A Survey of Wireless Cellular Network Generations and Their Channel Access Techniques

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Abstract - *The world of Wireless Cellular Communication (WCC) has achieved several top-notch transformations. This is due to the increasing innovations in Channel Access (CA) techniques. CA can be referred to as the methods of injecting life into a wireless network for the activation of varying air interfaces. It can also be defined as a technique used to ensure the modulated signal is properly fit-in a required communication channel for effective transmission. This transformation is recorded in every upgrade of air-interfaces in WCC generations. Air-interfaces mean variations in communication systems, which is consistent with frequency of operation ranges. WCC is divided into different successive generational shifts, which vary in frequencies of operation, in a successive ten-year circle. Starting in the 1970s, it has so far metamorphosed from Zero Generation (0G) through Fifth Generation (5G), with each air-interface frequency being activated by its varying CA techniques. In trying to meet the changing customer's demands and equipment advancements, which are the increasing operational bandwidth and mitigation of loss of transmission information, new and advanced air interfaces have now been assigned frequencies of deployment. This is possible as a result of constant innovations and upgrades in CAs, which serve as the reagents in the modification of modern wireless signal waveforms. This research conducted a survey on the existing commercial air-interface generations of WCC systems so far achieved/deployed relative to its CAs. Trusting that this will ignite researchers to conceive novel proposals on highly scalable CA techniques that will drive up-coming versions of air-interface frequencies of WCC networks.*

Keywords: WCC, Air-Interfaces, CA, Network Life, 0G, 5G.

1 Introduction

Cellular generations differ in four main aspects: radio systems, data rates, bandwidth, and switching schemes (Kumar, 2015). Precisely, Wireless Cellular Communication (WCC) started in the early 1970s but was made commercially available in the early 80s (Bliley's Technology, 2017). Consequently, in just four decades (in a ten-year circle rule), WCC technology has evolved from Zero Generation (0G) to Fifth Generation (5G). Its first mobile network was fully achieved by the activation of First Generation (1G) frequencies. Mobile frequency activation occurs as a result of the constant innovations and continuous advancement in Channel Access (CA) techniques, in conjunction with the required bandwidth and frequency of operations (Lu & Zheng, 2020). This is seen in the progressive performance of the wireless communication world. This transformation transits from 1G to the Second and a Half Generation (2.5G), to the Third Generation (3G) through 5G. 5G offers many advanced network resources that equipment users never experienced in the past, while Sixth Generation (6G) is at the developing stage with a projection of global coverage using technologies that could enhance the integration of satellite-terrestrial communication.

The 6G generation is likely to benefit from AI emerging technologies. Generative AIs, based on machine learning/deep learning models that generate new data from large datasets, can also have a significant impact on 6G wireless technologies research. For example, they could be used to predict new points of communication links, and find the fastest route for data packet transfer in the internet network. Other AI technologies, such as evolutionary algorithms that use neural network controllers, can be hybridised with generative models to predict optimal communication channels and network routes. For instance, the generative model can be used to generate new data from existing data where the dataset are not large enough for the training of deep neural network whose weights, parameters, or topologies/architectures are synthesized by evolutionary algorithms which are then used to make improved predictions.

These aforementioned generations of wireless communication are all geared towards meeting users' demands, equipment requirements, and advancements in wireless network services. This is obtained by overcoming the limitations of previous generations in areas of data rate, bandwidth utilization, effective power allocation, interference mitigation, and more.

To achieve the required network efficiency, various CA methods were proposed by scholars but the Multiple Access (MA) techniques in the frequency, time, or code domain were more widely accepted and commercially deployed (Liu et al., 2024). As illustrated in Figure 1, the Frequency Division Multiple Access (FDMA) technique is used to drive 1G objectives, the Time Division Multiple Access (TDMA) technique is deployed in 2G and 2.5G, and the Code Division Multiple Access (CDMA) is used to run the 3G and part of 4G. Advanced research to overcome the drawbacks noticed in CDMA conceived the development of the Orthogonal Frequency Division Multiplexing (OFDM) techniques that successfully made the 4G mandate fully realizable. A classical advancement in OFDM technique known as the Cyclic Prefix-OFDM (CP-OFDM) also enabled the Long-Term Evolution-Advanced (LTE-A) (Cai et al., 2018). The FDMA, TDMA, and CDMA are based on a serial kind of transmission, which has the disadvantage of greater loss of signal strength and information caused by self-jamming, adjacently placed symbols aliasing, shadowing, multipath fading, interference, and many more signal distortions (Zahra et al., 2021). The OFDM CA, on the other hand, is also noticed to be subdued by strings of signal anomalies, which results in transmission inefficiency (Zou et al., 2021). It is observed that in OFDM, the radio wave resources are not effectively used because of its inherent exhibition of high Peak to Average Power Ratio (PAPR) and Out-of-Bound Emission (OoBE). Its synchronous mode of transmission also impacted negatively on its transmitted resources in achieving the required spectrum slicing for higher air-interfaces.

