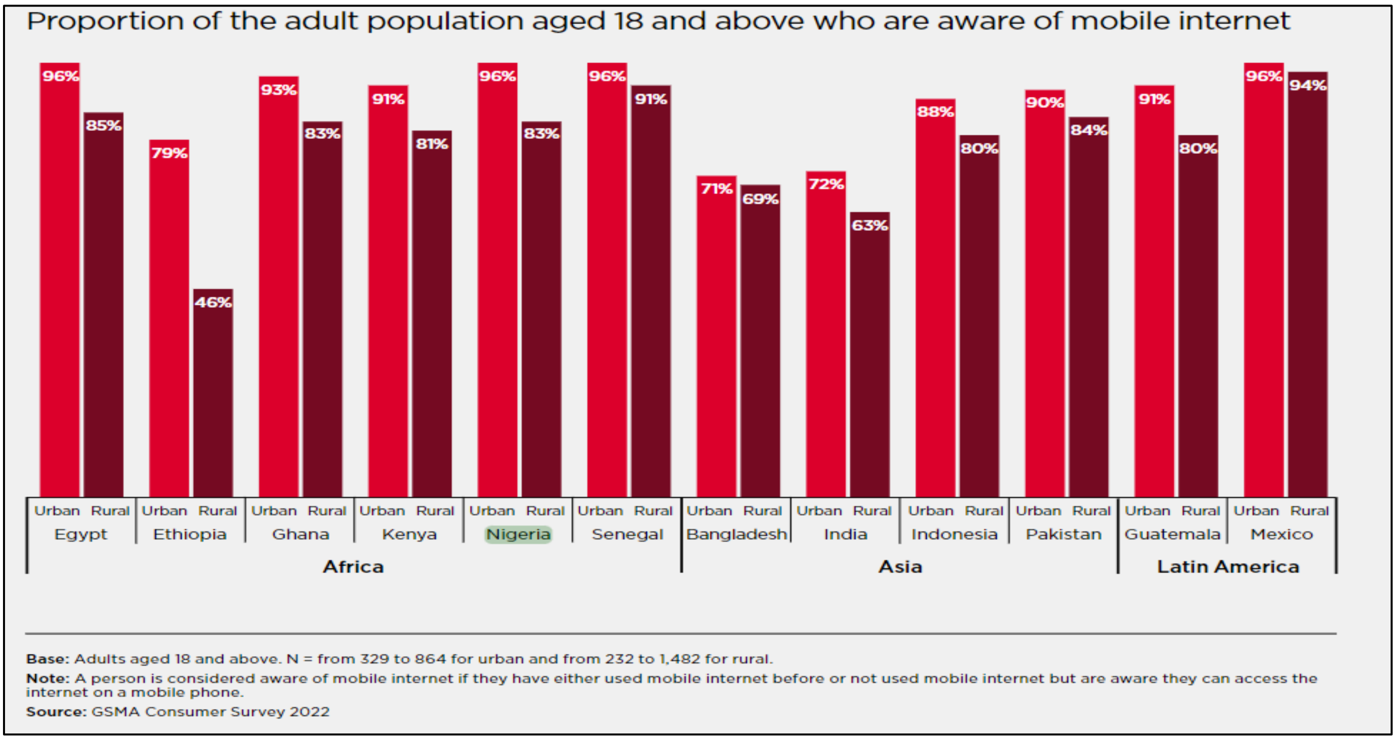
Fig 25 North America's 3G, 4G, and 5G coverage trend from 2015 to 2022 [103]

In 2022, the GSMA consumer survey considered 12 Low and Middle-Income Countries (LMIC) countries, including Bangladesh, Egypt, Ethiopia, Ghana, Guatemala, India, Indonesia, Kenya, Mexico, Nigeria, Pakistan, and Senegal [102].


Smartphone ownership, 2021-2022

Base: Adults aged 18 and above. N = from 327 to 864 for urban and from 221 to 1,482 for rural.
For further details on the questions asked, see Appendix 1.
Source: GSMA Consumer Survey 2021 and 2022

Fig 26 Smartphone Ownership rate in Urban and Rural Areas across 12 LMICs in 2021 and 2022 [102]



Proportion of the adult population aged 18 and above who are aware of mobile internet

Base: Adults aged 18 and above. N = from 329 to 864 for urban and from 232 to 1,482 for rural.

Note: A person is considered aware of mobile internet if they have either used mobile internet before or not used mobile internet but are aware they can access the internet on a mobile phone.

Source: GSMA Consumer Survey 2022

Fig 27 Mobile Internet Awareness Rate among Adults in Rural and Urban Areas across 12 LMICs in 2022 [102]

➢ *Causes of Digital Divide in Nigeria*

Several factors contribute to the digital divide in Nigeria. Some of these include;

