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Evolution towards fifth generation (5G) wireless networks: Current trends and challenges in the deployment of millimetre wave, massive MIMO, and small cells

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Abstract The exponential increase in mobile data traffic is considered to be a critical driver towards the new era, or 5G, of mobile wireless networks. 5G will require a paradigm shift that includes very high carrier frequency spectra with massive bandwidths, extreme base station densities, and unprecedented numbers of antennas to support the enormous increase in the volume of traffic. This paper discusses several design choices, features, and technical challenges that illustrate potential research topics and challenges for the future generation of mobile networks. This article does not provide a final solution but highlights the most promising lines of research from the recent literature in common directions for the 5G project. The potential physical layer technologies that are considered for future wireless communications include spatial multiplexing using massive multi-user multiple-input multiple-output (MIMO) techniques with millimetre-waves (mm-waves) in small cell geometries. These technologies are discussed in detail along with the areas for future research.

Keywords 5G cellular systems · Massive MU-MIMO · Millimetre wave · Small cell networks · C-RAN · 5G base station

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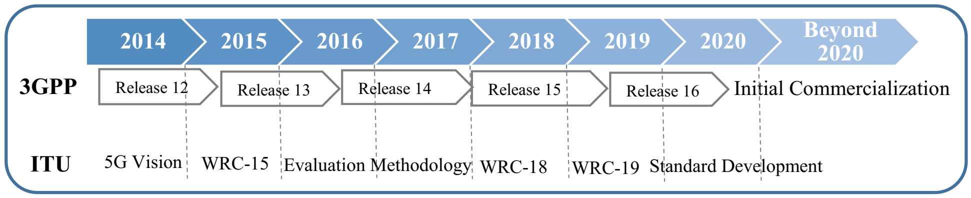
1 Introduction

Mobile communication has been one of the most successful technological innovations in modern history. The last five years have witnessed a tremendous development in cellular networks, which offer data-oriented services that include, but are not limited to, multimedia, online gaming, and high-quality video streaming. As a result, the number of mobile subscribers and the amount of data traffic have increased explosively. In 2012, the number of mobile subscribers reached 4.5 billion, and the average amount of data traffic requested by each mobile subscriber was 10 GB per year. The number of mobile subscribers increases every day and will reach an estimated 7.6 billion by 2020. Data traffic will increase to 82 GB per subscriber per year [1] due to the unprecedented demand for data high bandwidth video streaming, which will represent more than half of global mobile data traffic [2]. Moreover, with the advent of the concept of the Internet of Things (IoT), as many as 50 billion wireless devices are predicted to be connected globally by 2020 [3], which will lead to an exponential surge in network traffic. The network traffic beyond 2020 is predicted to grow to more than 1,000 times that at the end of 2010 [4]. This unprecedented growth in traffic will require a significant increase of wireless network capacity. These challenges are considered to be a critical driver towards the 5G, of mobile wireless networks. History has shown that the mobile industry undergoes a major shift in technology approximately once every 10 years [5,6]. The concept and vision of 5G began in 2014. 5G technology is rapidly coming into the limelight, and commercial 5G mobile wireless networks are expected to be deployed by 2020. Figure 1 shows the timeline towards 5G network implementation.

This paper discusses several design choices and features that provide an understanding of the new generation of

Fig. 1 Timeline towards 5G [7]



mobile networks. This article does not provide a final solution but highlights the most promising lines of research. The motivations behind this work can be summarized as:

- To discuss the technical challenges and recent results related to mm-wave and massive multiple-input multiple-output (massive MIMO) systems in the context of future 5G mobile wireless networks.
- To discuss the technical design considerations of 5G small cells to open new horizons for further research.
- To provide researchers with several new references that are relevant to research on 5G communication networks.

The remainder of this paper is organized as follows: Sect. 2 highlights the major milestones for legacy cellular technology, and Sect. 3 presents a brief overview of the key functional and technical features of the 5G mobile system. Section 4 highlights the mm-wave technology for wireless communication systems and discusses why the 5G wireless community should consider the mm-wave spectrum for mobile broadband applications as well as the challenges of using these frequencies. This section also presents open research issues that need to be investigated in future studies. Massive MIMO is discussed in Sect. 5, which highlights the benefits of using massive MU-MIMO systems, channel measurements, and open topics of research. Section 6 discusses wireless standards and design considerations for small cell network architectures (cloud radio access network (C-RAN)). Section 7 presents the main conclusions of the paper.

2 Major milestones in cellular technology

To date, four generations of cellular communications systems have been adopted. A new generation has emerged roughly every 10 years since approximately 1980, including first generation analog FM cellular systems in 1981, the second generation digital technology in 1992, 3G in 2001, and 4G LTE-A in 2011 [5,6]. A brief overview of the evolving wireless technologies is as follows:

2.1 First generation (1G)

The first generation of mobile communication was announced in the late 1970s. Major subscribers were advanced mobile phone system (AMPS) in North America, nordic mobile telephone (NMT) in Scandinavia, total access communication system (TACS) in the United Kingdom and Japan Total Access Communications System (JTACS) in Japan. The 1G technology was a basic analogue system that was designed for voice communications with a data rate of up to 2.4 kbps, which uses frequency modulation (FM), frequency division multiple access (FDMA) transmission technology and a bandwidth (BW) of 30 kHz. However, 1G has many disadvantages such as, (i) low quality and security without encryption due to used analogue modulation, (ii) limited subscribers due to used FDMA technique, (iii) power radiation of base station being unsafe and lack of a handoff process, (iv) limited to voice service, and (v) incompatible systems that lack a unified international standard [8–10].

2.2 Second generation (2G)

Global systems for mobile communications (GSM) was the first 2nd generation system; and it was announced in the early 1990s. The GSM was a basic digital cellular system that was designed for voice communications with a data rate of up to 9.6 kbps, which uses Gaussian minimum shift keying (GMSK) modulation, time division multiple access (TDMA) transmission technology and BW of 200 kHz. This generation is characterized by (i) the development of unified international standard for mobile communications, which prompted to growth in mobile communications technology worldwide, (ii) enhanced services, (iii) enhanced security in the network by a digital encryption, (iv) improved system capacity, and (v) handset battery that lasts longer as radio signals use less power. However, GSM suffers from a low data rate, which prompted for an improvement in the cellular system by general packet radio services (GPRS) technology [8–10].

GPRS is considered 2.5G and uses packet switching technology along with circuit switching that was adopted in GSM, which an improved data rate of up to 50 kbps with similar modulation technique, transmission technology and BW that is used in GSM. Essentially, GPRS is an evolutionary step toward enhanced data GSM environment (EDGE). EDGE is considered a pre-3G radio technology and designed to deliver data at rates of up to 200 kbps. The EDGE standard is built on the existing GSM standard, using the same transmission technology and BW; but utilises the eight-phase shift keying (8 PSK) modulation technique along with GMSK. The 8 PSK offers higher data rates with reduced coverage, whereas GMSK will be used as a robust mode for wide area coverage. The EDGE has been added to enhanced the packet-switched services and enabled new high speed data applications such as multimedia applications [9,10].

2.3 Third generation (3G)

3G systems introduced high-speed Internet access and highly improved video and audio streaming capabilities using technologies such as wideband code division multiple access (W-CDMA) and high speed packet access (HSPA). HSPA is an amalgamation of two mobile telephony protocols, high speed downlink packet access (HSDPA) and high speed uplink packet access (HSUPA), which extends and improves the performance of existing 3G mobile telecommunication networks utilizing W-CDMA protocols. An improved 3GPP (3^{rd} generation partnership project) standard, evolved HSPA (also known as HSPA+), was released in late 2008 with subsequent worldwide utilization beginning in 2010. However, 3.9G long term evolution (LTE) includes capabilities that exceed those of 3G mobile communications [9,10]. Nevertheless, ITU and 3GPP have later decided that LTE can be named as 4G technology [5].

2.4 Fourth generation (4G)

LTE is an orthogonal frequency-division multiplexing (OFDM) based radio access technology that supports scalable transmission bandwidths up to 20 MHz and advanced multi-antenna transmission. multiple-input multiple-output (MIMO) is a key technology that supports the high data rates in the system and enables multi-stream transmissions for high spectrum efficiency, improved link quality, and the adaptation of radiation patterns for signal gain and interference mitigation via adaptive beamforming using antenna arrays. The LTE technology increased the peak mobile data rates to 100 Megabits per second (Mbps). Because the demand for capacity in mobile broadband communications increases dramatically every year, the wireless technology roadmap was extended to LTE-advanced (LTE-A) [11], which is theoretically capable of peak throughput rates that exceed 1 Gigabit per second (Gbps).

A 4G system improves the prevailing communication networks by imparting a complete and reliable solution based on IP. Three main lines of research have been extensively investigated by the wireless community to fulfill the capacity requirements of 4G mobile networks:

i. Network densification: this technique is deployed in areas with large numbers of subscribers, such as stadiums, concerts, public venues, or shopping malls. This approach is intended to improve network coverage and increase spectrum reuse through the deployment of small low-cost and low-power cells that decrease the distance between the mobile terminal and the base station (BS). The small cells have a coverage radius of 50–150 m and radiate at low power (0.1–10 W), thereby increasing both the energy efficiency and signal-to-interference-plus-noise ratio (SINR) due to the low loss path. In addition, in current developments operators seek to make the small cell a plug-and-play fashion, are self-configured for all necessary parameters and do not require any regular maintenance [12,13].
ii. Enhanced spectral efficiency: coordinated transmission/reception schemes and inter-cell interference mitigation solutions exploit advanced signal processing and spatial diversity to reduce co-channel interference and increase the spectral efficiency [14,15].
iii. Spectrum extension: in LTE-A, bandwidth extensions (up to 100 MHz) are supported via carrier aggregation to combine different component carriers, which may have different sizes and be in a non-continuous spectrum. Although the joint implementation of these mechanisms may provide very high data rates that are theoretically more than 1 Gbps for stationary users, further increases are limited due to the smaller number of available frequencies [11,16].