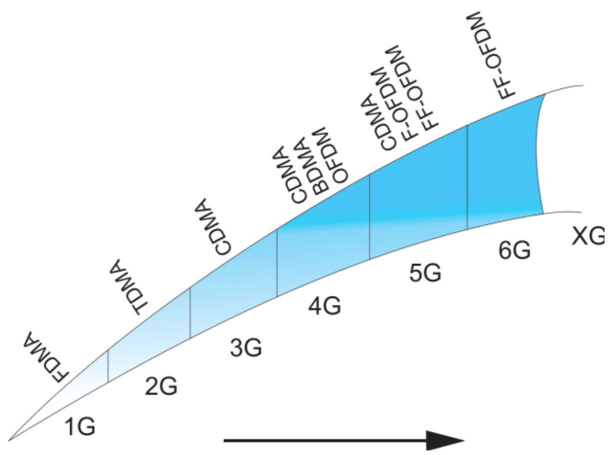

Figure 1: Wireless network air-interfaces relative to each channel access technique

In order to relax synchronization and achieve the required asynchronous transmission to meet the present-day proliferations of WCC devices and users' services, special cases of OFDM CA techniques were developed (Zhang et al., 2017). One of which is the Orthogonal Frequency Division Multiple Access (OFDMA). The OFDMA-CA is orthogonally engineered to allocate subsets of subcarriers that are aliases to each other for the modulating of the parallel data samples. This helps in overcoming the demerit experienced in earlier MA techniques (Arrano & Azurdia-Meza, 2016; Ramadhan, 2019). These drawbacks of OFDM led to the development of more successive and modified versions of MA in the classes of Orthogonal Multiple Access (OMA) and Non-Orthogonal Multiple Access (NOMA) transmissions (Liu et al., 2024). This is to enable the expectations of advanced air-interfaces in the areas of peak data rates in ultra-high reliability, data rates in gigabits and terabits per second, extremely low latency, and massive connectivity (Cai et al., 2018).

Some of the OMA CA techniques are Windowed OFDM (W-OFDM), Filter Bank Multi-Carrier (FBMC), Universal Filtered Multi-Carrier (UFMC), Generalized Frequency Division Multiplexing (GFDM), Filtered-OFDM (F-OFDM), and Feedback Filtered OFDM (FF-OFDM), and more (Sahrab & Yaseen, 2021; Augustine et al., 2021). These OMA schemes can only support limited numbers of users due to drawbacks in the numbers of orthogonal Resource Blocks (RB), which limits the SE and the capacity of the network (Cai et al., 2018). In order to support a massive number of applications and dramatically different classes of users in 5G networks, various new NOMA CA schemes were developed. Some of these emerging NOMA techniques consists of Power Domain (PD), Pattern Division Multiple Access (PDMA), Lattice Partition Multiple Access (LPMA), Building-block sparce constellation based Orthogonal Multiple Access (BOMA), Sparce Code Multiple Access (SCMA), Low-Density Spread CDMA (LDS-CDMA), and their variants (Cai et al., 2018; Liu et al., 2024). Unlike the OMA, the NOMA facilitate users to utilize the same spectrum with advanced transceiver configuration to manage interference in multiple access. While the OMA techniques are driven by Fourier and spatial based techniques, the NOMA is considered in both power, code, and spatial domain techniques (Liu et al., 2024).

Depending on the requirement, these classes of CA schemes make it possible for the message signal to be suppressed or superimposed and modulated in an EMW radio domain with negligible loss in energy and information. This advancement in the innovations of CA technique has proven its uniqueness of capability in the area of accentuating useful signals from interference and many more signal distortions suffered by earlier generations of wireless mobile technologies. The motivations behind this survey are to:

a) exploit on the successes and drawbacks of existing generations of WCC air-interfaces relative to their CA schemes;
b) explore on the objectives of the present generation of air-interfaces relative to their CA schemes;
c) highlight on the need for more advanced and sophisticated access schemes with high scalability that could overcome the Red Trend Curve (RTD) currently experienced in the 5G air-interface in order to drive the upcoming resources of WCC generations; and
d) stress on the need for a paradigm shift in access technology using AI and/or the development of novel frameworks to advance the course of Next Generations (XG) of air-interfaces.

2 The Evolution of Mobile Cellular Network Technology

In a ten-year cycle, the human society has been transformed through five generations of wireless mobile networks of WCC evolution. These mobile generations are namely 1G, 2G, 3G, 4G, and 5G networks (Attaran, 2021). Each generation of WCC has different landmarks in practice, capabilities, and values, which distinguish it from the previous air-interfaces (Kumar & Sumit, 2021). 1G brought about the mass-market mobile telephony, 2G made the wireless handover possible, and the reliable mobile telephony and global interoperability that made SMS text messaging possible were provided by 3G. 4G also gave a significant improvement in high-speed and data capability and made online platforms for mobile internet services available (Attaran, 2021). The most powerful cellular wireless network recently unveiled is 5G. It is built with extraordinary data capabilities, infinite data broadcast, and unrestricted call volumes. The 1G to 5G evolution was characterized mainly by a shift in the CA methods using OMA and NOMA modulation schemes, which were also advanced to amicably meet the objectives of 5G and Next Generation Multiple Access (NGMA) techniques (Chávez-Santiago et al., 2015; Liu et al., 2024). These modulation schemes were also noticed with some inherent limitations that impede them from driving the objectives of the next generation (XG) of WCC effectively. The five generations of wireless mobile networks so far deployed are elaborated and the prospective 6G is also discussed.

