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Evaluation of Development Level and Technical Contribution of Recent Technologies Adopted to Meet the Challenges of 5G Wireless Cellular Networks

Saleh Albadran

Department of Electrical Engineering, College of Engineering, University of Hail, Hail 55211, Saudi Arabia; s.abadran@uoh.edu.sa

Abstract: The evolution of the global wireless market is accompanied by an increased need in terms of speed and number of users, lower latency, better coverage, better spectral efficiency and quality of service, etc. To meet these needs, 5G has recently been introduced as an effective solution which targets, via the large scale deployment of symmetric antennas, a wide variety of sectors such as energy, health, media, industry, transport and especially wireless cellular networks which are among the most important pillars of modern societies. Multiple Input, Multiple Output (MIMO) systems, which have been extended to “Massive MIMO” mode and which consist of increasing the number of radiating elements involved in the transmission and reception of the radio link, are a very promising solution for improving the spectral efficiency of wireless communication systems (WCSs). Motivated by the aforementioned developments, the present paper investigates the increased capacity of MIMO systems to improve transmission in WCSs using 5G. It carefully focuses on the evaluation of the development level and technical contribution of MIMO systems and millimeter wave (mmWave) bands in 5G wireless cellular networks (WCNs) and gives important recommendations.



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1. Introduction

Since the 1980s, when the first analog communication systems appeared, a succession of new and more advanced systems were developed and introduced each decade to improve quality of service (QoS). In recent years, the telecommunications sector has experienced spectacular developments marked by the emergence of different technologies, making it possible to communicate in increasingly more efficient ways. From the initial transport of voice between two users, continuous efforts in this area have succeeded in sharing data which can take many forms: messages, texts, photos, videos, etc. Most significantly, the use of mobile networks has become more and more spread worldwide.

According to the Cisco company, global mobile data traffic has exceeded in 2017 its 2012 level by a factor of 12.6. This phenomenal growth continues today and the total mobile traffic has increased by a factor of ten between 2019 and 2022 [1]. Therefore, the future cellular infrastructure has to be ready to support new usages and specially to meet modern wireless communication standards and users' satisfaction. In particular, the last decade has seen a dramatic increase in mobile data traffic due to the wide deployment of the use of machine-to-machine (M2M) communications systems and smart devices in most applications/sectors. According to recent forecasts by the International Telecommunication Union (ITU), the increase in the volume of global mobile traffic between 2010 and 2030 will be by more than 660 times (Figure 1) [1].

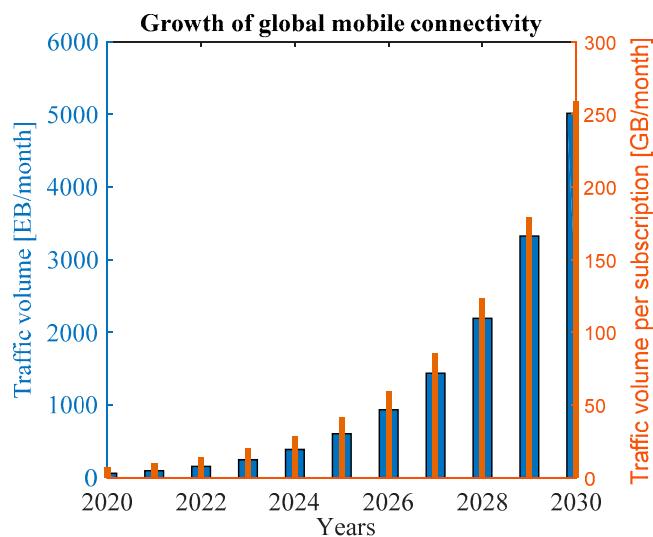


Figure 1. Growth of global mobile connectivity.

In fact, various standards for cellular networks, from 1G to 5G via 2G, 3G and 4G, have been introduced [2]. According to Figure 2, which shows the various wireless communication network technologies and their main characteristics, 2G, 3G and 4G generations have become unable to respond optimally to the constraints of speed, technology, frequency, data capacity, latency, etc. [3]. This is due to the frequency selectivity of the channels and the multiple paths that may be taken by the same signal [4,5].

Faced with these challenges, 5G wireless communications have the capability to satisfy the objectives concerning the transmission of digital information at higher speeds, increased demands on the quality of service and the resolution of the problem of limited network capacity compared to the bandwidth or the transmission power [6]. To achieve these objectives, 5G combines several techniques, amongst them the multi-antenna technique (Multiple Input, Multiple Output (MIMO)) which allows increasing the capacity of communication systems based on the installation of several antennas, having a symmetrical structure, for transmission and reception. This allows the system to be more robust against the fading of the transmission channel since it reduces the energy consumption and exploits the spatial diversity in a better way, and thus improves the quality of transmission [7,8].

In this regard, it would be very important to conduct a detailed investigation of all the techniques used to further enhance the performance of 5G wireless cellular networks and propose methodologies to assess their efficiency. Particular attention will be paid to the evaluation of the contribution of MIMO systems and other new technologies to satisfy the various needs facing 5G wireless communications and determine the best solutions that serve as reduced-complexity guides on future research directions for 5G and future wireless communications.