- Leadership: Nigeria gained independence in 1960 and has since experienced bad leadership for over half its life with several cases of bribery, misappropriation, and embezzlement of government funds [98]. Policymakers in Nigeria are unable to provide an enabling environment and a proper ICT roadmap for sustainable ICT development activities [104]. There are usually cases of inconsistent policies where important policies are canceled by the same government that initiated them due to the merger of ministries [104]. The new ministers do not share the visions of their predecessors, leading to a "back-to-square-one" situation [104]. The government's regulatory policies from political factors often frustrate efforts towards creating a conducive environment for ICTs [104].
- Urban-Rural Disparity: About 46% of Nigeria's population are those living in rural areas [101]. However, urban regions have a growing number of internet browsing hubs, while poor telecommunication and electricity infrastructures in rural areas make these internet browsing hubs almost totally unavailable [98]. Even those with personal devices in rural areas cannot surf the internet due to poor electricity supply, as most ICT equipment is electricity-power-based [98].
- Poverty and Affordability: Nigeria is regarded as the poverty capital of Africa as the country accounts for 11.3% of the world population living in extreme poverty, with people living below 2.15 U.S. dollars a day [105]. As a result, the resources that would have been used to bridge the digital divide are channeled to poverty reduction schemes, and the government is unable to keep up with the pace of technological change [98]. According to the GSMA Consumer Survey 2022, about 39% of people living in Nigeria's urban areas and 34% of those in rural areas are unable to afford a smartphone to access the internet [102]. Similarly, 4% of people living in Nigeria's urban areas and 6% of those in rural areas are unable to afford internet subscriptions to access the internet [102].
- Literacy Skills: Citizens of Nigeria lack the skills needed to live, learn, and work in a society that requires communication and access to information through digital technologies for various reasons [104]. According to the GSMA Consumer Survey 2022, about 2% of people living in Nigeria's urban areas and 4% of those in rural areas do not know how to access the internet on a mobile phone [102]. About 3% of people living in Nigeria's urban areas and 3% of those in rural areas do not know how to use a mobile phone [102]. About 20% of people living in Nigeria's urban areas and 29% of those in rural areas do not know how to read or write [102]. About 2% of people living in Nigeria's urban areas and 2% of those in rural areas do not have time to learn how to access the internet on a mobile phone [102]. About 3% of people living in Nigeria's urban areas and 0% of those in rural areas claim not to have sufficient support in learning how to use the internet on a mobile phone [102].
- Relevance: People claim that one of the reasons for not accessing the internet is the lack of useful content and services that provide enough justification to invest time and resources into accessing the internet [102]. People claim that they do not find the internet useless or uninteresting, while others claim there is not enough information in their native language on the internet [102]. The underdeveloped and under-resourced local digital ecosystems in low- and middle-income countries (LMIC), including Nigeria, have decelerated the growth of local content, services, and applications to meet people's needs

in their language [102]. According to the GSMA Consumer Survey 2022, about 11% of people living in Nigeria's urban areas and 7% of those in rural areas are of the orientation that the internet is boring and of no use to them [102]. About 2% of people living in Nigeria's urban areas and 1% of those in rural areas do not access the internet because there is no sufficient content in their local language [102].

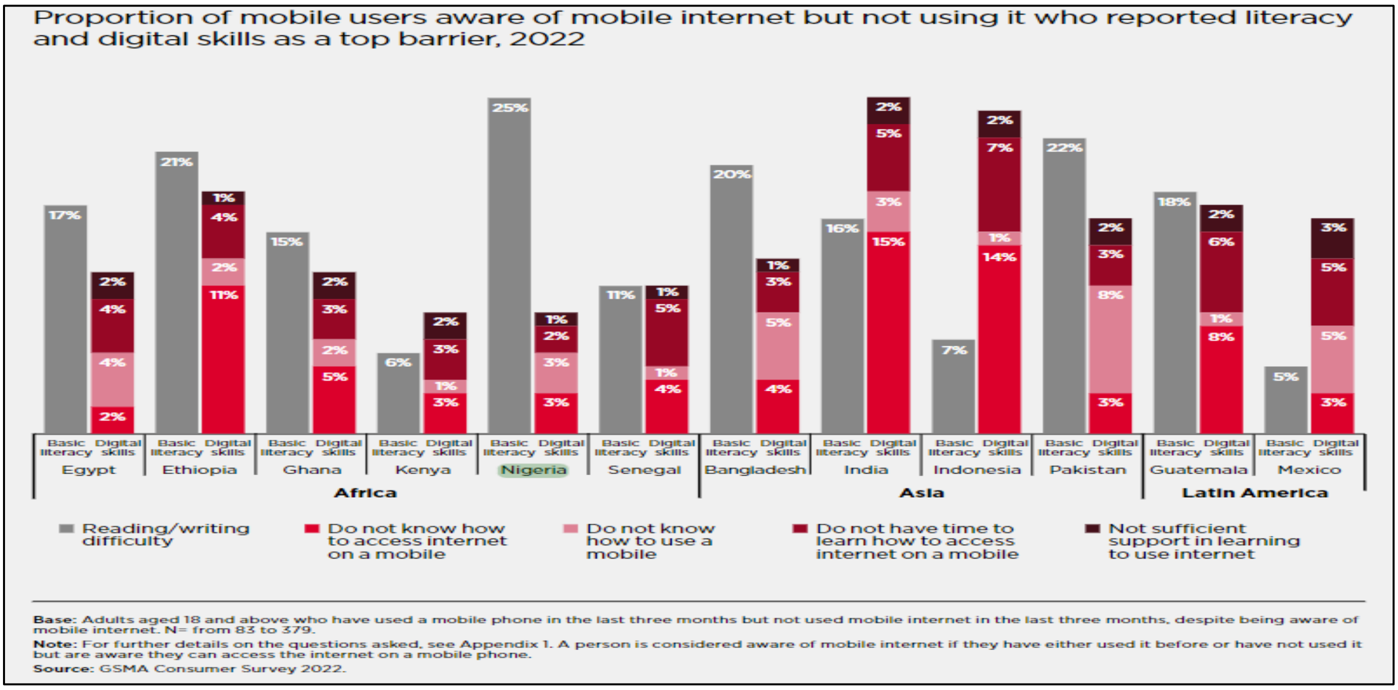
- Safety and Security: There are several concerns relating to safety and security that prevent people from accessing the internet, including online harassment or cyberbullying, misinformation, disinformation, identity theft, fraud, exposure to harmful content, and unwanted contacts like scam emails or unwanted messages [102]. According to the GSMA Consumer Survey 2022, about 2% of people living in Nigeria's urban areas and 2% of those in rural areas do not access the internet due to fear of harmful content [102]. About 4% of people living in Nigeria's urban areas and 1% of those in rural areas do not access the internet due to fear of contact with strangers [102]. About 2% of people living in Nigeria's urban areas and 2% of those in rural areas do not access the internet due to fear of information security [102].
- Education, Research, and Development/ Brain Drain: Education is one of the prerequisites to a sustainable adoption of technology infrastructures [104]. However, Nigeria's education sector, from primary to tertiary level, is underfunded [104]. The low ratio of scientists on the continents, including Nigeria, compared to other parts of the world, slows down research and development activities to improve technology infrastructures [104]. As a result of the low standard of living, intellectuals in Africa migrate to Western countries for greener pastures, causing a brain drain of people that could provide potential solutions [104].
- Access: Accessing the internet is mutually exclusive to various factors such as power supply, Quality of Service of the internet and telecommunication services/ Ineffective management of network traffic and infrastructure, and Smartphone ownership [102] [104]. The following point elaborates on the cause of digital divide due to access in Nigeria;