Figure 2 summarizes the major milestones of the four legacy generations (1G–4G) of cellular communication systems.

However, the continuous increase in mobile data traffic is considered to be a critical driver towards 5G systems. 5G will not be an incremental advance of 4G but will need to be a paradigm shift that includes very high carrier frequencies with massive bandwidths, extreme base station and device densities, and unprecedented numbers of antennas to support the enormous increase in the volume of traffic. In addition, unlike the previous four generations, 5G will also be highly integrative; it will link any new 5G air interface and spectrum to LTE and provide universal high-rate coverage and a seamless user experience [7,17].

3 Current visions of 5G cellular wireless networks

Since the fourth quarter of 2014, 5G mobile wireless networks have received significant attention from both academia and industry. The key challenge is to meet several goals, which are described in Fig. 3 at a similar cost and energy consumption as today's networks. Thus, 5G mobile wireless networks will adopt a set of new technologies to support the increase in the volume of traffic in future wireless communications [3,7]. Figure 4 summarises the 5G key technologies

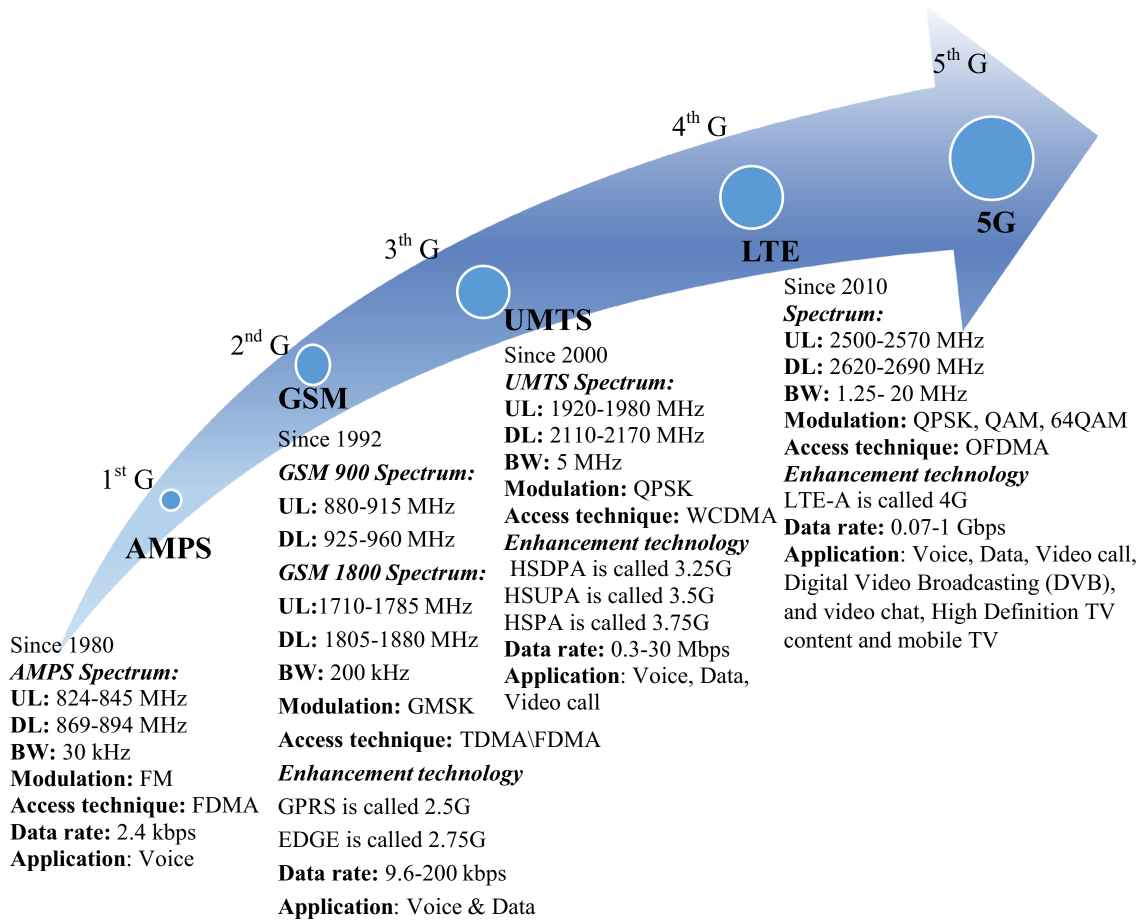


Fig. 2 Major milestones for the four legacy generations of cellular communication systems

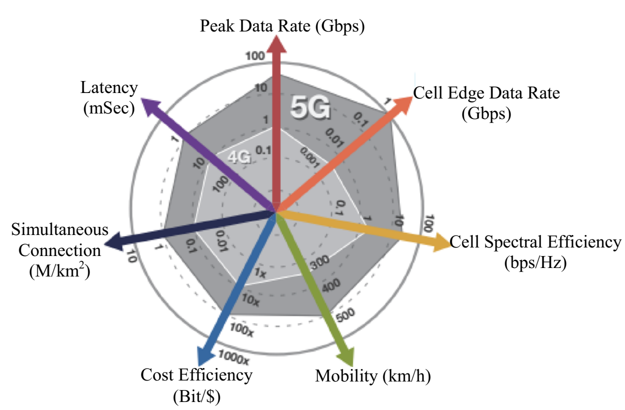


Fig. 3 Key performance indicator for the evolution from 4G to 5G [26]

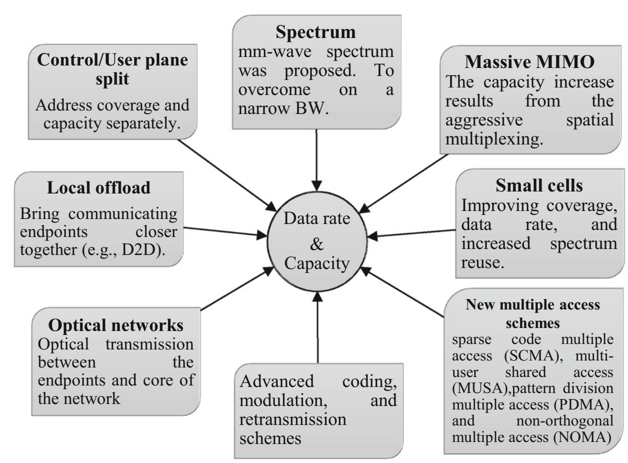


Fig. 4 The key 5G considerations to provide high capacity [27]

for supporting the increase in the volume of traffic. However, most research works focus on the mm-wave, massive MIMO and small cells deployment, which explains that these three techniques are more interesting to researchers in the present time. Therefore, this paper serves to focus on a discussion of these three techniques to provide an interesting reference to readers and open new horizons for further research. Moreover, according to the basic Shannon formula, the network capacity is directly proportional to both the number of antennas and channel bandwidth multiplied by the logarithm of the SINR. The key 5G considerations to provide high capacity for mobile subscribers in PHY layer at this stage are:

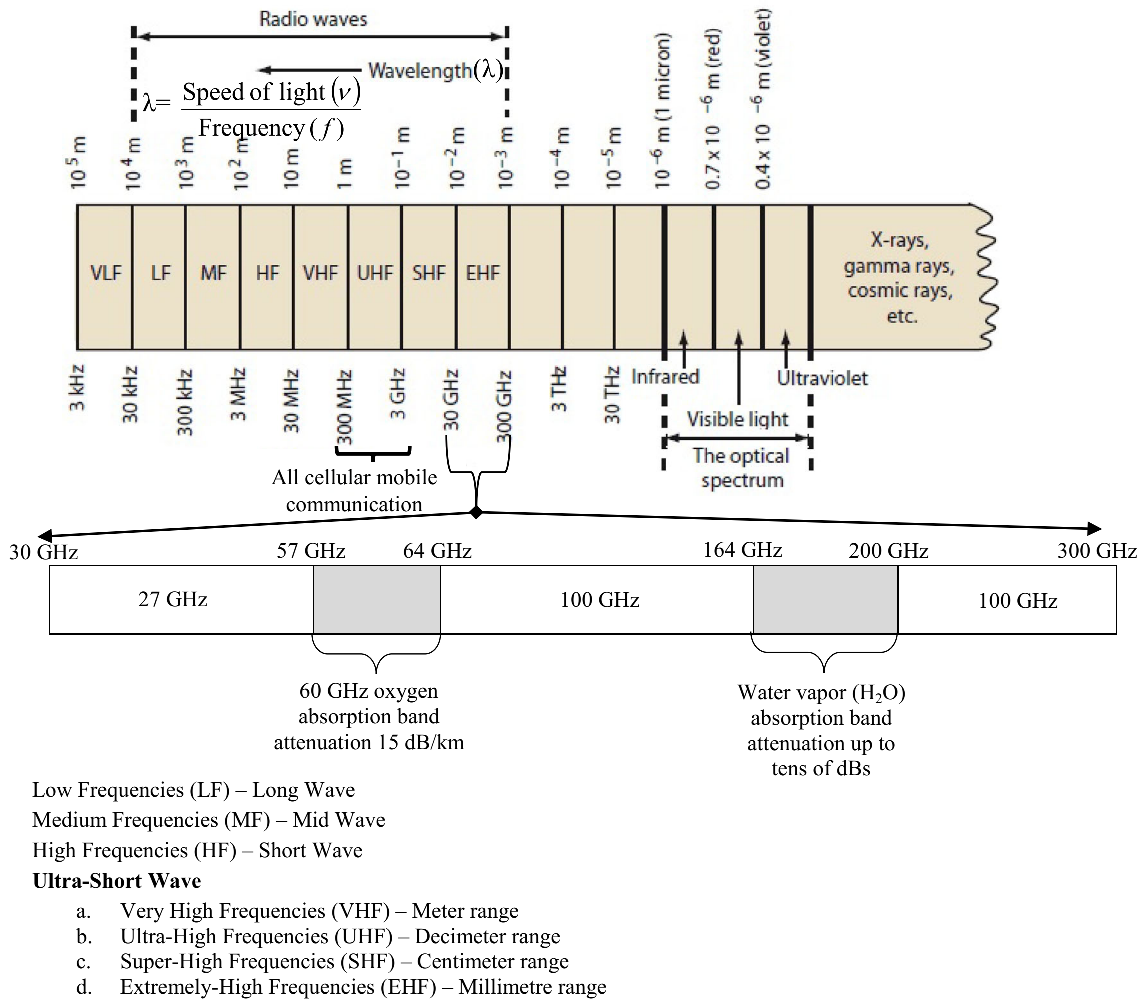


Fig. 5 Millimeter-wave spectrum [18]