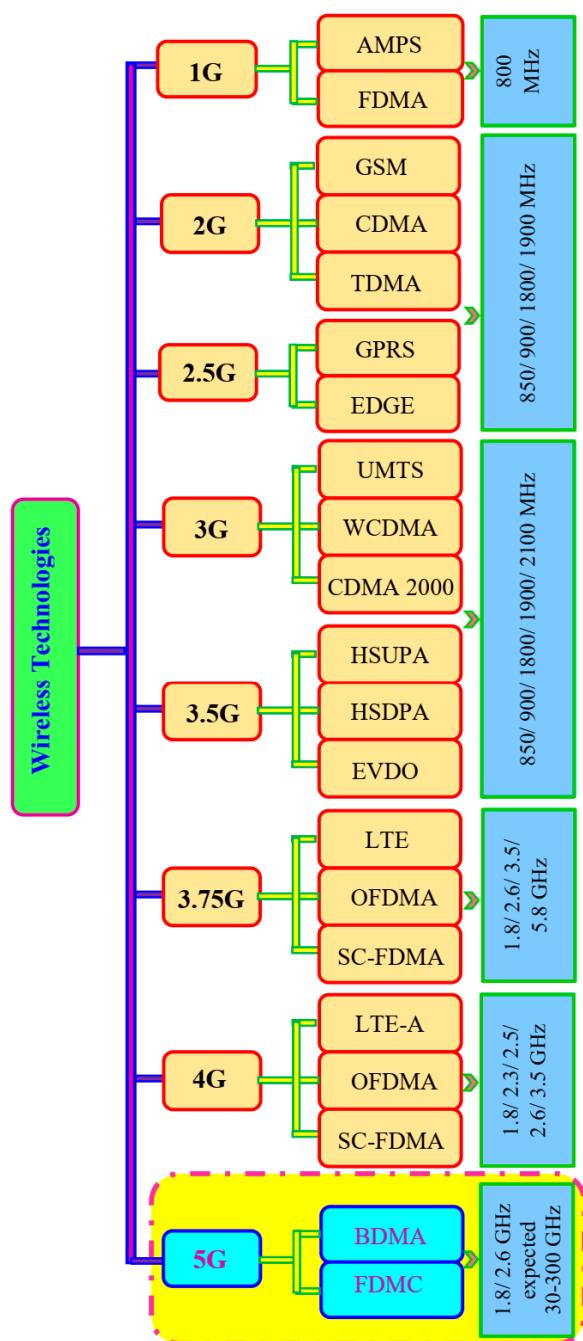


Figure 2. Wireless communication network technologies: Access technologies and frequency bands.

2. Related Works

From one year to the next, the demand for speed and quality of service for wireless communications continues to grow. The need for instantaneity and interaction in exchanges, the integration of multimedia services of different forms with variable bit rates and of high quality requires performance that can meet user expectations [9]. On the other hand, the number of wireless terminals is constantly increasing, which implies the coexistence of users in the same environment. The multitude of communication standards and protocols make the radio spectrum a highly congested resource where the number of interferers increases considerably [10]. Current techniques associated with suitable modulations and coding implementing a point-to-point link have approached the theoretical limit of Shannon [11]. However, the spectral efficiency acquired by these techniques has not yet managed to overcome the limits of the performances that they must satisfy. Recently,

considerable improvements in the theoretical capacity of broadcaster-rich channels, such as wireless local area networks (WLAN1), have been achieved with multi-antenna MIMO architectures for transmission and reception [12]. With the introduction of a new dimension, that of space, and the emergence of the field of space–time processing, the contributions are essentially the achievement of a theoretical capacity exceeding the Shannon limit and the improvement of the quality of service by reducing signal fading by exploiting multiple paths [13].

With the increasing development in wireless communication networks (WCNs) and the emergence of the fifth generation (5G) mobile networks, MIMO systems have attracted widespread public attention for guaranteeing the resilient, reliable and cost-effective exploitation of 5G WCNs [14]. Nevertheless, and in order to alleviate the complexity of studying such systems, researchers have resorted in several cases to neglect several factors that can impact the practical execution and the accuracy of MIMO results. To overcome this, particular attention has been paid to MIMO systems; they are among the most popular topics in wireless communication and have reached a much focused spot on the modern “hottest wireless technology” list [15,16]. Various studies have taken an explicit interest in the question of estimating the direction of departures (DODs) and direction of arrivals (DOAs) for the source separation in MIMO systems [17]. Two main other subjects were dealt with: Multi-user MIMO systems (MU-MIMO) [18–20] and Massive MIMO systems [21]. In [22], the authors proposed a parametric method of antenna processing. This method, previously used in radar systems, is based on tensors algebra in the context of radio communications. According to comparative studies, this method is considered efficient enough for users with sufficient spacing and with a number of sources greater than the number of sensors. Furthermore, 5G is also appealed to be able to estimate a large number of channels and connect many users to the network at the same time by accessing the network uplink and identifying active users while minimizing latency with reduced spectrum and power overheads. To respond to these challenges, MU-MIMO systems have been introduced. Nejah et al. [19] proposed two types of authentication, one so-called blind and the other semi-blind, to identify active users and their channels, respectively. The proposed approach exploited the embedded signaling and, more precisely, the modulation constellations with a randomized rotated code for the uplink of MU-MIMO systems [19]. In addition, the study of a channel identification technique for a MU-MIMO system was carried out to estimate the directions of arrival/departure and to deduce therefrom the parameters of the impulse responses of the channel. In a different context, that of cognitive radio, the multidimensional model for estimating direction parameters was also deployed using a decision algorithm for channel allocation [23]. The effect of power amplifier (PA) nonlinearity on MU-MIMO orthogonal frequency division multiplexing (MU-MIMO-OFDM) systems has been also studied for a base station (BS) using linear precoding for data transmission in the case of single-antenna users through a correlated channel [24].