- Computers and other ICT devices depend on power supply to stay on or charge their batteries. Epileptic power supply has been one of the main issues facing Nigeria, and only a few privileged Nigerians can afford alternatives like power generators and solar-powered systems [104]. The lack of good electricity infrastructure and erratic power supply problem has hindered ICT training and development efforts, most especially in Nigeria's rural areas [102] [104].
- Poor Quality of Service of the Internet and Telecommunication Services/ Ineffective Management of Network Traffic and Infrastructure: Telecommunication service providers in Nigeria, including MTN, Airtel, Globacom, and 9mobile, outsource their managed services to the major telecommunication vendors, including Huawei, Nokia, and ZTE, [99] [104]. These vendors are responsible for providing and installing the hardware such as fibers, baseband units (BBU), BSC, radio network controller (RNC), remote radio unit (RRU), Antennas, routers, switches, and so on used at the service provider's base station [Author's Construct]. The vendors are also responsible for remotely monitoring each of the base stations, providing radio frequency planning and optimization and data communication [Author's Construct].

However, network coverage has various root cause problems, including low signal strength, equipment capability, service data rate, path loss, and network interference. Low signal strength occurs due to low transmit power; Path loss occurs due to site density, that is, when there are insufficient base stations, engineering parameter problems, i.e., improper antenna height, down tilt angles, azimuth, gains, and loss, geography and terrains such as tall buildings, and mountains causing poor indoor coverage and insufficient sites, and incorrect frequency bands as under the same coverage, high frequencies require more sites than low frequencies [29].