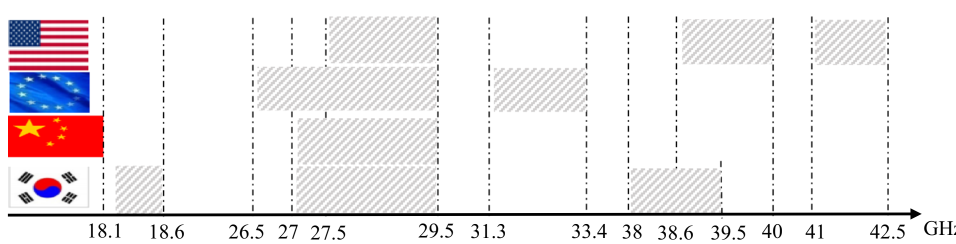


Fig. 6 Candidate spectrums for 5G wireless communication [32]

- To overcome the reduced amount of available spectrum frequencies. The millimetre-wave technology was recently proposed to enable broadband radio access and backhauling in future wireless networks. In addition, mm-wave communication systems can achieve multi-gigabit data rates at distances of up to several kilometres [18, 19].
- Massive MIMO is another method that can increase the capacity by 10 times or more and simultaneously improve the radiated energy efficiency by approximately 100 times. The capacity increase results from the aggressive spatial multiplexing that is used in massive MIMO. The dramatic increase in energy efficiency is possible due to a large number of antennas, which can accurately focus energy into small regions in space (narrow beams) [20–22].
- Small cells will play a significant role in developing a cellular network that can overcome the explosive surge in mobile traffic at a little cost to the network operator. A small cell is a low power, low cost radio BS (depends on backhauling requirements of dense small cell deployments; further discussion is available in Subsect. 6.1.2)

which primary design objective is to provide superior cellular coverage in residential areas. In general, the radio coverage of small cell BSs can range from tens of meters to a few hundred meters; hence, they provide a high data rate while saving energy due to the shorter distances between the transmitter and the receiver [23–25].

4 Millimetre-wave communications

Almost all current mobile communication systems use spectra in the range of 300 MHz–3 GHz. Advances in current electronic fabrication allow the use of mm-wave spectra to meet the needs of mobile subscribers and provide larger bandwidths for 5G [18]. This section discusses the reasons that the 5G wireless community should examine the 30–300 GHz spectrum for mobile broadband applications, the challenges that face the use of these frequencies in wireless communication systems, and the open research issues that need to be investigated in future studies.

4.1 Millimetre-wave spectrum

The mm-wave spectrum is attractive for future wireless systems because of the massive amount of raw bandwidth that is available for cellular and backhaul services [28–30]. Possibilities for accommodating additional IMT bands are being considered in the scope of the ITU-R World Radio Conference 2015 (WRC-15). The highest priority for further work with frequencies above 6 GHz is with frequencies between 40 and 90 GHz [18,31]. We refer to the 3–300 GHz spectrum collectively as mm-wave bands with wavelengths that range from 1 to 100 mm (Fig. 5).

Almost all commercial radio communications, including AM/FM radio, high-definition TV, satellite communications, GPS, Wi-Fi, and cellular, utilize a narrow band of the RF spectrum from 300 MHz to 3 GHz. 5G cellular systems are likely to operate in mm-wave frequency bands of 30–300 GHz, where the large available bandwidth will enable unprecedented connection speeds to mobile users and traffic capacity to network operators. It is worth noting that the frequencies in the 57–64 GHz oxygen absorption band can experience an attenuation of approximately 15 dB/km because oxygen molecules (O_2) absorb electromagnetic energy at approximately 60 GHz. The absorption rate by water vapor (H_2O) depends on the amount of water vapor and reaches tens of dBs in the range of 164 – 200 GHz. However, in 2003, the Federal Communications Commission (FCC) announced the availability of the 71–76 GHz (5 GHz bandwidth), 81–86 GHz (5 GHz bandwidth), and 92–95 GHz (3 GHz bandwidth) frequency bands, which are collectively referred to as E-band, for ultra-high-speed data communications, including point-to-point wireless local area networks, mobile backhaul, and broadband Internet access [18]. Accordingly, Fig. 6 shows the candidate spectrums for use in future 5G wireless networks among the current standardization bodies alongside with regional competitors.

4.2 Millimetre-wave propagation characteristics

The new path loss prediction models that are appropriate for use for mm-wave bands in various localities around the world are still not well known. However, several research [33–36] have conducted to estimate propagation path loss model based on real-world measurements at different ranges of mm-wave bands (26, 28, 38 and 73 GHz). Table 1 presents a summary of the main studies that have investigated mm-wave propagation path loss models for 5G cellular networks.

Advantages of the previous studies: These studies have analysed the path loss characteristics based on real-world measurements at different ranges of mm-wave bands. The previous path loss models were based on measurements obtained using the considered mm-wave bands, which provide a vision for researchers, mobile network operators and vendors. Although poor foliage penetration has been observed, the largest challenges were atmospheric, and free-space path loss.

Shortcomings The most important parameter for the estimation of channel path loss is the surrounding environment, which has a significant impact on the signal reception. However, the depth and height of the building, road side structures, and rain attenuation that are considered in measurements are not clear. Moreover, the authors in these studies have researched on the path loss characteristics based on their country, and as such these studies lack a unified international standard.

However, this proposal still requires significant research to overcome its main challenges, including supporting mobility for the optimum beam selection and designing transmission techniques that alleviate the need for feedback about the channel state information (CSI) to the transmitter.

4.3 Open research issues in millimetre-wave

The major challenge at high frequencies is that the path losses are much higher than at lower frequencies. These high attenuations can be overcome using the following solutions:

i. Reduce the coverage to small distances (100–200 m), which decreases the transmission power, increases the SINR and spectral efficiency, provides a low loss path, and prolongs the handset lifetime due to the short transmit-receive distance. However, this solution requires a greater number of cells for the same coverage area. Sulyman *et al.* [35] showed that at least four times more cells are required as BSs in 3G and 4G systems.

Table 1 Summary of studies on mm-wave propagation model for 5G cellular networks

Reference	Description	
Shu *et al.* (2016) [33]	Investigation	Proposed a two candidate large-scale propagation path loss models, (i) the alpha-beta-gamma model and (ii) the close-in free space reference distance model, in urban micro and macro cellular scenarios. Comparisons are made using the data obtained from 20 propagation measurement campaigns or ray-tracing studies from 2 GHz to 73.5 GHz over distances ranging from 5 m to 1429 m.
	Propagation model	(i) The Alpha-Beta-Gamma (ABG) model $P_L = 10\alpha \log_{10}\left(\frac{d}{d_o}\right) + \beta + 10\gamma \log_{10}\left(\frac{f}{f_o}\right) + x_\sigma$ where P_L denotes the path loss in dB over frequency and distance, α and γ are coefficients showing the dependence of path loss on distance and frequency, respectively, β is an optimized offset value for path loss in dB. The coefficients α, β, and γ are obtained from measured data using the closed-form solutions. d is the transmitter-receiver separation distance with $d_o = 1$ m reference distance, f is the carrier frequency with $f_o = 1$ GHz reference frequency. x_σ is the typical lognormal random shadowing variable with 0 dB mean and standard deviation σ. (ii) The close-in free space reference distance (CI) model $P_L = FSPL + 10n \log_{10}(d) + x_\sigma$ where *FSPL* denotes the free space path loss in dB at T-R separation distance of 1 m reference distance; and n denotes the single model parameter, the path loss exponent (PLE).
	Results	The results shown that the CI model has a very similar goodness of fit in both LOS and NLOS environments, while offering substantial simplicity and more stable behavior across frequencies and distances, as compared to the ABG model.
Minoru *et al.* (2015) [34]	Investigation	Proposed a path loss model that is based on the Rec. ITU-R P.1411 model, which can cover the frequency range from microwave to mm-wave bands. The path loss characteristics were analyzed based on measurements obtained using the 2 to 37 GHz band in street microcell environments.
	Propagation model	$P_L = \beta_{const} + \left(\alpha_f \log_{10} f + C_f\right)\left(\alpha_d \log_{10} d + C_d\right)$ The unit of frequency (f) is MHZ and the unit of distance (d) is meter. The fitting parameters are calculated for β_{const} equal 4.15, α_f equal 1.41, C_f equal -7.82, α_d equal 0.79, C_d equal 1.
	Results	The results shown that the proposed model can cover the frequency range from 2 GHz to 37 GHz for LOS and NLOS microcell environments. However, root mean square error (RMSE) was 2.2 dB and 4.7 dB at 2 GHz and 37 GHz, respectively.
Sulyman *et al.* (2014) [35]	Investigation	Proposed a new path loss model that is based on the Stanford University Interim (SUI) model, that are suitable for cellular planning in the 28 and 38 GHz bands that stem from simple modifications of current path loss models.
	Propagation model	(i) The Proposed path loss model for mmWave in NLOS $P_L = \alpha_{NLOS}\left(P_{L\_SUI}(d) - P_{L\_SUI}(d_o)\right) + FSPL(d_o) + x_\sigma$ where $P_{L\_SUI}(d)$ and $P_{L\_SUI}(d_o)$ denotes the SUI path loss in dB at distance d and reference distance $d_o = 1$m, respectively. (ii) The Proposed path loss model for mmWave in LOS $P_L = \alpha_{LOS}(FSPL(d) - FSPL(d_o)) + FSPL(d_o) + x_\sigma$ where α_{NLOS} and α_{LOS} are the mean slope correction factor obtained directly from the empirical results.
	Results	The simulation results for the proposed propagation model that estimate mm-wave are matched with real measurements in both heavy and light urban areas.
Akdeniz *et al.* (2014) [36]	Investigation	The authors used real measurements at 28 and 73 GHz, to derive detailed spatial statistical models of the channels and uses these models to provide a realistic assessment of mm-wave micro and pico cellular networks in a dense urban deployment. Statistical models are derived for key channel parameters, including the path loss, number of spatial clusters, angular dispersion, and outage. It is found that, even in highly NLOS environments.
	Propagation model	For LOS and NLOS, $P_L = \alpha + 10\beta \log_{10}(d) + x_\sigma$ α and β are the least square fits of floating intercept and slope over the measured distances (30 to 200 m).
	Results	The models derived from the real measurements, are based on outdoor street-level locations. However, the proposed model evaluation with indoor will need further study.