Massive MIMO systems have also been introduced as a key element of the present and future of 5G WCNs especially for a symmetric network characterized by a common number of antennas between all the transmitters and the same number of antennas for all the receivers. In this regard, the feasibility of a time-frequency estimation of the directions of arrival within the framework of a Massive MIMO system has been studied [9,21]. In addition, the pilot contamination problem was tackled to resolve this source separation problem in the time, frequency and space domains and allow the Massive MIMO base station to discriminate between its users and those of other cells and, subsequently, cancel the effect of pilot contamination. In [21], it has been proved that maximal energy efficiency can be achieved by a Massive MIMO setup wherein hundreds of antennas are installed to serve a quite large number of users who use zero-forcing (ZF) processing.

Despite these advantages, the development of Massive MIMO systems faces many drawbacks. Indeed, the search for solid support for various Internet of things (IoT) services is the basis of the development of 5G mobile networks. This is because IoT services rely

heavily on the new radio (NR) for which many air interfaces are designed for the future generation Node B (gNB) and user equipment (UE). Consequently, a new technique called Massive MU-MIMO is emerging as a favorable solution to satisfy the tremendous demand for high-speed wireless networks. In the literature, this technique is attracting the attention of many researchers [22,25,26]. In [27], it has been shown that the emerging MU-MIMO concept is very efficient in IoT networks, even under such unfavorable conditions as random user's deployment and shadow fading because it succeeds in enabling ultra-reliable and low-latency communications (URLLCs) with pilot-assisted channel estimation (PACE) and zero-forcing (ZF) detection. In addition, full duplex (FD) wireless transmission is considered at the heart of discussions on the definition of 5G given its ability to increase the user throughput and the spectral efficiency in WCNs [28].

In the same context of the exponential digitization of the world where everything has become connected, 4G based on the LTE (Long Term Evolution) standard and IP technology has encountered serious problems mainly linked to the overload of the frequency spectrum and of course to other deficits. To meet the current requirements and those of the future due to the growth of connected objects known by various categories of use, the new 5G standard has responded to the deficits related to the increased throughput or bandwidth and has achieved an ultra-short latency and reduced power consumption with ubiquitous quality service [29]. This has been accomplished by the introduction of different technologies and even by the combination of several of them [30,31].

In recent years, the maximum bandwidth allocated to all cellular technologies has been limited to 780 MHz and, therefore, the release up of frequency bands has become a major priority to overcome the global bandwidth shortage. In this context, 5G WCNs use an extended frequency spectrum to cover medium and high frequencies integrating mmWave technology [32,33]. Within this framework, a simple, low-profile, compact, dual-polarization, low-cost and suspended patch antenna has been designed to operate in a 3.3–3.8 GHz band used for a 5G base station with a gain of 8.95 ± 0.25 dBi [34]. In [29,35], a Sub-6 GHz dual-band 8×8 MIMO antenna and Sub-6 GHz 5G NR broadband eight-antenna array have been designed, respectively, for 5G smartphones. Unlike this antenna consisting of a monopole operating in 3.1–3.85 and 4.8–6 GHz for the low band and the high band respectively, another dipole frequency-reconfigurable antenna has shown two resonant modes centered at 3.5 and 5.5 GHz or, to be more specific, two bandwidths that are 2.89–4.07 GHz and 5.1–6.19 GHz [36]. Otherwise, some researchers have dealt with cases treating the combination of mmWave and Sub-6 GHz for 5G antenna systems [30,37]. Here, it is important to mention that the use of mmWave technology is primarily motivated by the fact that the sub-bands 6 GHz are almost saturated.

According to the conducted literature review, it has been widely proven that MIMO systems are contributing to satisfying the various needs facing 5G wireless communication systems. This paper is concerned with the evaluation of the development level and the technical contribution of various MIMO, mmWave and full duplex technologies in 5G wireless cellular networks.

To accomplish the goals and objectives, the rest of the paper will be as follows:

- To summarize the features of MIMO wireless technologies, beginning with the evolution of such systems from Single Input, Single Output (SISO) systems
- To discuss MIMO, MU-MIMO, Massive MIMO and Massive MU-MIMO techniques used to push 5G performance further and methodologies to assess their efficiency
- To evaluate the contribution of different MIMO systems, mmWave technology and full duplex, in terms of benefits, to satisfy the various needs facing 5G wireless communications as well as their challenges
- To provide a guide on future research directions, outline the substantial conclusions and suggest future works for 5G and beyond wireless cellular networks

3. MIMO Wireless Technologies Features

3.1. From SISO to MIMO

Traditional communications systems have been based on only two antennas: one transmitting and the other receiving. With the necessity to keep up with the exponentially growing mobile communications service needs for transmitting more data, increasing transmission capacity through the use of multiple antennas has become a tangible reality. SISO, SIMO (Single Input, Multiple Output), MISO (Multiple Input, Single Output) and MIMO techniques have been proposed to allow data transfers [38]. In what follows, an overview of these main multiplexing techniques used in mobile networks is given.

3.1.1. SISO Systems

SISO systems are the simplest links as they use single antennas at the BS base stations (transmitters) and UEs (receivers).

For a SISO system with the gain of channel h and a signal-to-noise ratio at the receiving antenna γ , and if we assume that the channel state information (CSI) is unknown, the capacity is expressed by:

$$C = \log_2(1 + \gamma|h|^2) \quad (1)$$

Given that $E(|h_i|^2) = 1$.