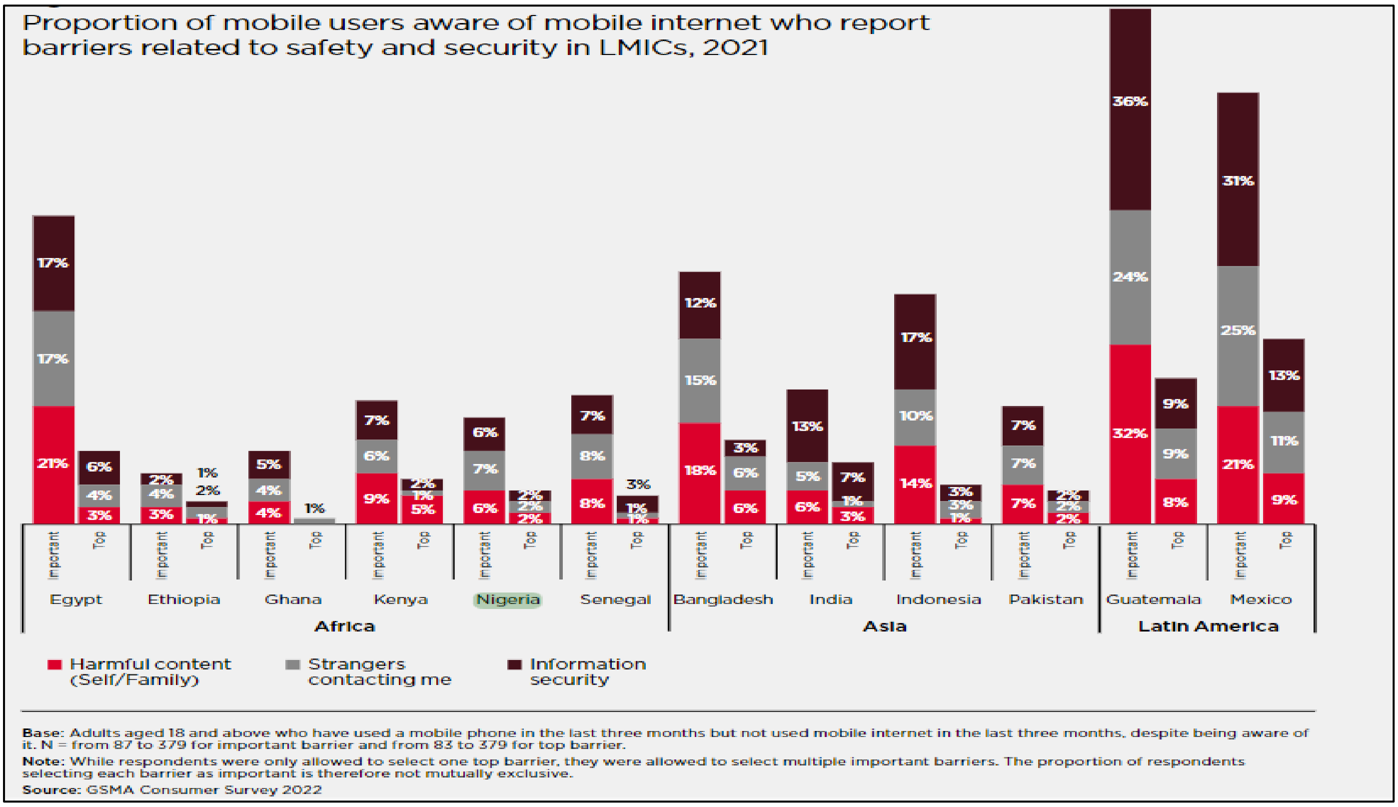
Furthermore, improper handover timeliness by the telecommunication vendor's radio frequency engineers due to parameter problems or missing neighboring cells also causes network downtime. Handover is the process of transferring a call or data session from one base station to another to maintain uninterrupted service [29]. We could have intra-network interference and inter-network interference. Intra-network inference occurs due to overshoot coverage, interference between neighboring cells, frequency primary scrambling code (PSC)/Public Service Identity (PSI) conflict, Adjacent-channel/co-channel interference, and Pilot pollution due to the detection of too many plot/reference signals from different base stations or cell towers, Overshoot coverage, and interference between neighboring cells. We could also have inter-network interference, where the disruption of signal quality comes from other networks or from illegal equipment such as Network Booster or Network Jammer.

Network Jammer are devices that emit radio frequencies that interferes with the communication between mobile stations and cell towers to blocks cellular signals preventing mobile devices from connecting to cellular networks. However, they are useful for security reasons in military bases, prisons, and government facilities to prevent unauthorized communication. However, some Nigerian citizens deliberately use these devices to block communication in open spaces. On the other hand, Network Boosters are devices that capture weak signals from cell towers, amplify the signals, and rebroadcast the amplified signal within a specified area. Network boosters are mainly used by businesses in congested areas to improve mobile signal strength, reduce dropped calls, and enhance data speeds. However, the rebroadcasting of the amplified signals to a specific area causes network downtime in other areas that the cell towers should cover. Network boosters are mostly used by businesses in the Alaba International market and the Eko Idumota market in Lagos, Nigeria, due to congestion in those areas. Telecommunication vendors and Network providers are cooperating with the Nigeria Communication Commission (NCC) and law enforcement agencies to reduce the use of Network boosters in these areas.


Proportion of mobile users aware of mobile internet but not using it who reported literacy and digital skills as a top barrier, 2022

Base: Adults aged 18 and above who have used a mobile phone in the last three months but not used mobile internet in the last three months, despite being aware of mobile internet. N= from 83 to 379.
Note: For further details on the questions asked, see Appendix 1. A person is considered aware of mobile internet if they have either used it before or have not used it but are aware they can access the internet on a mobile phone.
Source: GSMA Consumer Survey 2022.

Fig 28 Mobile Internet awareness and non-usage rate across 12 LMICs due to lack of literacy and digital skills in 2022 [102].


Proportion of mobile users aware of mobile internet who report barriers related to safety and security in LMICs, 2021

Base: Adults aged 18 and above who have used a mobile phone in the last three months but not used mobile internet in the last three months, despite being aware of it. N = from 87 to 379 for important barrier and from 83 to 379 for top barrier.
Note: While respondents were only allowed to select one top barrier, they were allowed to select multiple important barriers. The proportion of respondents selecting each barrier as important is therefore not mutually exclusive.
Source: GSMA Consumer Survey 2022

Fig 29 Mobile Internet awareness and non-usage rate across 12 LMICs due to safety and security issues in 2021 [102]

As of 2022, Nigeria had a 19% inflation rate, with affordability being the major barrier to mobile internet use [102].