The costs of network deployment scale linearly with the number of cells [37], which leads to an increase in the overall network cost of at least 4 times. Therefore, the optimal deployment of small cells needs to be studied further and analysed thoroughly.

ii. Use high-order beamforming [38]. Because the root mean square (RMS) of the power delay profile (PDP) of a millimetre-wave channel in an urban environment is 1–10 ns and the coherent bandwidth of the channel is approximately 10–100 MHz [18], a key challenge for narrow beams is the difficulty in establishing associations between users and BSs for both initial access and handoff. To find each other, a user and a BS may need to scan many angular positions where a narrow beam could be found. Developing solutions to this problem, particularly in the context of high mobility, is an important research challenge [17].

iii. Millimetre-wave signals cannot easily penetrate buildings; mm-waves that are transmitted from outdoor base stations may be confined to streets and other outdoor structures [18]. Therefore, 5G network architecture must be investigated in future studies.

iv. The Doppler spread of a wireless channel depends on the carrier frequency and mobility. The maximum Doppler shift for carrier frequencies of 3–60 GHz at speeds of 3–350 km/h ranges from 10 Hz to 20 kHz [18]. However, the narrow beams at the transmitter and receiver will significantly decrease the angular spread of the incoming waves, which in turn reduces the Doppler spread.

5 Massive MIMO

MIMO research began in the late 1990s [39] and has increased over the last two decades. MIMO has been applied to many wireless standards because it can significantly improve the capacity and reliability of wireless systems. Today, MIMO is considered to be a primary milestone in the evolution of 3G and 4G cellular networks. In essence, MIMO embodies the spatial dimension of the communication that arises once numerous antennas are available at BSs and mobile devices. If the entries of the resulting channel matrix exhibit sufficient statistical independence by virtue of spacing, cross-polarization and/or angular disposition, multiple spatial dimensions become available for signaling, and the spectral efficiency increases accordingly [40].

The initial research on MIMO has focused on single-user MIMO (SU-MIMO); however, the dimensions are limited by the number of antennas that can be accommodated on a mobile device. Each mobile device contains only two to four antennas [41]. By having each BS communicate with several users concurrently, the focus of research has recently shifted to more practical multi-user MIMO (MU-MIMO) systems that can effectively pull together the antennas at those users and overcome this bottleneck [17]. The signaling dimensions are then given by the least of the aggregate number of antennas of those users and the number of antennas at the BS. As a result, MU-MIMO has become an integral part of communications standards such as IEEE 802.11 (WiFi), IEEE 802.16 (WiMAX), and LTE and is being deployed throughout the world. In most MIMO implementations, the BS employs only a few (i.e., fewer than 10) antennas, and the corresponding improvement in spectral efficiency, while important, is still relatively modest. LTE-A uses MIMO with as many as eight antennas per BS sector. Because of form factors and other limitations, this appears to be the maximum level that MIMO could be leveraged. The complexity of pre-coding and decoding is considered the main reason that makes the maximum antennas that used with LTE-A are 8. In multi-antenna techniques pre-coding is used to map the modulation symbols onto the different antennas. The type of pre-coding depends on the multi-antenna technique used as well as on the number of layers and the number of antenna ports. The aim with pre-coding is to achieve the best possible data reception at the receiver.

Marzetta (2007) was instrumental in articulating a vision that increased the number of antennas by more than an order of magnitude [42,43]. He proposed equipping BSs with more antennas than the number of active users per time–frequency signaling resource. Under reasonable time–frequency selectivities, accurate channel estimations can be conducted for a maximum of tens of users per resource; thus, this condition puts the number of antennas per BS into the hundreds. This bold idea was initially called "large-scale antenna systems" but is now more popularly known as "massive MIMO".

5.1 Benefits of using massive MU-MIMO

System capacity massive MIMO systems have gained attention for use in future wireless networks due to their high data rates and connection reliability. Multiple signal paths due to multiple antennas at the transmitter or receiver are responsible for the large throughput. Massive MIMO systems can increase the system capacity by a factor of 10 [20]. In addition, the spectral efficiency can be increased by a factor of 20 when 256 antennas are used in the transmitter and receiver compared with four antenna systems [31].

i. Energy efficiency (EE) the energy consumption of cellular base stations is a growing concern worldwide. It is now widely acknowledged that cellular communication networks will have greater economic and ecological impacts in the coming years. A relatively new research discipline called "*green cellular networks*" addresses this concern [44]. This puts mobile operators under immense pressure to meet the demands of both environmental conservation and cost reduction and has led to the search for solutions to improve energy efficiency in cellular networks [45]. The BS accounts for 57 % of the total energy consumption in cellular networks, and the power amplifier (PA) has the highest energy consumption of the BS [46]. Reducing the power at the PA is therefore the primary focus in creating green cellular networks considering the hardware cost, linearity, and peak-to-average power ratio (PAPR).

In massive MIMO systems, the expensive and high-power amplifiers that are used in conventional systems are replaced by hundreds of low-cost amplifiers with output powers in the milliwatt range [47] because the narrow beams between the transmitter and receiver provide a dramatic increase in energy efficiency [21]. Moreover, massive MIMO systems reduce the constraints on the accuracy and linearity of each amplifier and RF chain; only their combined action matters. In a way, massive MIMO relies on the law of large numbers to ensure that noise, fading, and hardware imperfections average out by combining the signals from a large number of antennas [20].

Both MIMO systems and small cell networks (SCNs) are expected to achieve high EE for high throughput cellular networks using several mechanisms. Massive MIMO improves EE by exploiting a large array gain, while SCN improves EE by deploying numerous low-power BSs to reduce the propagation losses and increase the opportunity of BS sleep. EEs are compared to the SEs of massive MIMOs and SCN in [48].

ii. Degrees of freedom a massive MIMO system has a large surplus of degrees of freedom. For example, when 200 antennas serve 20 terminals, 180 degrees of freedom are unused. These degrees of freedom can be used for hardware-friendly signal shaping. In particular, each antenna can transmit signals with very small peak-to-average ratios or even a constant envelope at a very modest penalty in terms of increased total radiated power [20].

However, the concept of massive MIMO systems is intrinsically related to its use at high frequencies (e.g., mm-wave bands), which will decrease the size of each of these elements. Many different configurations for the real antenna arrays can be used, including distributed antennas or linear, and cylindrical arrays [20,31]. The linear array spans a large physical dimension in space, while the cylindrical array is relatively small in size. However, the linear array achieves higher average sum-rates than the cylindrical array, if we randomly select the same number of antennas on both arrays. The reason is that the linear array has very high angular resolution due to its large aperture, which helps to spatially separate the users, especially when users are closely located at BS. In addition, the cylindrical array has a smaller aperture, thus lower angular resolution. Due to its circular arrangement, some antennas may face the "wrong" direction. However, the cylindrical array achieves perform better, when the antenna gains of the patch elements are taken into account. As for the performance of the power-based antenna, cylindrical array considered to better than the linear array, due to a large number of RF transceivers that can be switched off.

5.2 Massive MIMO channel measurements

This section highlights studies of massive MIMO channel measurements from the literature, which are summarized in Table 2.

5.3 Open research issues

Several challenges must first be overcome for massive MIMO to become a reality, including:

5.3.1 Channel estimation/feedback and pilot contamination

Channel state information (CSI) is crucial for achieving multi-antenna gains in MIMO systems. CSI becomes more challenging in massive MIMO systems due to a large number of antennas. In addition, massive MIMO systems require a large number of pilots for both frequency-division duplexing (FDD) and time-division duplexing (TDD) [39]. Moreover because of the restrictions of the coherence interval duration and increasing numbers of users, the same set of orthogonal pilots is reused for adjacent cells; thus, pilot contamination [53–55] can occur in a multi-cell MIMO system. When the BS estimates the channel for a particular user, it may obtain a channel estimate that is contaminated by adjacent cell users that share the same pilot. Pilot contamination has been shown to limit the performance benefits and degrades the capacity of massive MIMO systems [43]. In addition, Jung et al. [56] discussed the optimal number of users in massive MU-MIMO systems; as the number of BS antennas increases, the received SINR increases linearly. However, because the number of pilots is equal to the number of BS antennas, the number of subcarriers for the data signals decreases as the number of BS antennas increases. Simulation results have shown that the throughput increases until 50 antennas are used and subsequently decreases.