, the theoretical capacity (bits/s/Hz) is expressed by:

$$C_t = \log_2(1 + \gamma) \quad (2)$$

3.1.2. SIMO Systems

The SIMO channel is a conventional multi-antenna system providing a channel or a transmission antenna and several reception antennas for the mobile phone.

For a SIMO system with one transmitting antenna and N receiving antenna, if h_i is the complex gain between the transmitting antenna and the i th receiving antenna, its capacity is expressed as follows:

$$C = \log_2\left(1 + \gamma \sum_{i=1}^N |h_i|^2\right) \quad (3)$$

Its Shannon capacity is:

$$C_t = E(C) = \log_2(1 + \gamma N^2) \quad (4)$$

3.1.3. MISO Systems

The MISO channel model is basically the reverse of SIMO. It uses several transmit antennas (BS) and a single receive antenna for the mobile phone.

3.1.4. MIMO Systems

Continued efforts to increase performance, in terms of improving capacity, increasing spectral efficiency and minimizing the effects of multipath interference, gave rise to the discovery of MIMO systems. These MIMO systems are more efficient than their predecessors from a capacity and reliability point of view thanks to the important advantages related mainly to multiplexing, diversity and array gains [27,39].

For a MIMO system including M transmitting antenna and N receiving antenna, the matrix H is given by:

$$H = \begin{bmatrix} h_{11} & h_{12} & \cdot & \cdot & h_{1M} \\ h_{21} & h_{22} & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & h_{ij} & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ h_{N1} & h_{N2} & \cdot & \cdot & h_{NM} \end{bmatrix} \quad (5)$$

Depending on the number of the transmitting antenna i and that of the receiving antenna j , h_{ij} is the complex gain of the channel between these antennas; hence, the capacity of the MIMO system is established by Equation (6):

$$C = \log_2 \left(\det \left[I_N + \frac{\gamma}{M} H H^H \right] \right) \quad (6)$$

As depicted in Figure 3, simulations have been developed to compare the performance of these different systems in terms of capacity vs. signal to noise ratio (SNR) [2]. It has been found that the capacity of MIMO systems outperforms all other systems. Furthermore, this capacity increases with the increase in the SNR, of course, when the number of antennas on the transmitter and the receiver sides increases.

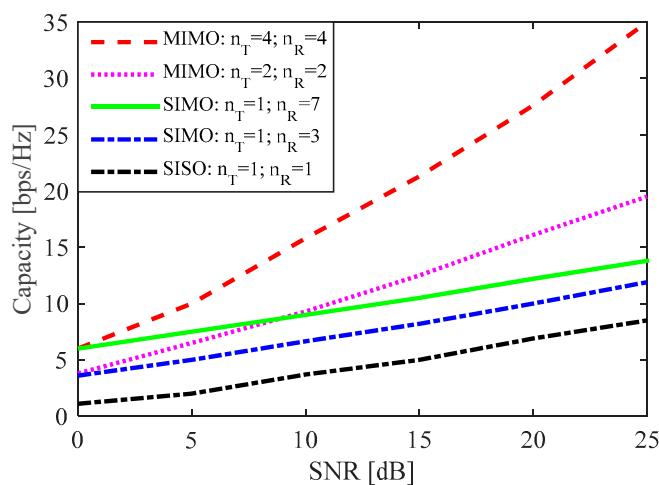


Figure 3. Capacity of Single Input, Single Output (SISO), Single Input, Multiple Output (SIMO) and Multiple Input, Multiple Output (MIMO) systems vs. signal to noise ratio (SNR) for different numbers of antennas.

3.2. Recent Wireless Technologies: From MIMO to Massive MIMO

From their inception, MIMO systems have brought various advantages that have proven their effectiveness, in terms of capacity, range, etc., to wireless communications networks. MIMO systems have mainly taken advantage of the multi-path environment, ensuring the increase in transmission capacity and obtaining independent signals on the antennas by using the different propagation channels created by diffraction and/or by reflection of waves.

Despite these successes, various new levels of complementary processing are always being improved upon, which aim to enable MIMO wireless communication systems to achieve more purposes. Regarding the techniques of encoding signals in a MIMO system, three main approaches can be distinguished:

3.2.1. Techniques of Encoding Signals in a MIMO System

- Multiplexing by orthogonal frequency division (OFDM):

OFDM is the basis of most broadband transmission applications. It consists of dividing the signal to be transmitted on numerous carriers, orthogonal to each other, and at different frequencies [40].

The use of OFDM with MIMO systems makes it possible to have high speed communications without interference between the transmitted signals and with the possibility of recovering information lost on other carrier frequencies. Nonetheless, OFDM requires frequency and time synchronization and the estimation of the MIMO channel of MIMO-OFDM systems to constantly ensure orthogonality between carriers which can easily be damaged by OFDM's sensitivity to carrier frequency error.

- Spatial Division Multiplexing (SDM):

It is an approach capable of increasing the data throughput and improving bandwidth utilization. Indeed, during SDM, several independent data streams are simultaneously multiplexed in a spectral channel [41]. To achieve this, an analog-to-digital converter and a different RF radio-frequency chain are necessarily used in a MIMO system for each antenna. In addition, each spatial stream must have its own pair of transmit/receive antennas at each end of the radio link. The MIMO–SDM combination is found to be cost effective as it has been characterized by inherent security at the physical layer [42].