➢ *Impact of Digital Divide in Nigeria*

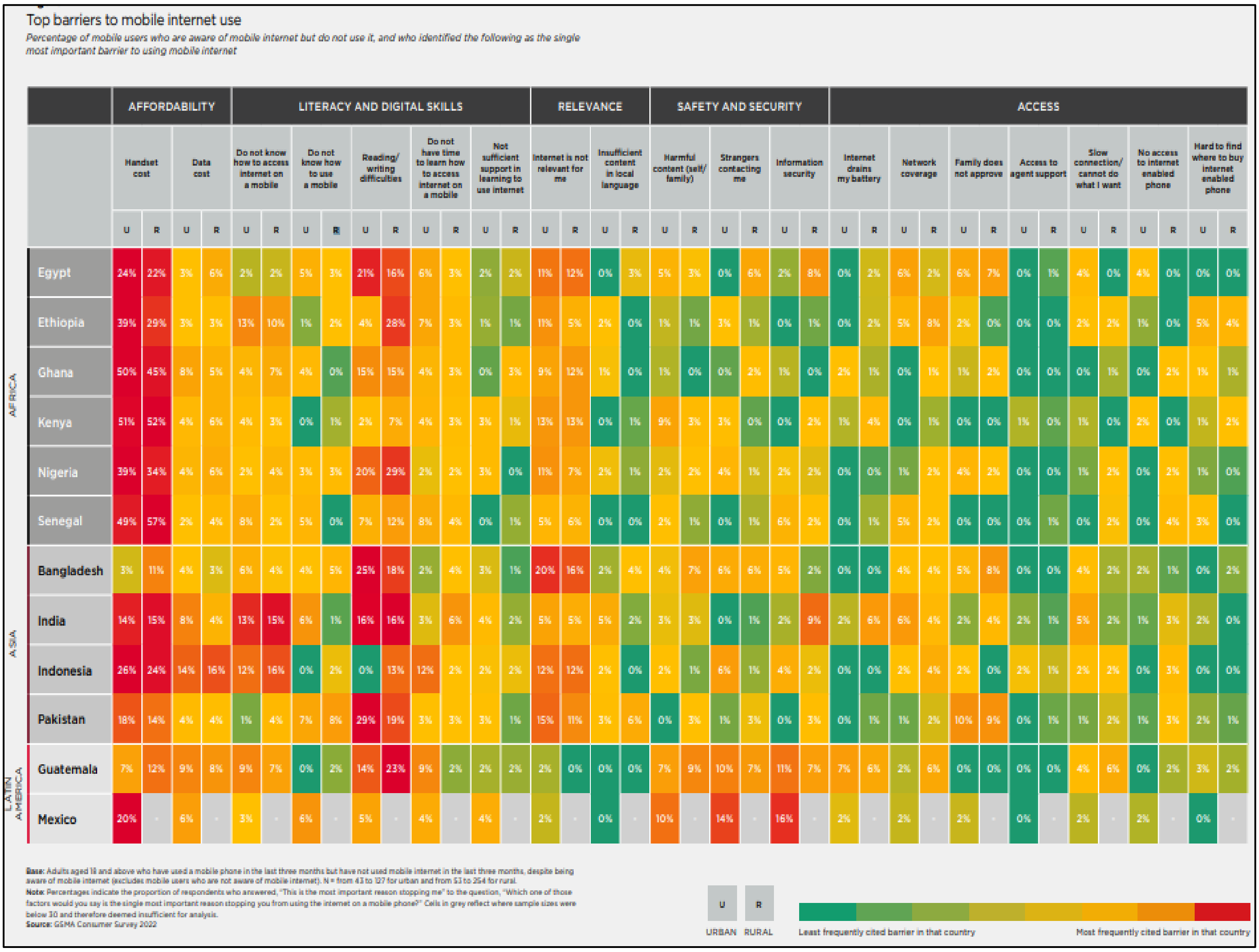
- The digital divide has caused a lack of inclusive society by increasing the socio-economic gap between the rich and the poor, abled and disabled, and so on [98].
- Digital divide in Nigeria has reduced the potential for commercial use by local entrepreneurs resulting to low e-commerce, unemployment and reduced economic growth [104].
- Lack of access to technology-driven instructional resources has caused low academic excellence [104].
- Digital divide in Nigeria has Increased poverty rate as many households lack internet services to access

opportunities for employment, or participate in modern world [98] [104].

- Digital divide in Nigeria has caused poor ICT based health delivery system due to low delivery of public health campaigns and basic hygiene [104].

➢ *Ways of Bridging Digital Divide in Nigeria (From Government and Citizens Perspective) [98]*

- Provision of ICT equipment in rural areas [98].
- The introduction of social security, as well as improved salaries and minimum wage, cushioned the effect of abject poverty [98].
- Using public spaces such as public schools, community centers, and public libraries as the primary locations for accessing and teaching computer skills to both adults and children [98].
- Investment in alternative power supply to sustain rural areas development and also bridge the gap between rural and urban areas in Nigeria [98].
- Creation of ICT policies to manage research activities, formulate sustainable ICT programs, and make computer education compulsory at primary and secondary school levels [98] [104].
- The Nigerian government and regulatory authorities such as NITDA (National Information Technology Development Agency), NCC (Nigerian Communications Commission), and CPN (Computer Professionals Registration Council of Nigeria) should provide a regulatory environment that favors telecommunication companies and consumers with the confidence and trust that will facilitate ICT-enabled development [104]
- The ministry of ICT should be headed by ICT-professional, who are knowledgeable enough to advise government on ICT implementation issues [104].
- Financial Institutions and other investment companies should invest more in IT projects to develop the ICT sector and support competent ICT companies [104].
- Subsidizing cost of computing hardware and access to telecommunication system such as open source and wireless technologies [98] [104].
- Telecommunication vendors such as Huawei provide real-time monitoring of network providers' base stations to identify the causes of network downtime and provide solutions to it. However, the majority of the solutions are manually done by RF optimization engineers. IoT networks or Machine learning algorithms could be integrated to provide faster-fixing solutions to network downtime [Author's construct].