To solve this problem, recent study [55] has discussed several approaches that address pilot contamination. Although they attempted to alleviate pilot contamination between multiple cells, these studies used orthogonal pilots in a single cell, which implies large pilot resource consumption especially for short coherence intervals. Zhang et al. [57] proposed a semi-orthogonal pilot design with simultaneous data and pilot transmissions and exploited the asymptotic

Table 2 Studies of massive MIMO channel measurements from the literature

Reference	Description
Gao *et al.* (2015) [49]	This study investigated how massive MIMO systems perform in channels using measurements from real propagation environments. Channel measurements were performed at 2.6 GHz using a virtual uniform linear array (ULA) with a physically large aperture and a smaller practical uniform cylindrical array (UCA), each of which had 128 antenna ports. The investigation showed that the measured channels for both array types achieved performance similar to that in independent and identically distributed (i.i.d.) Rayleigh channels.
Dahman *et al.* (2015) [50]	In space division multiple access (SDMA) systems, users are separated based on their positions. The BS signals typically reach the users through multipath clusters. The goal of this study was to determine the probability that a randomly-selected user will receive the signal from the BS via at least one non-shared multipath cluster. Simulations were performed using the COST 2100 model in outdoor and indoor scenarios and showed very good agreement; the maximum error was 0:04.
Panzner et al. (2014) [41]	This study highlighted deployment and implementation strategies for massive MIMO systems in the context of 5G indoor small cell scenarios. A stand-alone MIMO system at a single location, a distributed MIMO system without cooperation, and a MIMO system with full cooperation were investigated for 20, 24, 36 and 200 transmitting antennas.
Vieira et al. (2014) [51]	This study developed a solution for a massive MIMO system in a practical testbed, which operated with a 20 MHz bandwidth and 100 antennas at the BS. The unique features of this system were: (i) high throughput that processed up to 100 Gbps of real-time baseband data in both the transmit and receive directions, (ii) low latency (less than 500 msec), and (iii) a flexible extension up to 128 antennas.
Truong et al. (2013) [52]	This study discussed the impact of channel aging on the performance of massive MIMO systems. The analytical results of aging showed how capacity is lost over time in the channel. In addition, the numerical results from a multi-cell network showed that massive MIMO systems work even with some channel variation and that channel prediction can partially overcome channel aging effects.

channel orthogonality in massive MIMO systems, which was applied with a successive interference cancellation (SIC)-based channel estimation to mitigate the mutual interference between the data and he pilot. The simulation results showed that the proposed pilot design can significantly improve the performance and decrease pilot resource consumption compared with conventional orthogonal pilots.

Developing solutions to the pilot contamination issue is an important research challenge. In addition, new methods of channel estimation and feedback schemes will need to be developed for massive MIMO to achieve mainstream status.

5.3.2 Mobility

5G networks must operate at speeds of up to 1000 km/h (Fig. 3). A significant amount of research is required to overcome the challenges associated with the optimum beam selection and the design of transmission techniques that alleviate the need for feedback on CSI to the transmitter. Thus, the performance of massive MIMO systems is very sensitive to the speed, and the computational burden could make multiuser solutions unaffordable [31].

5.3.3 Distributed large MIMO systems and performance evaluation

One of the challenges for massive MIMO is the design of an effective antenna deployment strategy. A large bulk of the work on massive MIMO assumes co-located arrays but the distributed option has potential for increased throughput and shadow fading diversity [58]. A massive, centralised array is simpler to construct and requires less backhaul. In contrast, a fully distributed array is more complex and has higher latency and backhaul requirements, but may provide a more superior performance. The advantages of a distributed array have been investigated in traditional MIMO systems as well as for remote radio heads/units and cloud radio access network [59–61]. Nevertheless, massive MIMO deployment scenarios with the effect of propagation parameters, system size, correlation and channel estimation error remain as open issues that require further investigation.

5.3.4 Low complexity pre-coding and decoding algorithm

This technology is focus on reaping high spectral efficiency benefits. However, there is currently a lack of focus on the development of low-complexity algorithms for the detection and channel estimation of massive MIMO systems. A key component of a MIMO system is the MIMO detector, which functions to recover the symbols that are transmitted simultaneously from multiple transmitting antennas. However, in practical applications, the MIMO detector is often the bottleneck for overall performance and complexity. The complexities involved in optimum detectors are based on maximum likelihood (ML) or maximum a posteriori (MAP) criterion which are exponential in the number of transmit antennas [62,63]. Accordingly, such complexities are prohibitively high for massive MIMO. Therefore, there is a need for massive MIMO detectors, which are able to perform close to the performance of the optimum detector, but at practically affordable complexities. Today, with neural networks and artificial intelligence algorithms there is a possibility for optimal performance along with a reduction in complexity. However, such proposal would require a further study in the future.

5.3.5 Coordinated multiple points (CoMP)

CoMP with 5G massive MIMO will play a crucial role in improving communication quality, EE, coverage and throughput of the cellular networks [64]. In addition, mobile users can be served with a relatively stable performance and quality even when they are located in other cells. However, CoMP systems with 5G massive MIMO analysed, backhauling, and cooperative framework and processing are still open issues that require an in-depth study, in order for the operator to maximize the benefits of the new network and keep costs under control.

6 Deployment of small cells in wireless networks

Big things come in small packages; this is a particularly appropriate description of small cell deployment in cellular networks. The concept of deploying small cells to improve the throughput and energy efficiency of cellular networks is not new. It has been proposed that 5G wireless networks should support higher data rate volumes (1000 times higher mobile data rate volume per area), higher typical user data rates (10–100 times higher than 4G), and lower energy consumption; thus, the deployment of small cells has attracted the attention of mobile operators to improve indoor or local area system capacity and service coverage. Small cells play a significant role in developing cellular networks that can overcome the explosive increase in mobile traffic at a little cost to the network operator [24,25].

The idea is based on a very dense deployment of BSs that are much smaller than a typical macro cell. In essence, a small cell BS can be considered as a cellular BS that is designed to serve a limited coverage area that is approximately 100 times smaller than that of a traditional macro cell. Small cells target a coverage radius of 50–150 m and radiate at low power (0.1–10 W), which increases the energy efficiency and reduces the path loss by decreasing the distance between the user and the BS [9].

Several studies have focused on determining the optimal small cell deployment while considering different performance metrics. Guo et al. [65] proposed a theoretical framework to maximize the spectral efficiency of the network and to avoid interference caused by small cell placement. Cheng et al. [66] and Shimodaira et al. [67] adopted system throughput as the performance metric to determine the optimal locations for static small cells. Chen et al. [68] further considered the impact of different deployment topologies, including random and grid topologies, on the throughput and spatial outage performance. Pak et al. [69] studied effective small-cell deployment scenarios in terms of the SINR performance. They considered three deployment scenarios:

i. The random deployment in this scenario, the small-cells are randomly and uniformly deployed in the macro cell area. The random small-cell distribution aims to obtain the baseline simulation result.
ii. The deployment of the worst-performing user the authors tested the deploy small-cells near the worst-performance users. The worst-performance user is selected among active users according to the receive-signal power from the macro BS. After the selection, the selected users are connected to the deployed small-cell directly, and
iii. The cell-edge deployment Small-cells are located precisely on the boundaries between neighboring macro BSs.

The authors compared the performance of three different small-cell deployment scenarios using cumulative distribution function (CDF) of SINR. The SINR is obtained considering various factors, antenna pattern, path loss, correlation loss, penetration and loss. As the number of small-cells increases, the average performance increases by the increased number of users connected to small-cells. However, the additional small-cells interfere the conventional small-cell users, thereby they worsen the performance of the top and low 10 % users. Simulation results indicated that the cell-edge deployment is the best deployment strategy of the three scenarios because it most efficiently utilizes the trade-off between the signal strength enhancement and the interference from neighboring small cells. Coletti et al. [70,71] and Hu et al. [72] devised outage-minimum deployment mechanisms under realistic metropolitan scenarios.

However, small cell deployment still face a major challenge, which is an inter-cell interference (between small cells) and cross-cell interference (between the macrocell and small cells) increase the complexity of the deployment problem. However, further discussion is available in Subsect. 6.2.

6.1 Small cell architectures

The successful deployment of small cell networks relies on integrating the small cells into the existing mobile access networks to provide seamless device-to-core network connectivity. This section begins with a summary of the small cell architecture in legacy mobile wireless networks and then highlights the considerations for designing small cell architectures in the 5G environment.