- Space–Time Block Code (STBC):

The STBC is able to send different signals on each antenna, as in the case of SDM. The STBC manages to improve the robustness of the receiver through the diversity of the transmission channel and the introduction of information redundancy between the receiver and the transmitter. The STBC channel includes M^*N independent fading channels. On the one hand, the STBC technique is very efficient in the sense of overcoming the reduction in data transmission capacity because it does not impose any knowledge of the state of the channel (CSI) [43]. However, this method cannot, in any case, guarantee a linear relationship between the number of elements used and the transmission capacity. To achieve this, one of the solutions proposed for MIMO systems is to combine STBC with SDM. Due to the fact that they use several antennas, at the BS level as well as at the UE level, bringing advantages in relation to multiplexing, diversity and matrix gains, MIMO systems achieve better performance in terms of capacity and reliability compared to those of SISOs [44]. However, it is important to note that one of the concerns associated with MIMO operation is the existence of a trade-off between maximum diversity and multiplexing gains.

3.2.2. MIMO Systems Techniques

MIMO systems potentially increase the performance of wireless communications systems, in particular the range and reliability of links independent of the propagation channel. Consequently, this contribution of MIMO systems in terms of transmission rate and emission of independent information by appropriate spatial processing is very important because of its use in the majority of communication standards such as IEEE 802.11n and IEEE 802.16 [45,46] as well as Long term evolution (LTE) and its improved version LTE Advanced (LTEA) [47]. The use of these technologies began with the modest integration of MIMO links ($N_e \times 2$) where $N_e \geq 2$ in 4G mobile networks. However, it was with 5G that the integration of Massive MIMO systems with a high number, up to a few hundred, of antennas on the base station was achieved. In the literature [16,42,44], among MIMO technologies, it is important to draw attention to single-user MIMO (SU-MIMO), multi-user MIMO (MU-MIMO) configurations [48].

- SU-MIMO

The SU-MIMO system corresponds to a simple MIMO link between two points in space devoting all the time-frequency resources to one terminal, while exploiting the techniques of spatial multiplexing, emission diversity and beamforming [49,50].

- MU-MIMO

The MU-MIMO system makes it possible to achieve gains compared to SU-MIMO especially in the event of spatial correlation between the channels. Indeed, this configuration corresponds to a set of MIMO links between one or more points in space on transmission and one or more points in space on reception using the same time-frequency resources [51,52]. Intuitively, MU-MIMO can increase the capacity or spectral efficiency of a transmission network without increasing the bandwidth [53].

- Massive MIMO

The transition between MU-MIMO and Massive MIMO occurs when the number of antennas on the base station (N_e) becomes very large (up to a few hundred) and exceeds that of users K [54–57]. Massive MIMO presents various advantages such as:

- increased spectral efficiency because many users are served at the same time
- increased energy efficiency because the energy may well be focused on a very small region of the space
- decreased latency because it is based on the law of large numbers to avoid fading.

The comparison of the various aforementioned MIMO configurations and their advantages in terms of multiplexing, diversity, and array gain are given in Table 1.

Table 1. Advantages of single-user MIMO (SU-MIMO), multi-user MIMO (MU-MIMO) and Massive-MIMO antenna technologies.

	MIMO Antenna Technology		
	SU-MIMO	MU-MIMO	Massive MIMO
Multiplexing gain	thumb up	thumb up	thumb up
Diversity gain	thumb up	thumb up	thumb up
Array gain	thumb up	thumb up	thumb up

On the other hand, the challenges to be solved for such configurations (SU-MIMO, MU-MIMO and Massive MIMO) are also discussed and summarized in Table 2.

Table 2. Challenges to be solved for SU-MIMO, MU-MIMO and Massive-MIMO antenna technologies.

	MIMO Antenna Technology		
	SU-MIMO	MU-MIMO	Massive MIMO
mmWave Bandwidth	thumb down	thumb down	thumb down
Computational Complexity	thumb down	thumb down	thumb down
Chanel Estimation	thumb down	thumb down	thumb down
Pilot Contamination	thumb down	thumb down	thumb down
Signal Detection	thumb down	thumb down	thumb down
Precoding	thumb down	thumb down	thumb down
Hardware Impairment	thumb down	thumb down	thumb down
User Scheduling	thumb down	thumb down	thumb down

After discussing the contributions and challenges to be met for the different techniques of MIMO systems, the next section focuses on the technical contributions of some other new methods used in 5G WCNs.

4. Technical Contributions of New Methods Used in 5G Wireless Cellular Networks

4.1. High Transmission Speed

The transmission speed of 5G is faster than that of 4G by about 10 to 100 times. Indeed, with values reaching 15 or 20 Gbit/s and with the use of the cloud, 5G has managed to directly and instantly access programs, files, and remote applications [58–60]. With the increasing use of the cloud, the giant internal memories of devices are no longer essential as information storage, and even software activation have become possible remotely in the cloud [61].

4.2. Low Latency

With the arrival of 5G, the latency (defined as the time that elapses from the command on the device until the action is taken) of this technology is greatly reduced compared to that of 4G; indeed, it is of the order of one or two milliseconds (ms) whereas it is of the order of a few tens of ms for 4G (20 to 40) [62,63]. Thanks to this reduced latency, navigation has become more responsive. This acceleration has revolutionized wireless uses in many areas such as audiovisual, machine control, industry, logistics, telemedicine (remote surgical procedures) and even remote and/or automated transport [64].