2.1 First Generation

The WCC mobile air-interface mobile networks originated from 1G. It was developed in the 1980s using analogue cellular technology with a frequency of 150 MHz and only operates on voice call transmission modulation (Salih et al., 2020). It enables the use of multiple cell sites and the ability to hand-off calls as the user travels between cells during a conversation (Attaran, 2021). It operates on circuit switching. The first commercial edition was launched in Japan by NTT in 1979, and years later an upgraded version was launched in the US by Bell Laboratory in 1984. 1G networks are built on a speed of 2.4 Kbps only and is based on Advanced Mobile Phone System (AMPS) technologies. This is useful for language advantages and Total Access Communications System (TACS) (Salih et al., 2020; Kumar & Sumit, 2021). The AMPS device is modulated and multiplexed to reduce radio communication traffic in frequency using FDMA. 1G has a frequency range from 824 MHz to 894 MHz and uses a channel of 30 kHz (Kumar & Sumit, 2021). The FDMA has a limitation of allotting a single channel per carrier, which results in lots of bandwidth wastage. It also has narrow bandwidth and high cell site cost. As such, it could only transport one phone circuit at a time. This results in nonlinear intermodulation products. The intermodulation frequencies also cause time consumption and Adjacent Channel Interference (ACI) in network planning.

1G WCC has several additional disadvantages, which include deprived battery lifespan, deprived sound quality, inadequate storage, low telephone power, poor health, low-quality handling, low spectrum performance, weak voice links, and unreliable handoff (Kumar & Sumit, 2021; Attaran, 2021). The utilization of analogue signals (which are easily affected by impairment) is the biggest drawback to the 1G WCC scheme. This makes it slow and less reliable in transmission (Kumar & Sumit, 2021).

2.2 Second Generation

The 2G WCC air-interface was built on digital standards (Attaran, 2021). It was launched in the early 1990s. It operates on circuit switching. This was the first digital wireless network that enabled the advent of prepaid mobile phones and helped in rapid phone-to-network signalling. It initialized the text messaging SMS on Global System for Mobile Communication (GSM) networks and eventually on all digital networks. 2G has driven below a normal GSM in Finland through 1991 (Salih et al., 2020). Its frequency ranges from 30 kHz to 200 kHz. The 2G wireless networking networks of modes of inventions is based on these three: IS-136 in 1996, IS-54 (TDMA) in 1991, and IS-95 (CDMA) in 1993. The drawbacks in TDMA are that each user has a predefined time slot so that users roaming from one cell to another are not allotted the same time slot. The network is subjected to multipath distortion, network and spectrum planning is intensive, and too few users result in ideal channels of communication between rural and urban environments.

In advancement to 2G is 2.5G, which utilizes both circuit and packet switching modes of operation. The WCC system of 2.5G is deployed based on General Packet Radio Service (GPRS), CDMA, and Enhanced Data-rate for GSM Evolution (EDGE), which are embedded into the circuit of the wireless device (Kumar & Sumit, 2021). Interestingly, the 2G and 2.5G digital capabilities allow signal data rate ranges of 64 kbps and 144 kbps, respectively. This enables content such as strong signal quality, still imaging, text messages, and multimedia messages (voice and image messages). Additional advantages of the WCC 2G digital system compared to 1G include voice clarity, noise reduction, and battery power consumption reduction. Environment friendliness is part of the benefits of digital signals; as such, to achieve safety in voice calls and data transmission, digital encryption is adopted (Attaran, 2021). The biggest disadvantage of the 2G scheme to overawe the coming 3G scheme is its slow signal speed as compared to users' needs.

2.3 Third Generation

The 3G WCC air-interface provides high-speed data transfer capability for downloading information from the Internet and for sending videos with the speed of 2 Mbps (Attaran, 2021). Its frequencies were first introduced for commercial purposes in 1998. Its high-speed web surfing and video messaging operate on 15-20 MHz bandwidth and a frequency of 2100 MHz (Salih et al., 2020; Kumar & Sumit, 2021). 3G WCC uses fully packet switching instead of circuit switching, which is a great improvement over 2G (Attaran, 2021). In order to ensure stable communication over long distances, 3G technology passes signals using a network of phone towers. 3G handsets enable high connection speed of television content, massive media streaming of radio, and also provide video-conferencing support. It is estimated to offer a real-time speed of 2 Mbps for uploads and a maximum of 7.2 Mbps for downloads. An enhanced mobile telephony communications protocol in the mid-2000s developed an advanced 3G in the High-Speed Packet Access (HSPA) family, known as 3.5G, 3G+, or turbo 3G, which was implemented. The Universal Terrestrial Mobile Systems (UTMS) and Universal Mobile Telecommunications System (UMTS) operate based on 3G+ to have improved system capacity and higher data transfer speeds (Salih et al., 2020; Attaran, 2021).

The 3rd Generation Partnership Project (3GPP) is an association saddled with the responsibility to form the 3G standards and help in its deployment, which is in line with the International Telecommunication Union (ITU)-approved frequencies framework. The International Mobile Telecommunications (IMT) 2000 normal is also characterized by the 3GPP template (Salih et al., 2020). The 3G WCC network was first unveiled in Europe as UMTS, whilst its American version is tagged CDMA 2000 based on the channel access techniques used. The air-interface system for UMTS, known as Wideband Code Division Multiple Access (WCDMA) and Time Division-Synchronous Code Division Multiple Access (TD-SCDMA), is also an additional version of IMT 2000 3G stock coming from China (Kumar & Sumit, 2021). The major problem of the CDMA technique is synchronization and self-jamming (Zahra et al., 2020). Another problem with CDMA is scalability because of the increasing demand for higher data and transmission rates, which degrade its performance with an increase in the number of packets or users (Arrano & Azurdia-Meza, 2016).