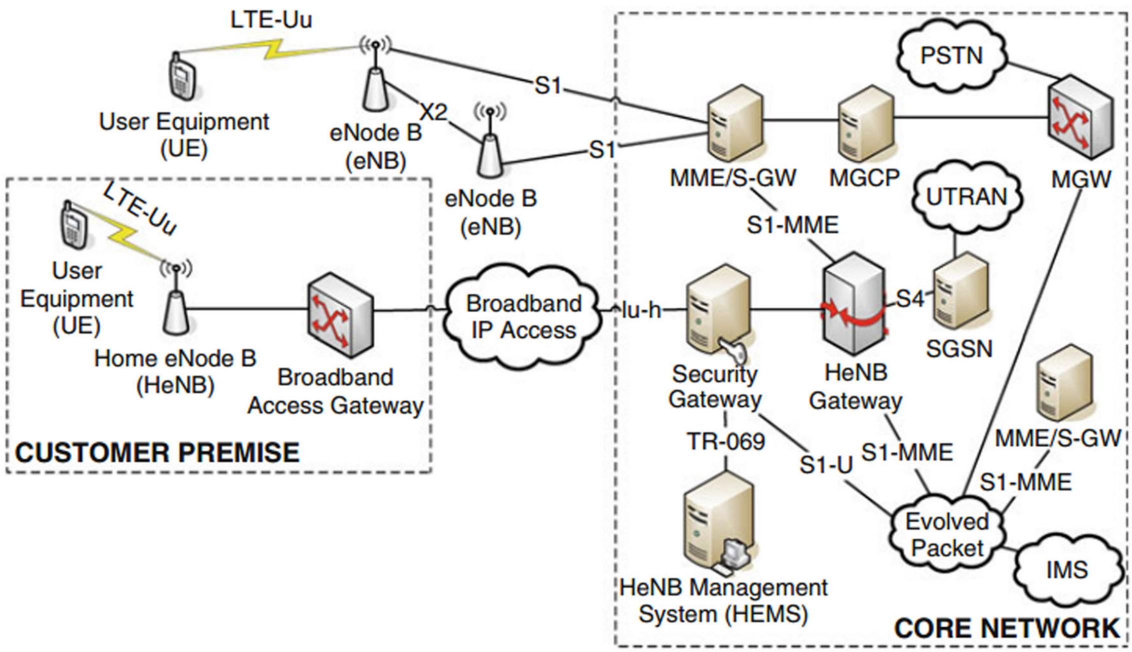


Fig. 7 3GPP LTE small cell network architecture [73]

6.1.1 3GPP LTE small cell architecture

Evolved-UTRAN (E-UTRAN) is an evolution of the 3GPP UMTS radio access technology that uses LTE as the radio interface, and Evolved Packet Core (EPC) is defined to accommodate the high-speed LTE access. E-UTRAN consists of multiple evolved Node Bs (eNBs), which connect with each other via the $X2$ interface to support handover and with the EPC via the $S1$ interface for traffic and control purposes. Each eNB connects to the mobility management entity (MME) via the *S1-MME* interface and to the serving gateway (S-GW) via the $S1-U$ interface. Figure 7 shows the generic LTE architecture model and the structure of small cells that are integrated into the LTE.

The procedures that run between the home evolved NodeB (HeNB) and the EPC are the same as those between the eNB and the EPC. In this architecture, the HeNB gateway (HeNB GW) is used as the $S1$ interface between the HeNB and the EPC and thus supports a large number of HeNBs. While the HeNB GW appears to the MME as an eNB, the former appears to the HeNB as the MME. Therefore, a HeNB is architecturally indistinguishable from an eNB in the EPC. Handover support from a HeNB to an eNB and vice versa is available.

6.1.2 5G small cell design considerations

Small cell deployments are one of the most popular long-term strategies for mobile operators worldwide because they provide the necessary near-term capacity boost and flexibility [27].The data rate is calculated in symbols per second. It is further converted into bits per second based on how many bits a symbol can carry, which is dependent on the MCS. Low-order modulation, such as QPSK, is more robust and able to tolerate higher levels of interference but provides a lower transmission bit rate, whereas the high-order modulation 64QAM offers a higher bit rate but is more susceptible to errors due to its higher sensitivity to interference, noise and channel estimation errors. Therefore, the high-order modulation 64QAM is useful only when the SINR is sufficiently high. For 5G mm-wave small cell with a 500 MHz BW, this means that there are 694 resource blocks (RBs), where each RB has 12 subcarriers with subcarrier space of 60 kHz. In addition, each subcarrier has seven symbols for normal CP and the time of the slot is 0.1 ms [74]. Hence, the number of symbols per RB is $12 \times 7 \times 10 = 840$ symbols per ms; making up 582,960 symbols per ms. When 1/8 QPSK is used at the edge of the cell (2 bits per symbol with a coding rate of 1/8), the data rate will be 0.146 Gbps for a single chain. Hence, with 8 antennas, the data rate will be eight times that of a single chain, i.e., 1.167 Gbps. In addition, with a high-order modulation 64QAM the total data rate with 500 MHz BW and 8 antennas will be up to 22.4 Gbps. Figure 8 below summarises the data rate versus MCS and BW at eight antennas.

6.2 5G base station architecture

A traditional cellular network consists of many stand-alone BSs–with each BS covering a cell, processing and trans-

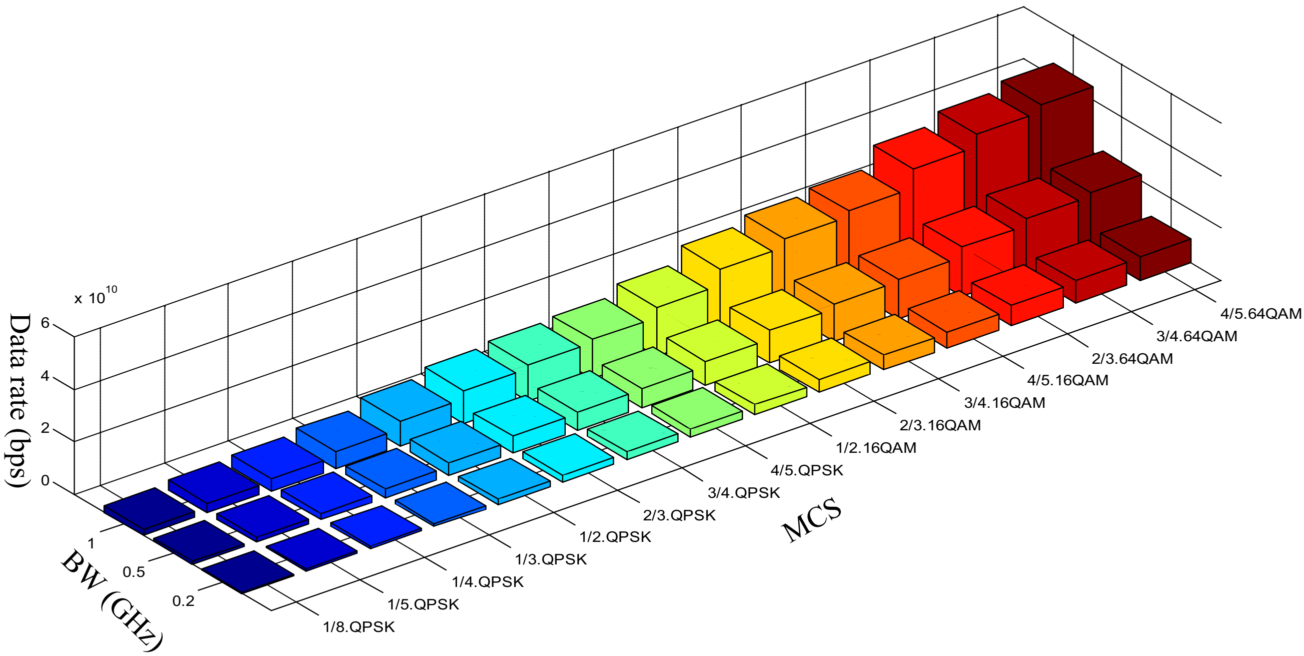
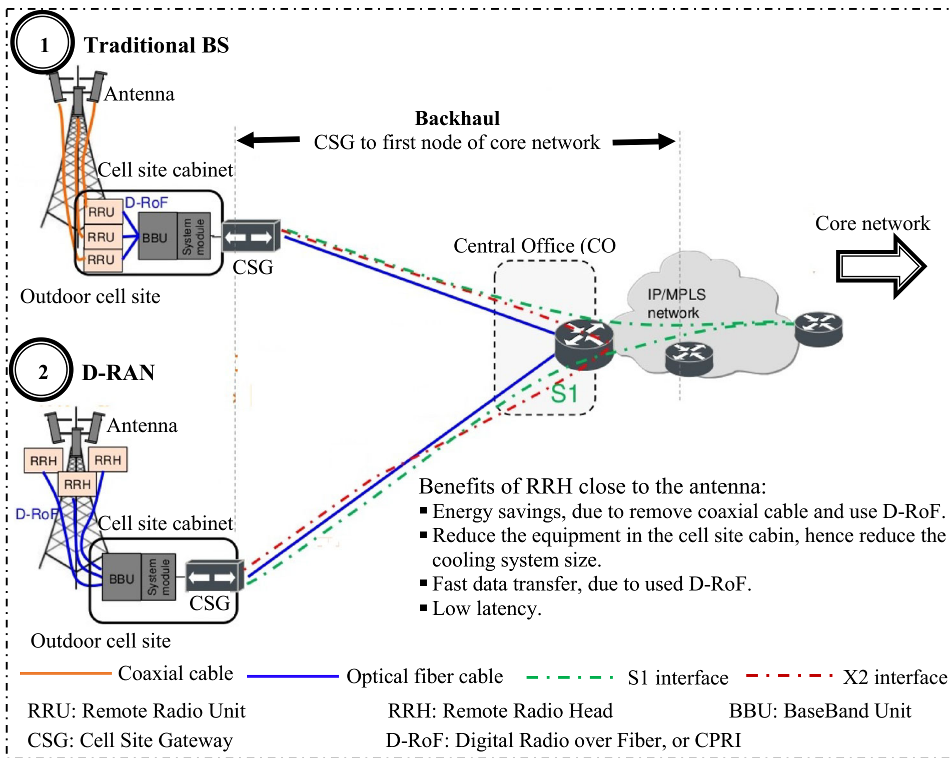


Fig. 8 The data rate versus MCS and BW at eight antennas

Fig. 9 Traditional cellular system and D-RAN architecture



mitting its signal to and from the mobile terminal, and forwarding the data payload to and from the mobile terminal and out to the core network via the backhaul, as shown in Fig. 10. Moreover, each BS has its cooling, backhaul, backup battery and monitoring system [45]. As a result, this has led to a rethinking of the cellular concept. As for 3G, a Distributed RAN (D-RAN) architecture (as shown in Fig. 9) was introduced by Nokia, Huawei and other leading telecom equipment vendors.