4.3. Multiplied Number of Connected Devices

With 5G, the density of devices that can be connected to the network has increased significantly to reach 1 million per km². Therefore, the IoT has become more favored because a very large number of devices (100 times more) are instantly connected to the internet and can exchange information [65]. With these developments, 5G has become able to handle real-time data transmission between these devices more quickly [66]. By placing sensors in different points of a city, this principle will lead to smart cities and self-driving cars as well as other services.

4.4. Network Slicing

For 5G, one of the most promising options is the implementation of virtual networks or subnetworks, allowing to satisfy, in a programmable way, a connectivity more adapted to specific needs [67]. Here, connections qualified as emergencies are prioritized over others by the application of different latencies, thus leading to the elimination of any overloads. This new feature offered by 5G is called “network slicing” [68–70]. Network slicing enables a dedicated and stable provision of generous bandwidth to meet the requirements of a use case and therefore ensures network security by limiting possible cyber-attacks to such a slice.

4.5. Energy Efficiency

As detailed previously, special attention has been paid to revolutionary wireless technologies to meet the ambitious goals of the fifth generation (5G) cellular networks. The main focus of these efforts has been on challenges in terms of system capacity, data rate, spectral efficiency (SE), average cell throughput and energy efficiency (EE) [71–73]. Indeed, the progress of mobile telephone networks is not limited to the quality of service delivered to customers or to the operational performance, but it is expanding to include the degree to which it takes into account the issues related to energy consumption and even societal and environmental ones. As a result, generation-to-generation progress has managed to achieve an energy efficiency gain of a factor of about 10 [74]. In this context, the developers of 5G networks have focused on integrating energy issues from their design phase in order to reduce the energy consumption of 5G by a factor of 20 compared to 4G [75–77].

5. Role of the Massive MIMO and Other Technologies in 5G Wireless Cellular Networks

5.1. Massive MIMO

Massive MIMO systems have attracted attention thanks to their performance in terms of spectral and power efficiency and overall system robustness [5,21,22]. This is mainly due to the possibility of obtaining a capacity of the channels by resorting to a simple correspondence filtering or a receiver so that the inter-channel interference (ICI) is averaged in these systems for the high number of antennas according to the law of large numbers (LLN) [44].

From an economic point of view, the linear requirement of antenna amplifiers is lower in cases where each antenna is affected with less power. Under these conditions, the Massive MIMO system can be designed by combining the components at low cost [54,71].

From an algorithmic and planning standpoint, when operating MU-MIMO in Massive MIMOs, the design of the middle access control (MAC) layer is greatly simplified [55–57].

Although Massive MIMO technology is well judged to be a promising choice for 5G wireless communication networks, several strategic and forward-looking recommendations must be made to meet the main challenges constraining the practical deployment of 5G and beyond 5G (B5G).

5.2. mmWave Technology

Various works [32,33] have shown that the frequency bands of 5G are not easy to determine precisely and that the 5G spectrum has been designed to include three main frequency bands which do not necessarily have the same characteristics. Indeed, the lower frequency bands are those responsible for the best mobile coverage, the higher frequency bands are those which provide the best speeds, and the medium bands allow a compromise between the range of the signal and the speed. In this context, we can distinguish the following.

5.2.1. Low Frequencies

This range, from around 650 MHz to 1 GHz, allows signals to be propagated from a single access point to cover a considerably large area [32]. One of its drawbacks is that if the capacities of the channels are the same for low and high frequencies, the lack of available spectra results in an insufficient number of channels which are capable of delivering the high connection speeds desired to be reached by 5G.

5.2.2. Mid Frequencies: Sub-6 GHz

This frequency range is between 1 GHz and 6 GHz. The technical justification for this choice lies in the fact that the main gains, in terms of the performance and efficiency of 5G, are based on the portions of the spectrum that are around WiFi [34]. Therefore, service providers can take advantage of frequencies below 6 GHz as a new exploitable spectrum, ensuring wider channels and better latency [29–35]. However, the major problem of this frequency band is that a large part of its spectrum is in free use and that the interference problem caused by the multitude of users must be solved.

5.2.3. High Frequencies: (Above 6 GHz)

To further its sophistication and optimization, 5G is increasingly looking to expand its amount of bandwidth to meet its gigabit-scale throughput targets. Unfortunately, the sub-6 GHz and 1 GHz frequencies are not able to provide enough space. To meet this challenge, a new approach called millimeter waves has been proposed. This technology, whose history began with the studies of J.C. BOSE [78] in 1890, has recently become a reality. Indeed, it was just in 2019 with the rise of 5G that researchers have renovated this technology in 5G millimeter wave networks which will obviously be more strategic during the large deployment of 5G.

Millimeter wave technology is capable of operating between important frequencies, such as 24 and 60 GHz [32,79]. Equally, other variable bandwidths that can exceed the 100 GHz limit have been considered as candidate frequencies for the next generation [80]. These considerably high frequency bands allow blazing connection speeds because of the large transmission channels allowed.

- mmWave propagation Model

The received power (P_{rx}) by a wireless system can be expressed as a dependence on the transmitted power (P_{tx}), the distance between the antennas (R) and the transmit (G_{tx}) and receive (G_{rx}) gains according to the Friis Equation (7) [30]:

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} + 20 \log\left(\frac{C}{4\pi R f}\right) [\text{dB}] \quad (7)$$

Here, C is the speed of light and f is the frequency.

The above relationship between the received power and the frequency shows that the higher frequencies generate considerable attenuation compared to the lower ones. Therefore, this technology is more suitable for short distance communications.