The most important highlights for 3G WCC that make it better than its predecessors include increased data transmission rates and bandwidth, improved broadband, high-speed connectivity, increased email usage, high-speed web, 3D video games, mobile TV, TV calls, and power efficiency (Kumar & Sumit, 2021). The biggest drawbacks for 3G that are required of 4G and other advanced generations of networks to curtail are service operators' spendings of large amounts for 3G permits and infrastructures. Aside from the issue surrounding the high cost and supply of phone services, the demands for high-power utilization and special hardware need to be addressed (Kumar & Sumit, 2021).

2.4 Fourth Generation

The 4G WCC broadband infrastructure enabled seamless roaming from one device/network to another. It also interoperates between existing and future wireless network facilities by ensuring flexible access (Salih et al., 2020; Kumar & Sumit, 2021). 4G air-interface gives similar services as 3G but a little advanced multimedia, global accessibility, video streaming, TV digital media wide range transportability through gadgets, simpler information transferring, and many more. It was first launched in Stockholm followed by Oslo Norway in 2009 using Long Time Evolution (LTE) 4G normal technology, which uses OFDMA, OFDM, and Single Carrier -FDMA (SC-FDMA) as driven access factors (Salih et al., 2020). The 3GPP created LTE as a 4G Remote Interchange Standard (RIS). The ITU as a regulatory body set-up a 100 Mbps speed for 4G at full velocity. It was developed with a prospected speed improvements of 10-fold over the existing 3G technologies (Attaran, 2021). Its commercial version was first deployed in the United States by Verizon in 2011.

The 4G download standard speed is around 14 Mbps through 150 Mbps. Its peak data rate of 1Gbps was enabled by the American version known as LTE-A. It is an Internet Protocol (IP) based network, even for voice data. To send and receive data in packets, 4G uses a standard communications protocol. This standard enables it data to traverse all networks without being corrupted nor scrambled, that is, not all frequencies can be jammed illegally and privacy infringements is improved (Kumar & Sumit, 2021). The new frequencies created by 4G means a new path for the mobile tower. In its data transmission, the 4G WCC systems totally eliminated circuit switching by adopting an all-IP network design (Attaran, 2021).

With its capability to allow users to download gigabytes of data even in seconds. The 4G WCC air-interface enable users HD video streaming and web browse ability. Its technology turns smartphones into modern-age computers. 4G WCC frequencies fully complies with the proposal for high data rate and Quality of Service (QoS) requirements implemented in wireless wideband, Mobile TV (M-TV), and Multimedia Messaging Service (MMS) (Kumar & Sumit, 2021). The 4G's in its highlights has so far achieved 10Mbps- 1Gbps data rate, high security, low per-bit storage cost, high-quality digital videos, provision in video content creation, higher battery use. Its facilities run on a technology known as the evolved Node B (eNodeB) and mainly in the Evolved Packet Core (EPC). The 4G network is effective for internet data rates but not good for voice services. These services are both discharged into Wi-Fi or 3G wireless facilities, respectively. The aforementioned 4G drawbacks were anticipated to be resolved by the 5G technology.

One of the most deployable technologies used in driving the 4G WCC frequencies is the OFDM. This is as a result of increasing EU demands for better services. Between 2002 and 2004 the ITU and the 3GPP began studying the technology that would be used in the upcoming networks (Arrano & Azurdia-Meza, 2016). This latter arose because 3G CDMA-based systems were starting to experience problems in allowing further technological progress towards the predicted transmission rates for the coming years, known as the Red Trend Curve (RTC). When 4G was launched in 2010, the CDMA2000 (3G), obtained by intensive operations and perhaps by over-straightening its limits of technology, was able to obtain a downlink data transmission rate of about 14.7 Mbps using Evolution-Data Optimization Revision B (EV-DO Rev. B) techniques. EV-DO Rev. B is a telecommunication standard for data transmission in radio signals, typically deployed to triple the peak broadband data rate for broadband internet access in the existing EV-DO Rev. A.

The 4G WCC technology target has so far been successfully driven by OFDM and CP-OFDM schemes (Ramadhan, 2019). The former has the limitation of large side lobe emission and high Peak to Average Power Ratio (PAPR); the latter has poor spectral confinement, causes bandwidth wastage, and has an inflexible waveform. These drawbacks could not drive the present burden of EUs (Ramadhan, 2019).

2.5 Fifth Generation

The 5G WCC air-interface with the speed of approximately 1–10 Gbps, corresponds to the next frequencies of mobile network standards that is beyond the 4G LTE (Attaran, 2021). The 5G networks provide lower battery consumption, lower prices, and lower end-to-end latency than 4G wireless networks. These merits are because it uses Ultra-Wide Band (UWB) networks, which is achieved as a result of its higher band breadth at low energy levels. 5G system resources were in the market by the end of 2019 and began full commercial deployment in the year 2020 (Kumar & Sumit, 2021).