Top barriers to mobile internet use

Percentage of mobile users who are aware of mobile internet but do not use it, and who identified the following as the single most important barrier to using mobile internet

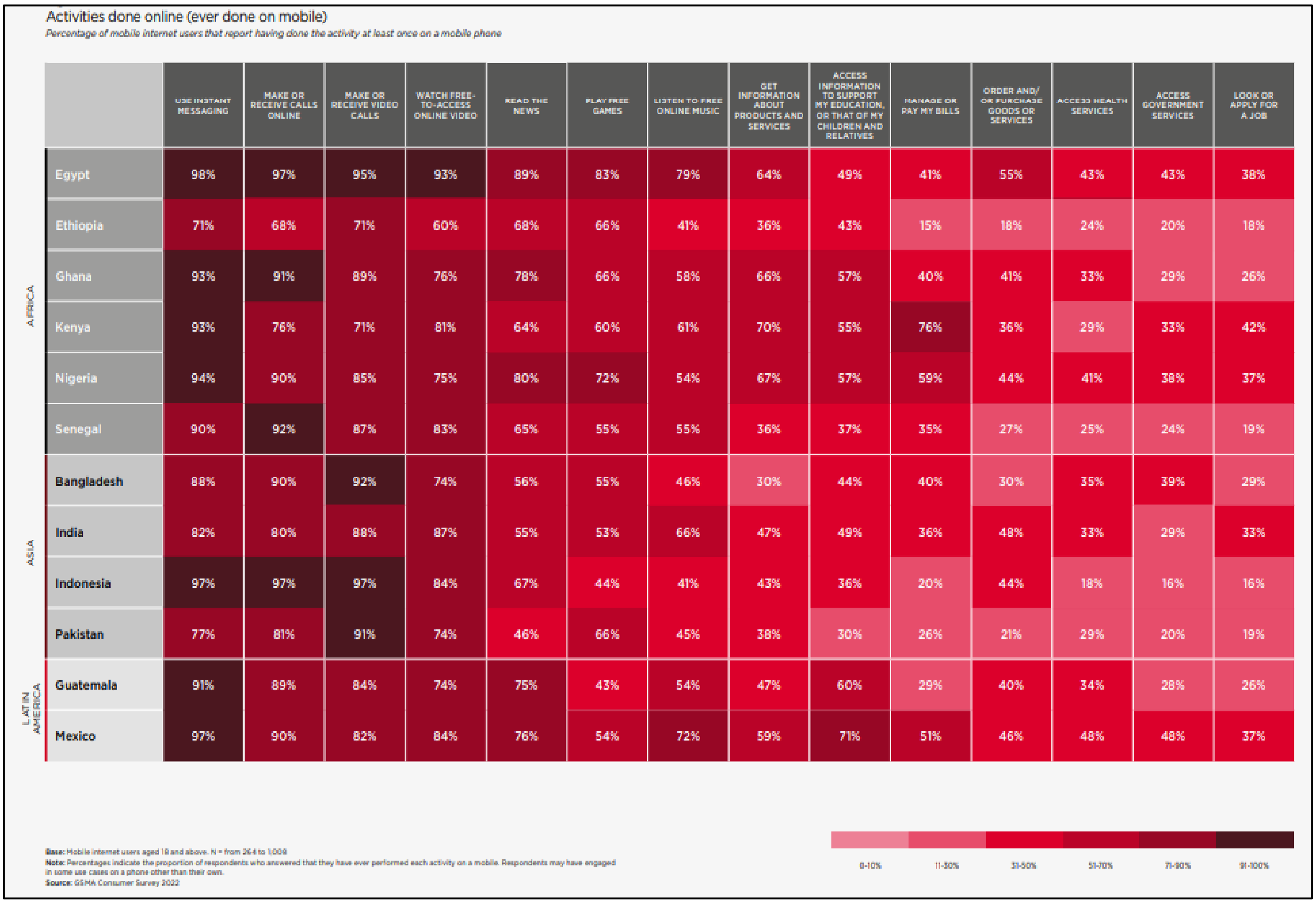
		AFFORDABILITY				LITERACY AND DIGITAL SKILLS										RELEVANCE				SAFETY AND SECURITY						ACCESS													
		Handset cost		Data cost		Do not know how to access internet on a mobile		Do not know how to use a mobile		Reading/ writing difficulties		Do not have time to learn how to access internet on a mobile		Not sufficient support in learning to use internet		Internet is not relevant for me		Insufficient content in local language		Harmful content (self/ family)		Strangers contacting me		Information security		Internet drains my battery		Network coverage		Family does not approve		Access to agent support		Slow connection/ cannot do what I want		No access to internet enabled phone		Hard to find where to buy internet enabled phone	
		U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R
AFRICA	Egypt	24%	22%	3%	6%	2%	2%	5%	3%	21%	16%	6%	3%	2%	2%	11%	12%	0%	3%	5%	3%	0%	6%	2%	8%	0%	2%	6%	2%	6%	7%	0%	1%	4%	0%	4%	0%	0%	0%
	Ethiopia	39%	29%	3%	3%	13%	10%	1%	2%	4%	28%	7%	3%	1%	1%	11%	5%	2%	0%	1%	1%	3%	1%	0%	1%	0%	2%	5%	8%	2%	0%	0%	0%	2%	2%	1%	0%	5%	4%
	Ghana	50%	45%	8%	5%	4%	7%	4%	0%	15%	15%	4%	3%	0%	3%	9%	12%	1%	0%	1%	0%	0%	2%	1%	0%	2%	1%	0%	1%	1%	2%	0%	0%	0%	1%	0%	2%	1%	1%
	Kenya	51%	52%	4%	6%	4%	3%	0%	1%	2%	7%	4%	3%	3%	1%	13%	13%	0%	1%	9%	3%	3%	0%	0%	2%	1%	4%	0%	1%	0%	0%	1%	0%	1%	0%	2%	0%	1%	2%
	Nigeria	39%	34%	4%	6%	2%	4%	3%	3%	20%	29%	2%	2%	3%	0%	11%	7%	2%	1%	2%	2%	4%	1%	2%	2%	0%	0%	1%	2%	4%	2%	0%	0%	1%	2%	0%	2%	1%	0%
	Senegal	49%	57%	2%	4%	8%	2%	5%	0%	7%	12%	8%	4%	0%	1%	5%	6%	0%	0%	2%	1%	0%	1%	6%	2%	0%	1%	5%	2%	0%	0%	0%	1%	0%	2%	0%	4%	3%	0%
ASIA	Bangladesh	3%	11%	4%	3%	6%	4%	4%	5%	25%	18%	2%	4%	3%	1%	20%	16%	2%	4%	4%	7%	6%	6%	5%	2%	0%	0%	4%	4%	5%	8%	0%	0%	4%	2%	2%	1%	0%	2%
	India	14%	15%	8%	4%	13%	15%	6%	1%	16%	16%	3%	6%	4%	2%	5%	5%	5%	2%	3%	3%	0%	1%	2%	9%	2%	6%	6%	4%	2%	4%	2%	1%	5%	2%	1%	3%	2%	0%
	Indonesia	26%	24%	14%	16%	12%	16%	0%	2%	0%	13%	12%	2%	2%	2%	12%	12%	2%	0%	2%	1%	6%	1%	4%	2%	0%	0%	2%	4%	2%	0%	2%	1%	2%	2%	0%	3%	0%	0%
	Pakistan	18%	14%	4%	4%	1%	4%	7%	8%	29%	19%	3%	3%	3%	1%	15%	11%	3%	6%	0%	3%	1%	3%	0%	3%	0%	1%	1%	2%	10%	9%	0%	1%	1%	2%	1%	3%	2%	1%
LATIN AMERICA	Guatemala	7%	12%	9%	8%	9%	7%	0%	2%	14%	23%	9%	2%	2%	2%	2%	0%	0%	0%	7%	9%	10%	7%	11%	7%	7%	6%	2%	6%	0%	0%	0%	0%	4%	6%	0%	2%	3%	2%
	Mexico	20%	-	6%	-	3%	-	6%	-	5%	-	4%	-	4%	-	2%	-	0%	-	10%	-	14%	-	16%	-	2%	-	2%	-	2%	-	0%	-	2%	-	2%	-	0%	-