- The main constraints of mmWave technology

For mmWave applications, the detrimental effects on the quality of the transmission are materialized by the atmospheric loss in terms of loss of decibels (dB) per kilometer of propagation. These losses mainly depend on humidity, rain, snowfall, air pollution and fog. Recent studies [81], [82] have shown the existence of three different frequency bands depending on the attenuation values. First, the bands between 26 GHz and 38 GHz are deemed the best suited for future 5G communications because they experience low attenuation. The second bands are those with free-space propagation characteristics and that are comparable to modern cellular frequencies (73 GHz). The third frequency family is unsuitable for indoor short-range communications, such as 60 GHz, and is characterized by high attenuation due to rain and absorption of oxygen compared to 28 and 38 GHz frequencies [83].

In addition, the main drawback of the enormous growth of using mmWave for NR application is the decrease in signal power due to molecular absorption. In [79], an in-depth study of the effect of atmospheric conditions on the propagation of mmWave frequencies, supposed to be more used in 5G WCNs, was presented. Particular attention has been paid to the factors of rain, diffraction, air pollutants and foliage and the losses generated on the frequencies centered on 28, 30 and 60 GHz.

From the above, it can be confirmed that 5G Sub-6 bands have satisfactory performance in covering larger geographic areas; however, they are not able to provide a sufficiently fast downlink. In contrast, mmWave 5G technology performs very well in terms of providing top-notch downlink speeds but this comes at the expense of geographic area coverage.

5.3. Full Duplex

Previously, communication systems shared resources over time or by frequency division according to the Half-Duplex principle [28]. Under these conditions, the reception and transmission of the signals are ensured in two different frequency bands or in two separate time intervals. Otherwise, the transmission and reception of a signal cannot be done simultaneously at the same frequency. In the case of LTE, the capacity of cellular networks is limited as the communication between the users and the base station is provided by separate uplink and downlink channels which are of equal width [84]. In order to exceed these limits, double the speed compared to half duplex transmissions and increase the spectral efficiency in WCNs, the use of full duplex (FD) technology has been introduced, thanks to the improvement in spectral efficiency that it can bring without any need to widen the frequency band [85]. This is achieved by the fact that, for a specific time slice, the transmission and reception of a signal can be done on the same frequency band.

Among the advantages of FD technology, a relay is able to exchange data between the destination terminal and the source terminal simultaneously. This significantly improves the delay for FD relay systems. On the security side, another remarkable advantage of FD transmissions is that the coexistence of data transmitted and received on the transmission link at the same time means that the signal, when captured by a foreign third party, is seen as being a mixture of signals that are difficult to decipher [86]. In addition, the ability to transmit and receive on the same spectrum greatly increases or even doubles the flexibility of the spectrum. Another advantage that should not be denied is related to the reduction in latency since the channel status information (CSI) can be received during data transmission.

When it first appeared, FD transmission was deemed impractical in WCSs because of certain technical constraints [85]. On the one hand, the first concern has been related to the very high level of self-interference that can be created when the transceiver sends a signal and receives another together. Otherwise, the processing of two signals (received and transmitted) at the same time makes it very difficult to design a flexible radio transceiver at the same working frequency [84]. To solve these problems and decrease this strong self-interference, the methods proposed to reduce self-interference can be grouped into passive and active cancellations [86].

5.4. Small Cell

One of the most promising technologies for 5G WCSs is that of small cells (SC) which can integrate femtocells, picocells and/or microcells [87,88]. This technology has greatly contributed to the management of broadband coverage both outside and inside buildings. Its fundamental principle is to reduce the distance between end-users and access points by integrating access nodes to reduce the coverage radius and the power consumed and improve latency. The use of these different cells has given rise to the appearance of new techniques, such as heterogeneous networks (HetNet) and ultra-dense networks (UDN) [89,90].

Knowing that the main challenges of the 5G standard are mainly related to certain requirements, such as increasing throughput or spectral capacity, achieving low latency, and reducing energy consumption, etc., the previous technologies have been exploited, individually or combined, to meet 5G expectations. Such expectations focus on three categories of 5G uses:

- Enhanced Mobile Broadband (eMBB): This category of use of 5G is designed to meet the growing demand for access to WCNs [91], multimedia services, content and data in terms of coverage and very high speed and bandwidth, especially in urban centers with high user density.
- Massive Machine Type Communications (mMTC): This category [92] is related to the possibility of automating industrial processes with massive machine type communications while ensuring reliability with good connectivity and reduced energy consumption.
- Ultra-Reliable and Low Latency (uRLLC): This scenario [93,94] is essential for applications requiring simultaneously extreme responsiveness and very reliable transmission such as WNCs, remote surgery, autonomous transport, and smart electricity networks [25].

It can be concluded that, among the new technologies on which the 5G standard is based, Massive MIMO systems have succeeded in increasing spectral efficiency and speed. The mmWave technology, in turn, has shown satisfactory efficiency in increasing bandwidth and therefore eliminating the problem of network saturation. In addition, the full duplex, which introduced the use of the bandwidth in a bidirectional way, was also very effective since it doubles the flexibility of the spectrum and reduces the latency to less than 1ms. Regarding small cell technology, it is very efficient in terms of densification and coverage of the network and reduction of interference and consumed energy, especially when combined with mmWave technology.

The focus of the present work on these four technologies was prompted by the special attention paid to them by the scientific community and the industrialists by considering them as ideal candidates to meet the requirements of 5G.