In comparison to earlier air-interface, 5G WCC frequencies offer unlimited broadcast data and extraordinarily high data capabilities. It works with the IP version 6 (IPv6) protocol. 5G is the present-day generation of wireless mobile broadband technology. Its main features include higher speed, reduced latency, simultaneous support for massive devices, energy saving, World Wide Wireless (WWW) Internet, proactive Software Defined Radio (SDR) stability, high data capability, big data transmission, massive data transfer in Gbps, high-resolution TV programs, multimedia newspapers, fast dial speeds, large memory telephones, smart hypermedia support, sound/visual illumination, effective voice/video networking, and flexible web services. Also, it is more efficient and attractive than previous generations of wireless technologies (Salih et al., 2020; Kumar & Sumit, 2021). In addition, it is the requirement for the Flexible Network Operations (FNO) (Stasio et al., 2018). Some of the 5G capabilities are summarized in Figure 2.

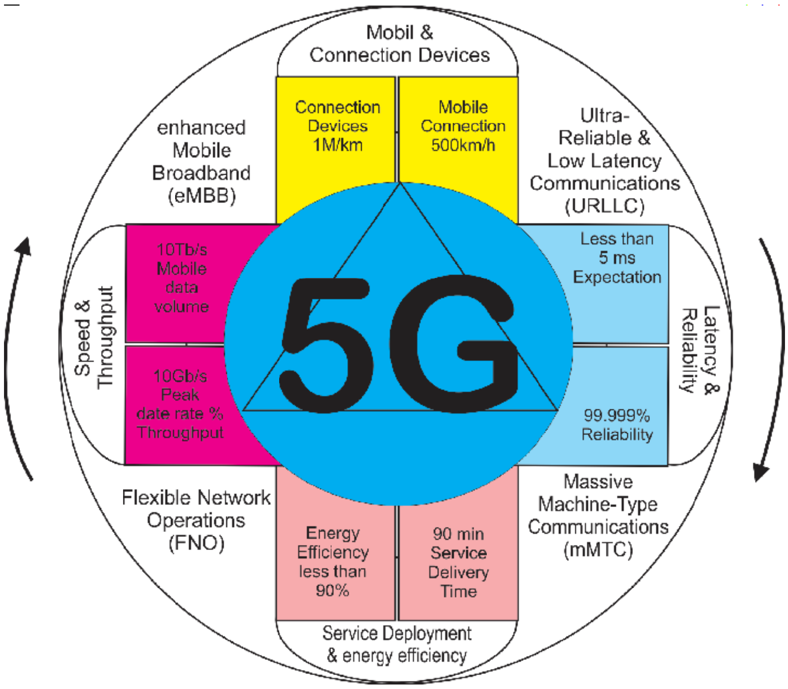

Figure 2: 5G networks capabilities

Network traffic in 5G is dominated by streaming or video applications (You et al., 2021). The distinguishing capabilities of the 5G WCC system include a user-experienced data rate of 0.1 Gbps, a peak data rate of 20 Gbps, end-to-end latency of 1 ms, 500 km/h mobility, an area traffic capacity of 10 Mbps/m², a connection density of 1 million devices/km², improved spectrum efficiency of about 3 times, and increased energy efficiency that is 100 times that of the wireless communication systems of 4G. The 5G network is built to have more outstanding features in network specificity (deterministic) latency, which uses Deterministic Networking (DetNet) for future demand to guarantee round-trip latency with punctuality and accuracy.

The 5G WCC networking infrastructure standard is segmented into two (Attaran, 2021); these are:

i) **Non-Stand Alone (NSA)**: This is the first 5G cellular network, which was commercially launched at the end of 2019. The signal traffic and control plane of the NSA infrastructural standard is based on existing 4G LTE. It is known as an improvement on the existing 4G LTE fast data architecture. NSA serves as the benchmark for initial 5G WCC commercial service in the year 2019 and the basis used to set up the next stand-alone standard/infrastructure.

ii) **Stand Alone (SA):** This is entirely a new core architecture. It made significant changes to how the wireless control plane transition operates. The 5G WCC SA structure was released in the year 2020. It enhanced subcarrier encoding and more flexible network slicing. It is designed to provide users improved performance at a low cost, better than 4G LTE and NSA.

Aside from NSA and SA, the 5G standards of WCC divide frequencies into two groups: Frequency 1 (FR1) (410 MHz – 7.12 GHz), also known as Sub-6G frequency, and Frequency 2 (FR) (24.25 GHz – 52.6 GHz) (Tikhomirov et al., 2018; Dilli, 2020). Most early deployments are in the FR1 slot. Research is ongoing in using FR2 and beyond, which are also known as Extremely High Frequencies (EHF) or millimeter waves (mmWave). The earlier stage of the 5G WCC network is allotted to operate on 3 GHz to 30 GHz frequencies. The higher frequency network of 30 GHz to 300 GHz is also booked for the microwave spectrum, which only allows short-distance communication with over 1 Gbps bandwidth (Salih et al., 2020). The large bandwidth and short frequency offer a more efficient network, which is experienced in its high-speed data transmission. The 5G technological scheme is used to join all accessible computer networks with just one Machine World-Wide (MWW) (Kumar & Sumit, 2021). Its flexible interoperability with Cognitive Radio (CR) and the Unparalleled Multi-Mode (UMM) stimulates effective functionality. Some of its top-notch functionality includes, simultaneously connected of networks using various wireless technologies, enhance the customer's location development, and incorporate various schemes to solve problems.