D-RAN in this architecture, the radio function unit is also known as the remote radio head (RRH), is separated from the digital function unit, or baseband unit (BBU) by fibre. Digital baseband signals are carried over fibre (D-RoF), using the open base station architecture initiative (OBSAI) or com-

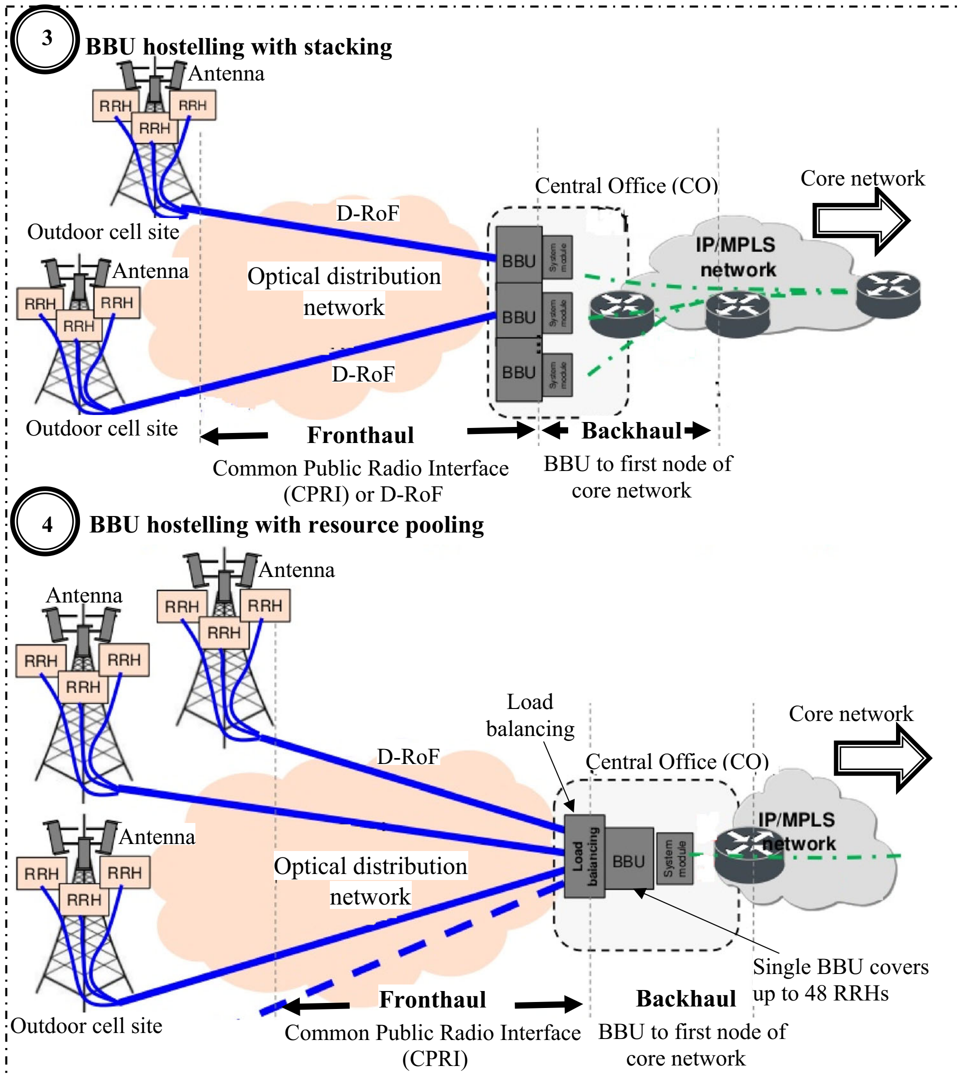


Fig. 10 C-RAN architecture [4,77]

mon public radio interface (CPRI) standard. The RRH can be installed at the top of the tower close to the antenna, thereby reducing any losses compared to a traditional BS where the RF signal has to travel through a long coaxial cable from the BS cabinet to the antenna at the top of the tower. The fibre link between the RRH and BBU also allows for more flexibility in network planning and deployment as they can be placed at a few hundred metres or a few kilometres away [75]. Nonetheless, the BBU is still located at the cell site cabinet; as users are mobile, the traffic of each BS fluctuates and as a result, the average utilization rate of each BS is relatively low. However, these processing resources cannot be shared with other BSs. Therefore, all BSs are designed to handle the maximum traffic, rather than average traffic, resulting in a waste of processing resources and power at idle times. This has led to the rethinking of a cellular concept which main trends are currently classified under the name of C-RAN [4], a proposed architecture for 5G cellular networks. Its name is derived from the four 'C's in the main characteristics of a C-RAN system, "Clean, Centralised processing, Collaborative radio, and a real-time Cloud Radio Access Network".

In C-RAN, the BSs are evolved into a system consisting of remote radio heads (RRHs) distributed at different geographic locations and a baseband process unit (BBU) pool in the wireless cloud at the central office, as shown in Fig. 10. The BBU is able to communicate with other BBUs within the BBU pool at a very high bandwidth (10 Gbit/s and above) and low latency. The RRHs are connected to the wireless network cloud via fronthaul networks. Although optical fibre is needed for the fronthaul, a microwave link or mm-wave could be an option for some small radio site configurations [76,77].

C-RAN architecture enjoys the advantage of many technological advances in wireless, optical and IT communications systems. For instance, it adopts the latest CPRI standard, low cost coarse wavelength division multiplexing (CWDM), dense wavelength division multiplexing (DWDM), optical transport network/wavelength-division multiplexing (OTN/WDM), passive optical network (PON), microwave link, and mm-wave to allow the transmission of baseband signal over long distances thus achieving large-scale centralised base station deployment. Additionally, it also applies recent Data Centre Network technology to allow a low cost, high reliability, low latency and high bandwidth interconnect network in the BBU pool.

In addition, with IoT concept everything will connect to the Internet via a cellular network and is accessible from anywhere. However, despite their widespread adoption, traditional IP networks are complex and very hard to manage. It is both difficult to configure the network according to predefined policies, and to reconfigure it to respond to faults, load and changes. To make matters even more difficult, current networks are also vertically integrated: the control and data planes are bundled together. software-defined networking (SDN) [78,79] is an emerging paradigm that promises to change this state of affairs, by breaking vertical integration, separating the network's control logic from the underlying routers and switches.

The main objectives for SDN are (i) to separate the data plane from the control plane, and (ii) to introduce novel network control functionalities based on an abstract representation of the network. These objectives are realized by (i) removing control decisions from the hardware, (ii) enabling the hardware to be programmable through an open and standardized interface, and (iii) using a network controller to define the behaviour and operation of the network forwarding infrastructure.

Several considerations must be taken into account when planning a small cell underlay network to enable the operator to maximize the benefits of the new network and to keep costs under control.

- *Scalability and integration* Small cells are expected to be massively deployed with many thousands of units in a single network. This requires an architecture that can support sufficient scalability within the same network. In addition, small cells should be easily integrated into existing mobile networks while minimizing the additional load on the legacy infrastructure.
  Wang et al. [74] presented perspectives on 5G small cells while focusing on new waveform design and developed several ideas about ultra-dense deployments. Specifically, they discussed the design principles and feasible ranges of the frame parameters and frame structures and presented an exemplary numerology. The deployment scenarios of small cell networks are introduced in [80]. Due to the challenges of random deployments, dynamic on-off, flexible connections to core cellular networks, and flat system architectures, several cooperative distributed algorithms based on subsets for time synchronization, carrier selection, and power control were introduced. Simulation results showed that these cooperative distributed algorithms can enable random deployments and significantly improve the performance of 5G hyper-dense small cell networks. Chou et al. [23] discussed the maximization of the service time provided by mobile small cells for all users by considering a finite number of mobile small cells and inter-cell/cross-cell interferences. The simulation results showed a significant increase of the total service time provided for all users.
- *Seamless Mobility* Users in wireless cellular environments are not stationary; they are in motion. Thus, seamless handovers between small cells should be considered to decrease the likelihood of dropped calls [81]. Soft handovers, or "make before break", improve the SINR at cell boundaries and improve the cell throughput at the cell edges. However, depending on the quality of the backhaul, there may be delays in switching the serving cell. In hard handovers, or "break before make", the users stay attached to their previous serving cell even if it is weaker; throughput degradation of 50 % or more compared to systems with soft handover can occur, which increases the likelihood of dropped calls [82].
- *Inter-tier interference* The successful rollout of small-cell wireless networks depends on how interference challenges are addressed. Unplanned (random) deployments of small cells are undesirable. Additionally, the concurrent operation of small cells and traditional macro cells will produce irregularly shaped cells and cause inter-tier interference, which will require advanced power control and resource allocation to avoid inter-cell interference [81,83].
  Tavares et al. [84] proposed maximum rank planning (MRP) as a novel inter-cell interference management technique for the ultra-dense uncoordinated deployment of small cells targeted by 5G networks. MRP reduces the number of MIMO spatial multiplexing streams, which leads to an increased probability that the interference rejection combining (IRC) receiver will have sufficient degrees of freedom to reject the strongest interferers. System-level simulation results showed that MRP outperforms conventional frequency reuse planning (FRP) in both low and high traffic load conditions with outage throughput gains of 44 and 49 %, respectively.
- *Security* Because they are deployed at end-user locations, small cells typically operate in insecure environments, such as street poles and traffic lights. Thus, any proposed small-cell network architecture must guarantee a sufficient level of security for both mobile networks and end users [85].
- *Self-organizing* 5G small cell networks should be deployed in a plug-and-play fashion, be self-configured for all necessary parameters at the time of deployment and installation, and not require any regular maintenance [86]. In addition, they should continuously monitor the

wireless channel quality of every link in the backhaul network. Data that are collected during the monitoring process are then used to manage the transmitted power as well as to implement techniques, such as coordinated scheduling, to reduce co-channel interference.