6. Recommendations and Future Research Directions

The recommendations drawn from this in-depth study may, when taken into consideration, be effective for improvements in 5G and even for B5G and 6G. Such recommendations can be summarized as follows:

- To take maximum advantage of the capacity gain of Massive MIMO systems while minimizing the overhead and overhead of CSI acquisition, the use of Time Division Duplex (TDD) and Frequency Division Duplex (FDD) systems is proposed as a solution to be further developed.
- More attention needs to be given to the design of the precoders and detectors for Massive MIMO systems with a number of transmitting antennas equal to or less than that of receiving antennas.
- Furthermore, the search for a compromise between the economy of space and the insertion of a high number of antennas by the theory of matrixes of cubes and the guarantee of the contribution to the gain in channel capacity of all antennas and not just those on the surface of a cubic array.
- One of the most important points is to take into account the phenomena generated by the increase in the antennas of transceivers, such as non-stationary effects and near field effects.
- mmWave Massive MIMO systems are also one of the promising alternatives that need to be further developed to meet the aspirations of current and future cellular communication systems.
- Even with the satisfactory deployment rate and the success of 5G, innovative manipulators in this sector are requested to solve today's challenges by further developing the recent solutions already in use and creating new solutions, such as mobile broadband and scalable IoT.
- Knowing that the natural resonance frequencies of molecules in the mmWave band lead to the degradation of their performance, more efforts should be made concerning the proposal of models, taking into account the effect of atmospheric pollutants according to the air quality index (AQI), especially with the acute air pollution in many cities.
- To ensure outdoor and indoor coverage and overcoming buildings obstacles, reducing the distance between the last access points of the network and users by small cell technology is a solution to be further developed.
- With the spectacular emergence and with the almost infinite potential of artificial intelligence (AI) in various common fields of application, more investment in AI and its giant capacity for learning and reasoning for performance development of intelligent 5G networks, in terms of efficiency and precision of calculations thus making it possible to manage massive amounts of data, is an inevitable solution. In a related context, it is essential to design robust, flexible and scalable learning frameworks that allow to communicate effectively with high dynamic networks requiring continuous updates.
- The development of hardware components by seeking to reduce their energy consumption and their cost and increase their storage and computing energy is also strongly recommended.
- The concern to adopt techniques of energy management and harvesting as well as wireless energy transfer (to sensors for example) becomes a real challenge for future WCNs, especially with the expansion of air, submarine and spatial infrastructures of these networks.
- More vigilance about the issue of management and security of users' personal data is increasingly a primary challenge.

- The broadcast nature of mmWave and MIMO signals that will be more used in 5G and B5G gives the possibility to open wireless communication accessibility to both legitimate users and malicious eavesdroppers, jammers and even attackers. To avoid passive interception of transmitted information, the design of effective security mechanisms has to be developed to avoid and combat the attacks.

7. Conclusions

To support the increase in transmission rate and the densification of networks, in terms of number of users, especially with the arrival of connected objects, the 5G network revolution has been ensured, in large part, by the integration of mmWave technology and Massive MIMO systems using a very large number of antennas for transmission and/or reception. In addition to these technologies, this paper studied, in depth, the technical concepts and contributions of various recent technologies, such as the full duplex and the small cells, to ensure the empowerment of 5G cellular networks. In addition, although it will take more time for companies interested in this field to fully understand the obstacles and opportunities that such technologies applied to 5G WCNs will bring, this article describes the main trends and challenges. In addition, this paper focuses on the proposal of some recommendations that will serve as motivation for researchers and industrialists interested in 5G and future technologies to take into account the consideration of the future generations of WCNs as a balanced ecosystem synchronizing technical capacities with socio-economic, environmental and other concerns. The findings of this paper are a valuable guidance for academia, researchers and industrialists in new and future WCNs fields.

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Nomenclature and Abbreviations

1G	Fifth-generation
2G	Second-generation
3G	Third-generation
4G	Fourth-generation
5G	Fifth-generation
6G	Sixth-generation
MIMO	Multiple Input, Multiple Output
WCS	Wireless communication system
WCNs	Wireless cellular network
QoS	Quality of service
M2M	Machine-to-machine
ITU	International Telecommunication Union
WLAN	Wireless local area networks
DODs	Direction of departures
DOAs	Direction of arrivals
OFDM	Orthogonal frequency division multiplexing
BS	Base station
ZF	Zero-forcing
IoT	Internet of things

NR	New radio
gNB	Next generation Node B
UE	User equipment
URLLCs	Ultra-reliable and low-latency communications
PACE	Pilot-assisted channel estimation
SISO	Single Input, Single Output
SIMO	Single Input, Multiple Output
MISO	Multiple Input, Single Output
CSI	Channel state information
SNR	Signal to noise ratio
SDM	Spatial Division Multiplexing
STBC	Space-Time Block Code
LTE	Long term evolution
LTEA	Advanced LTE
SU-MIMO	Single-user MIMO
MU-MIMO	Multi-user MIMO
SE	Spectral efficiency
EE	Energy efficiency
LLN	Law of large numbers
MAC	Middle access control
B5G	Beyond 5G
TDD	Time Division Duplex
FDD	Frequency Division Duplex
FD	Full-Duplex
HD	Half-Duplex
mmWave	Millimeter wave
AI	Artificial Intelligence
AQI	Air Quality Index
eMBB	Enhanced Mobile Broadband
mMTC	Massive Machine Type Communications
SC	Small Cell
HetNet	Heterogeneous Networks
UDN	Ultra Dense Networks
PA	Power Amplifier
ICI	Inter-channel interference

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