The CDMA and BDMA are the basic access footings for the 5G WCC system. One of its objectives is gradually achieved by the systematic adoption of filtered induced CA techniques to improve on the limitations of the LTE OFDM multi-carrier types of modulation and coding scheme. The filter's design is an essential method in generating the 5G waveform. Some of these improved versions of OMA CA that pave the actualization of 5G WCC systems are the, FBMC, GFDM, W-OFDM, F-OFDM, UFMC, and FF-OFDM (Augustine et al., 2025). The FBMC and GFDM are techniques based on pulse-shaping modulations, while F-OFDM, UFMC, and W-OFDM are designed based on sub-band filtering modulation (Yang et al., 2020; Pandey & Sharma, 2020; Taher et al., 2021).

To achieve better localization in the frequency domain and curtail the limitations noticed in OFDM, the filters in FBMC are used on each target subcarrier and the absence of the CP leads to high spectral efficiency. GFDM adopts a tail biting technique to shorten the cyclic prefix in OFDM, which may get better time-domain efficiency compared with FBMC. The UFMC uses short sub-band filters to minimize tailing in the time-domain and its constraints on filter length limit the OoBE suppression performance. The W-OFDM configures simple time domain window and its enhancement of time-domain efficiency totally depends on shortening the effect of the CP length, which is at the expense of sacrificing performance against multipath interference.

F-OFDM firstly divides its spectra into a series of contiguous sub-bands and the same filtering operation is performed on the granularity of each user to mitigate OoBE and PAPR (Yang et al., 2019). Moving toward the era of 6G, some of the notable drawback of the OMA schemes are the retention of chunks of interferences and poor power management which also degrades the required functionality of the network. With this, researches have proven that it cannot transmit effectively above FR1 objectives. The FF-OFDM is an advanced MA scheme built on the successes and drawbacks of these 5G driven OMA algorithms using sophisticated AI induced algorithms to curtail these limitations and advanced the course of next generation (XG) of wireless technology. In a parallel shift, the NOMA techniques, such as the PD, PTMA, BOMA, LPMA, LDS-CDMA, SCMA, and their variants, are developed to mitigate the excessive power and spectrum wastage in MA schemes. This is to advance the course of transmission latency, effective power allocation, achieve ultra-high heterogeneous connectivity, higher throughput, and improved SE (Liu et al., 2024).

The PD NOMA is a sophisticated power allocation and energy harvesting technique, the PTMA, BOMA, LPMA are techniques based on multiplexing in multiple domains, whilst the LDS-CDMA and SCMA are driven by code-domain NOMA. The PD has high SE and effective compatibility with other MA schemes but has drawback in user pairing and generate propagation errors. Other NOMA schemes such as the PTMA are more diverse and has low-connectivity receiver but it is difficult in design and create system redundancy in coding, the BOMA has simple structure and low complexity receiver but disadvantageous in flexibility and also lack user pairing, and the LPMA need not data user clustering but has limitation in channel coding specification. Furthermore, the LDS-CDMA is more suited for wideband transmission but generates redundancy in coding, while the SCMA does not need Channel State Information (CSI) and has more diversity than LDS but is characterized by redundancy in coding and is difficult to design optimal coding.

The integration of power-domain NOMA with cutting-edge technologies such as visible light communications, millimetre-Wave (mmWave)/terahertz (THz) communications, Multiple-Input Multiple-Output (MIMO), and Unmanned Aerial Vehicle (UAV), led to a massive turn-around and effective interoperability to meet the expected need of next generations of WCC networks.

Without restriction, the 5G network relative to its CA techniques is envisaged to generate high-speed information and networking everywhere. 5G WCC air-interface frequencies cannot operate effectively in remote area coverage (You et al., 2021). This has limited some of its applications, especially in Unmanned Aerial Vehicles (UAV). It is required of non-terrestrial networks like satellite communication to complement the terrestrial networks for cost-effective, ubiquitous service and seamless communication availability. An example of this is the UAV communication network, which is timely required for fast response in difficult and harsh terrains. The need for a Maritime Communication Network (MCN) to provide ships with high-quality communication services is long overdue; as such, a more versatile network to meet these present-day and futuristic demands is required.

2.6 Sixth Generation

5G will not meet all requirements of the future in 2030+ because of the proliferation of mobile devices and users' demands. This has triggered researchers to start focusing on the 6G WCC air-interface (You et al., 2021). In order to overcome the limitations of 5G, which include the provision of high-reliability networks, short-packet, low-latency services, and global coverage of the Internet of Everything (IoE), 6G WCC networks need to focus on being human-centric, instead of data-centric as its vision, application-centric, and/or machine-centric. This is possible by adopting a new paradigm shift as demonstrated in Figure 3, which, with the aid of Artificial Intelligence (AI) and Machine Learning (ML) technologies, will enable a new range of smart applications.