Base: Adults aged 18 and above who have used a mobile phone in the last three months but have not used mobile internet in the last three months, despite being aware of mobile internet (excludes mobile users who are not aware of mobile internet). N = from 43 to 127 for urban and from 53 to 254 for rural.
Note: Percentages indicate the proportion of respondents who answered, "This is the most important reason stopping me" to the question, "Which one of those factors would you say is the single most important reason stopping you from using the internet on a mobile phone?" Cells in grey reflect where sample sizes were below 30 and therefore deemed insufficient for analysis.
Source: GSMA Consumer Survey 2022

U URBAN R RURAL

Least frequently cited barrier in that country — Most frequently cited barrier in that country

Fig 30 Top Barriers to Mobile Internet usage across 12 LMICs [102].



Activities done online (ever done on mobile)

Percentage of mobile internet users that report having done the activity at least once on a mobile phone

		USE INSTANT MESSAGING	MAKE OR RECEIVE CALLS ONLINE	MAKE OR RECEIVE VIDEO CALLS	WATCH FREE-TO-ACCESS ONLINE VIDEO	READ THE NEWS	PLAY FREE GAMES	LISTEN TO FREE ONLINE MUSIC	GET INFORMATION ABOUT PRODUCTS AND SERVICES	ACCESS INFORMATION TO SUPPORT MY EDUCATION, OR THAT OF MY CHILDREN AND RELATIVES	MANAGE OR PAY MY BILLS	ORDER AND/ OR PURCHASE GOODS OR SERVICES	ACCESS HEALTH SERVICES	ACCESS GOVERNMENT SERVICES	LOOK OR APPLY FOR A JOB
AFRICA	Egypt	98%	97%	95%	93%	89%	83%	79%	64%	49%	41%	55%	43%	43%	38%
	Ethiopia	71%	68%	71%	60%	68%	66%	41%	36%	43%	15%	18%	24%	20%	18%
	Ghana	93%	91%	89%	76%	78%	66%	58%	66%	57%	40%	41%	33%	29%	26%
	Kenya	93%	76%	71%	81%	64%	60%	61%	70%	55%	76%	36%	29%	33%	42%
	Nigeria	94%	90%	85%	75%	80%	72%	54%	67%	57%	59%	44%	41%	38%	37%
	Senegal	90%	92%	87%	83%	65%	55%	55%	36%	37%	35%	27%	25%	24%	19%
ASIA	Bangladesh	88%	90%	92%	74%	56%	55%	46%	30%	44%	40%	30%	35%	39%	29%
	India	82%	80%	88%	87%	55%	53%	66%	47%	49%	36%	48%	33%	29%	33%
	Indonesia	97%	97%	97%	84%	67%	44%	41%	43%	36%	20%	44%	18%	16%	16%
	Pakistan	77%	81%	91%	74%	46%	66%	45%	38%	30%	26%	21%	29%	20%	19%
LATIN AMERICA	Guatemala	91%	89%	84%	74%	75%	43%	54%	47%	60%	29%	40%	34%	28%	26%
	Mexico	97%	90%	82%	84%	76%	54%	72%	59%	71%	51%	46%	48%	48%	37%