- *Backhaul/fronthaul capacity* Several solutions for small cell backhaul have been proposed [87,88]:

  i. Traditional microwave (6–56 GHz): Microwave technologies rely on complex radio frequency (RF) techniques, such as multipath propagation, channel aggregation, and cross-channel polarization, to deliver high capacities, which can result in prohibitive complexity for high-density small cell backhaul. In contrast, millimetre-wave wireless relies on generous RF spectrum availability to deliver high throughputs using simple single-channel configurations.

  ii. Unlicensed mm-wave (60 GHz) and licensed mm-wave: Millimetre-waves have short wavelengths, high frequencies, and large bandwidths. In addition, they interact with atmospheric constituents, such as oxygen and are attenuated through most solid materials. It is worth noting that oxygen absorption can cause attenuation of approximately 15 dB/km because oxygen molecules (O_2) absorb electromagnetic energy at approximately 60 GHz [18].

  iii. V-band (57–66 GHz) and E-band (70–80 GHz): As a result of a very short wavelength, diffraction and penetration through obstacles are currently hardly possible and thus only LOS links are feasible. Hence, the V-band is an appropriate choice for street-to-street and street-to-roof connections, while the E-band is a more effective solution for roof-to-roof links [89].

  Leveraging the legacy 4G network: The concurrent utilization of microwave and mm-wave frequencies could assist in overcoming some of the hurdles described above. An interesting proposal is the notion of "phantom cells" (called "soft cells" within 3GPP) [90,91], where mm-wave frequencies would be employed for payload data transmission from small-cell BSs, while the control plane would operate at microwave frequencies from macro BSs. This would ensure stable and reliable control connections that are based on arranging very fast data transmissions over short-range mm-wave links. Sporadic interruptions of these mm-wave links would then be far less consequential because the control links would remain in place, and lost data could be recovered through retransmissions.

  iv. Fibre optic is the most preferable solution in terms of both capacity and delay, in particular for C-RAN where multi-Gbps digital radio signals are transmitted over the CPRI interface. For relatively long distances, longer than 10 km fronthaul scenarios, the optical transport network (OTN) with wavelength-division multiplexing (WDM), which adopts a ring topology to enable full protection and operation, administration and maintenance (OAM), is considered. For shorter links less than 10 km, a point-to-multipoint (PtMP) unified passive optical network (Uni-PON) which uses an optical splitter to aggregate WDM signals from fronthaul links of multiple cells is suggested. As a complementary solution, point-to-point (PtP) fibre, which yields low fibre resource utilisation and weak protection, are also deployed [77,89,92]. However, there are some limitations in relation to the fibre-optic cable such as, synchronisation performance between RRH and BBU, particularly in phase and time. Table 3 below summarises the major fronthauling solutions for small cells.

However, fronthaul traffic has radically different features compared to those of backhaul traffic, and it poses specific challenges to the transport network. On the fronthaul, the dimensioning requirements take into account the state of the art. Depending on the cell site technologies, bandwidth requirements between the cell site and the central office where the BBU is localized will differ. Two standards (CPRI and OBSAI) exist for transport's interfaces in both of them the radio signal is digitised (D-RoF, digital radio over fiber). CPRI and OBSAI share a number of similarities. Three main critical characteristics will discuss below:

(i) High bit rate capacities need on fronthaul: Different radio access standards (GSM, WCDMA, LTE, and 5G) have different CPRI data throughputs, so different transmission solutions need to be considered. CPRI link rates go from 614.4 Mbit/s up to 9.8Gbit/s.

(ii) Maximum end-to-end latency: Since the link between RRH and BBU is at the level of the physical radio signal, the total latency that the radio signal can tolerate, includes the latency of the fronthaul. The most critical parameter comes from the up-link synchronization method Hybrid Automatic Repeat Request (HARQ)-retransmission protocol. In the case of retransmission, this parameter has a direct impact in case of retransmission, on peak data per user. After subtracting the mobile equipment processing time, considering maximum timing advance (667 μs, for LTE) and the assumption of a 10 km cell radius, the remaining time for round trip time propagation between RRH and BBU is only 700 μs for LTE with a chance of several more such requests depending upon interference and levels, signal strength

Table 3 Key fronthaul solutions

(1) Wireless solutions

Technology	Sub-6 GHz	Microwave	mm-wave	
			V-band	E-band
Frequency	Sub 6 GHz	6–56 GHz	57–66 GHz	70–80 GHz
Licensing	Licensed (3.5 GHz)	Licensed	Unlicensed (60 GHz)	Licensed
Distance	<1 km	<5 km	<1 km	
Capacity	Up to ∼500 Mb/s	Up to 5 Gb/s	Up to 10 Gb/s	
Topology	PtMP, PtP	PtMP, PtP	PtP	
Main advantages	LOS and NLOS, faster installation and lower deployment cost.	Large spectrum, high capacity, high-gain, long distance connection,	Available large spectrum, extremely high capacity up to several Gbps, unlicensed, high-frequency reuse factor.	
Main disadvantages	Lower capacities, interference sensitive, higher cost for licensed spectrum.	LOS required, node alignment may reduce the deployment scalability.	Short links, LOS required, very narrow beamwidth.	

(2) Wire solutions (D-RoF or CPRI)

Technology	CWDM	DWDM	OTN/WDM	Uni-PON	PtP Fiber
Wavelength	C-Band 1.55 μm		O-Band 1.31μm		
Distance	>10 km	>10 km	>10 km	<10 km	∼20 km
Capacity	Up to 100 Gb/s	Up to100 Gb/s	Up to 100 Gb/s	10 Gb/s	10 Gb/s
Topology	PtMP	PtMP	PtMP	PtMP	PtP
Main advantages	• Low-cost initial setup. • Easy upgrade. • Reliable and secure. • Simple to install and maintain. • Provides full performance monitoring.	• Less fiber cores to transmit and receive high capacity data. • A single core fiber cable could divide into multiple channels. • Easy network expansion.	• Large channels • Bidirectional (ring topology). • High efficiency, reliable and secure	• High efficiency, reliable and secure. • Provides full performance monitoring.	• Transmit and receive high capacity data.
Main disadvantages	• Lower number of channels. • Lower BW.	• Complicated transmitters and receivers. • Wide-band channel, CAPEX and OPEX high.	• Latency and synchronization (phase and time). • Power supply required. • High cost.	• Latency and synchronization (phase and time).	• Low fiber resource utilization. • Weak protection.

Table 4 Comparison between the three physical layer techniques that discussed

Technique	Impact	Benefits	Challenges
mm-wave	Fulfills the 5G requirement for greater bandwidths.	• Small antenna size. • Massive bandwidths. • Very high data rates.	• High attenuation, which reduces the coverage to small distances or requires the use of higher order beamforming.
Massive MIMO	Improves capacity and energy efficiency by exploiting a large array gain.	• Increased system capacity. • Increased energy efficiency. • Spatial dimensions limit the path loss.	• Channel estimation/feedback. • Pilot contamination. • Performance is sensitive to speed, which makes multi-user solutions unaffordable.
Small cell deployment	Capacity is directly proportional to the number of nodes.	• Improved SINR, spectral efficiency, and capacity. • Low power transmission. • Prolonged handset life.	• Cost. • Interference coordination.

and congestion; 400 μs for LTE Advanced, and 5G less than 400 μs with latency 100 μs. This includes both time delays for the fibers and equipment that could be placed on the link.

(iii) Jitter and synchronization: concerning synchronization on the fronthaul segment, the CPRI frame is divided into three parts, the first part is the I/Q data, the second contains the control and management information, and the third is required for synchronization. The CPRI specification defines the maximum jitter transfer bandwidth of the phase-locked loop (PLL). For 5G, time and phase synchronization is required. This also includes a requirement on the delay calibration mechanism. A phase accuracy requirement budget is allocated to the CPRI link and the contribution of the link itself shall be taken into account. It is appropriate that both phase noise and asymmetries are considered (in fact the error in the delay measurement is also impacted by asymmetry in the CPRI link). It has to be noticed that the budget allocated to the CPRI link is defined for a point to point connection and over a fiber link. Other transport solutions are not covered by the CPRI specification and need to be handled carefully especially when deploying services that required phase and time synchronization.

- *Cost-effective and energy savings* Hoydis et al. [93] showed how a large system analysis based on random matrix theory (RMT) can provide tight and tractable approximations of key performance measures of small cell networks. In addition, Ashraf et al. [94] discussed the energy consumption of small cell deployments in cellular networks with an emphasis on devising specialized sleep mode solutions for small cell BSs. The proposed algorithms allow the hardware components in the BS to be switched off during idle conditions so the energy consumption can be modulated according to variations in the traffic load. The algorithms were shown to offer energy savings of approximately 10–60 % compared to a network with no sleep modes in small cells.

7 Concluding remarks

The daunting requirements for 5G networks are already unleashing a flurry of creative thinking and a sense of urgency in bringing innovative new technologies to reality. Millimetre-wave cellular systems were considered to be a fantasy just five years ago; they are now considered to be nearly inevitable. This article has shown that spatial multiplexing using massive MIMO techniques with mm-waves along with small cell geometries appears to be a symbiotic convergence for increasing throughput. However, many technical challenges remain for future research. This article has provided references that will help researchers make progress toward this goal. Table 4 summarizes the impacts of the most significant techniques as well as the pros and cons of their use in 5G systems.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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