Encompassing all 5G network requirements, the 6G WCC air-interfaces are also expected to offer much higher data rates (Tbps), energy/spectral/cost efficiency, a 100 times increased connection near 100% global coverage, density, 10 times reduced latency, better security and intelligence level for full automation, accuracy in sub-centimetre geo-location, time synchronization in sub-millisecond. To achieve high energy and spectrum efficiency, including more flexible waveforms, advanced multiple CA approaches, multi-antenna technologies, channel coding methods, and a combination of diversity techniques are very essential. Meanwhile, novel network architectures are required to enable 6G WCC objectives, for example, Dynamic Network Slicing (DNS), Software Defined Network/Network Functions Virtualization (SDN/NFV, Cognitive Service Architecture (CSA), Service-Based Architecture (SBA), and Cell-Free Architectures (CFA). 6G WCC networks will be an integrated space-air-ground-sea networks to provide a complete global coverage, as illustrated in Figure 3.

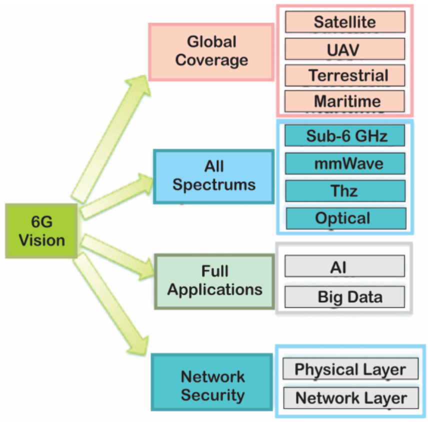

Figure 3: Vision of 6G wireless communication networks (You et al., 2021)

For global security and commercial activities, the handshake between UAV, satellite, and maritime communication is needed to increasingly expand the coverage range of the 6G WCC network. In 6G, all spectra are expected to be explored to provide a higher data rate. This includes the optical frequencies, THz, mmWave, and the sub-6 GHz. To have better network automation and management, it is proposed that flexible technologies in handling big data, like AI and ML, be incorporated with 6G WCC networks. It is glaring that AI-induced technology will enable more dynamic network resources fetching, slicing, caching, and computing capability to improve the performance and lay the footing of the next generation of networks. Last but by no means least is the highly aggressive network security achieved for both the network and physical layer when developing 6G networks. Industrial vertical signals, such as automated Internet of Things (IoT), Federated Learning Systems (FLS), Cellular Vehicle to Everything (C-V2X), Cloud Virtual Reality (CVR), Digital Twin Body Area Network (DTABN), and Energy Efficient Wireless Network Control (EEWNC), are fore-runners to largely boost the developments of 6G wireless communication networks.

So many access techniques have been proposed, while some have been developed to drive these 6G objectives. One of which is the FF-OFDM technique (Augustine et al., 2022). The FF-OFDM CA was developed to run higher versions of 5G, most especially 5G FR2-A, and possibly drive all 6G objectives. It is an Artificial Intelligence (AI)-induced technique that uses Machine Learning (ML) algorithms for its waveform realization. Its architecture obtained highly efficient spectrum slicing and spectrum shaping better than the previous CA schemes used in driving earlier generations of WCC systems. It is also an improved version that counters the limitation experienced in an F-OFDM, whose modification is performed at the Channel Estimation Region (CER) in order to negotiate a balance between the received data and the transmitted data. The FF-OFDM algorithm has the advantage of increasing system bandwidth, increasing data speed and throughput, effective interference mitigation, and high flexibility for network incorporation.

3 Summary of Findings

The Section presents a concise synopsis of the WCC generation of air-interfaces. This is to enable better comprehension of the survey conducted and to further stress the research objectives.

Table 1: Various air interface attributes

	1G	**2G**	**3G**	**4G**	**5G**	**Proposed 6G**
Year of Deployment	1980s	1990s	2000s	2010s	2020s	2030s
Location of First Commercialization	USA	Finland	Japan	South Korea	South Korea	N/A
Technology	AMPS, NMT, TACS	IS – 95, GSM	IMT2000, WCDMA	LTE, LTE-A, WiMAX	MIMO, mmWaves	SD-WAN, Cloud Edge computing, MPLS network, Optical network
Data Rate	2.4 kbps	64 kbps 144 kbps	2 Mbps UL 5 Mbps DL	100 Mbps – 1 Gbps	1 Gbps – 10 Gbps	11 Gbps – 1 Tbps
Switching Method	Circuit	Circuit Voice and Packet Data	Packet	Packet	All Packets	All Packets
Operational Frequency Range	800 MHz, 900 MHz	900 MHz, 1800 MHz	2100 MHz	850 MHz to 1800 MHz	Sub-6G = 410MHz – 7.125GHz, mmWaves = 24.250GHz - 52.600GHz	4.400 – 4.800 GHz, 7.125 – 8.400 GHz, 14.800 – 15.350 GHz
Carrier Frequency	30 kHz	30 kHz to 200 kHz	5 MHz	15 MHz	20 MHz, 50 MHz, 100 MHz, 200 MHz, 400 MHz	100 GHz and above
Bandwidth	Analog	30 - 200 kHz	15 - 25 MHz	100 MHz	3 GHz to 30 GHz to 300 GHz	160 MHz
Band Type	Narrow Band	Narrow Band	Wide-Band	Ultra Wide-band	Ultra Wide-band	Ultra-large
Access Schemes System	FDMA	TDMA, CDMA	CDMA	OFDM, BDMA	BDMA F-OFDM, FBMC	Smart F-OFDM plus IM, FF-OFDM