Base: Mobile internet users aged 18 and above. N = from 264 to 1,009
Note: Percentages indicate the proportion of respondents who answered that they have ever performed each activity on a mobile. Respondents may have engaged in some use cases on a phone other than their own.
Source: GSMA Consumer Survey 2022

Fig 31 Activities done Online across 12 LMICs [102]

- *Effects of Improved Connectivity/Emerging Technologies Like Starlink, How it can Work and be done in a Sustainable Way Using Nigeria as a Case Study.*

Improved connectivity caters to all the aforementioned impacts of the digital divide in Nigeria [106]. For instance, the proportion of households in extreme poverty decreases by 4% after one year of mobile broadband coverage and 7% after two years [106]. Between 2010 and 2015, about 2.5 million Nigerians were out of extreme poverty due to increased mobile broadband coverage [106]. The welfare effects of improved mobile broadband coverage are more pronounced and visible in rural households [106]. Some emerging technologies can also help in bridging the digital divide. For instance, Artificial Intelligence (AI) could help network operators conduct better planning and prevent fraud [107]. However, a sustainable approach to this is when government aligns national policies and regulatory frameworks to achieve the impact [107]. In 2024, the Global Symposium for Regulators (GSR-24) highlighted Africa's National Broadband Mapping Systems project, supported by the European Commission, to create broadband mapping systems to aid digital transformation in Africa [107]. The project has a budget of EUR 15 million over four years with 11 beneficiary countries, including Nigeria [107].

Another emerging technology is satellite networks, which provide a significant means of internet connectivity even to remote areas and are widely deployed globally [108]. The most common satellite internet service in Nigeria is Space X's Low Earth Orbit (LEO) constellations with Starlink [108]. Starlink provides internet coverage to Nigeria's remote areas lacking fiber backbone [109]. For better and more sustainable solutions, Starlink could also collaborate with telecommunication providers and energy companies to facilitate the deployment of satellite receivers in some rural areas and address unreliable power supply. Despite being a major internet service provider in Nigeria, Starlink is unaffordable for an average Nigerian citizen living in a remote area as the installation of a new Starlink kit cost NGN 590,000 (USD 353.4) with a monthly subscription of NGN 75,000 (USD 50) as of 2024, which is above the minimum wage of 70 000 Naira ($43) in Nigeria [110] [111] [112]. The government should provide a favorable regulatory environment, subsidies, and public-private partnerships to lower the cost of accessing emerging technologies like Starlink.

XI. CONCLUSION

The advancement of wireless technology illustrates the world's ongoing yearning for connectivity, innovation, and growth. From voice communication using analog technology in 1G to the paradigm shift in the introduction of multimedia data in 3G, each generation leap addressed the deficiencies of the preceding generation while bringing game-changing capabilities. At this point, the First Generation established the foundation for analog cellular systems, the Second Generation introduced digital networks that improved voice quality and enabled basic text communication, and the Third Generation revolutionized mobile technology with packet-based data services that enabled mobile internet access, video calls, and multimedia messaging. This progress has gone hand in glove not only to ensure efficiency and functionality for mobile networks but also to bring a sea change in the social perspective. These developments have, as a matter of fact, enabled seamless communication to and from any part of the world, giving rise to social media, and mobile applications that are increasingly interlinking people and businesses in ways unimaginable, from Basic Telephony to Dynamic Multimedia Services: A well-marked journey of integration and interlinking, which is continued by the Fourth and Fifth Generation networks. As wireless technology continues to evolve, it is not only a technical achievement but also a societal enabler that closes gaps in communication, spurs innovation, and creates economic growth. The progress shows advancement in different areas and how the development of new technologies has revolutionized the way we connect and communicate in the digital era. Understanding this history is crucial for anticipating the challenges and opportunities that future generations of wireless technology will bring, ensuring that they continue to drive positive global transformation. Further, there are new technologies that will be incorporated into the new 6G telecommunication systems, which are yet to be defined by the standard bodies. The review also analyzed the digital divide in Nigeria catering to ITU's Sustainable Development Goal (SDG) target SDG 9 (Industry, Innovation, and Infrastructure), specifically targeting 9c, which aims to "significantly increase access to information and communications technology and strive to provide universal and affordable access to the internet in underdeveloped countries".

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