Hang off/over	Horizontal	Horizontal	Horizontal	Horizontal & Vertical	Horizontal & Vertical	Horizontal & Vertical
Core Network	PSTN	PSTN	Packet N/W	Internet	IoT	IoT
Latency	1,000 ms - 8 s	300 – 1,000 ms	100 – 300 ms	10 – 100 ms	1 ms or less	10 – 100 μs
Applications	Voice calls only	Voice calls, short messages	Internet services, GPS	High-speed internet, mobile TV	High-resolution video stream	Smart cities, Industry 4.0, advanced healthcare

4 Area of Future Work and Recommendations

As a way forward, this review is suggesting a paradigm shift in the integration of MA schemes with other emerging technologies, such as AI-induced ML techniques, Semantic Communications (SC), and Reconfigurable Intelligent Surface (RIS) (Liu et al., 2024), and their variants. These proposed enablers have proven to outperform traditional MA techniques in data transmission efficacy.

ML is an AI-induced technique that has gained recommendations and acceptance in diverse fields of human endeavours because of its high accuracy in data sampling. It is a highly versatile technique that has caused massive turn-arounds in the fields of science and engineering. It has revolutionized industries, reshaped decision-making processes, and transformed how technologies interact. The ML is not left-out in the quest for next generations of wireless communication resources. It has been seen adopted and deployed effectively in the areas of data analysis, power management/allocation, energy harvesting, waveform modification, interference mitigation, network scalability, system flexibility, and many more (Yoro et al., 2025; Augustine et al., 2025). Because ML is designed by humans to reason like humans, it is liable to ethical problems generated from sentiment. Other disadvantages of ML include deterministic problems as a result of large data, lack of reproducibility, data dependency, and high computational cost.

The SC technology is based on semantic information transmission, aiming to achieve more intelligent, efficient, and reliable data transmission (Wei, 2023). The SC is a prospective next-generation data transmission technique proposed to overcome the limitations experienced in traditional communication methods in the areas of simple data transmission, accurate interpretation, and conveyance of the semantic meaning in the data. In as much as SC has proven to be one of the prospective technologies expected to drive 6G and beyond, it is also characterized by challenges at the development stages. These challenges encompassed meeting resource requirements, model collaboration and privacy security, context perception and identification, knowledge sharing, and many more.

The RIS is termed advanced intelligent radio (Hamza et al., 2025). As the World prepares for 6G, RIS is one of the emerging core facilitator networks that can generate many opportunities to improve the performance of future wireless communication systems and also other fields. It operates by allowing the wireless communication environment to be controlled in a programmable manner. RIS utilizes a semi-passive or passive layer to efficiently and intelligently reflect an incident electromagnetic wave, which differs from conventional technologies that use active components to manage signal transmission and reception. This new approach creates several latent strengths, making RIS an extremely appealing solution for future wireless systems (Chiaraviglio et al., 2021). Energy efficiency is one of the strongest points of RIS. Although RIS offers attractive benefits, several technical and practical barriers, like the generation of small gain due to its passive transmission and the lack of amplifying signals, posed a serious challenge for widespread implementation of this technology. These drawbacks and many more need to be amended to enable RIS to grow and become a credible and trustworthy technology in the near future of wireless networks.

The successes and limitations notable in these technologies in data transmission have again opened up another vacuum in the need for further intensive and extensive innovations in these technologies to enable effective drive of the 6G attributes and those of upcoming generations of WCC systems. Aside from this, the research is also recommending the development of novel technologies/techniques that could enhance effective achievement of the objectives of next-generation wireless systems.

5 Conclusion

This survey provided a detailed presentation on WCC air-interfaces relative to its CA scheme mostly used for commercial deployment. These varying CA schemes serve as network lives. Each generation of WCC air-interface has its CA scheme that propels it in achieving its designed objective. These CA schemes are systematic hybridized multiplexing and modulation techniques that are designed to ensure the message signal is properly impressed into the transmission channel to the receiver with very little loss of information and energy. The first mobile handoff network achieved in the 1G air-interface is successfully driven by FDMA.

The ground-breaking note messaging achieved by 2G is run by TDMA, whilst the CDMA as top-notch technology also enables 3G and 4G that achieve the internet and multi-media functions, respectively. It is able the drive the higher mandates of 3G but could not fully deliver that of 4G objective. This is because, the CDMA algorithm could only enhanced serial kinds of transmission which makes it vulnerable to threads and lacks the required scalability in driving higher data rate.

The 4G mandate was fully achieved by the development of advanced multi-carrier CA techniques of OFDM, OFDMA, CP-OFDM, and WOFDM, where signal information is divided into chunks and transmitted in different subcarriers. The 5G basics where also enabled by CDMA, BDMA, but were also advanced by special cases of OFDM techniques known as UFMC, FBMC, GFDM, and F-OFDM which could only drive 5G FR1. The FF-OFDM CA is employed to enable the higher versions of 5G; FR2, FR2-2, and FR2-A, which is also prospected to fully drive the 6G objective because of its AI capability. The survey is aimed at bringing to the light of researchers the theoretical knowledge of a wireless network life, its successes, drawbacks, and the need for new access schemes, and/or novel techniques to enable the next generations resources of WCC air-interfaces.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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