Digital Communications and Networks 4 (2018) 87–97

Contents lists available at ScienceDirect

Digital Communications and Networks

journal homepage: www.keaipublishing.com/en/journals/digital-communications-and-networks/

A survey of 5G technologies: regulatory, standardization and industrial perspectives

António Morgado, Kazi Mohammed Saidul Huq, Shahid Mumtaz *, Jonathan Rodriguez

Instituto de Telecomunicações, 3810-193 Aveiro, Portugal

ARTICLE INFO

Keywords:
5G
ITU
Next-generation wireless networks

ABSTRACT

In recent years, there have been significant developments in the research on 5th Generation (5G) networks. Several enabling technologies are being explored for the 5G mobile system era. The aim is to evolve a cellular network that is intrinsically flexible and remarkably pushes forward the limits of legacy mobile systems across all dimensions of performance metrics. All the stakeholders, such as regulatory bodies, standardization authorities, industrial fora, mobile operators and vendors, must work in unison to bring 5G to fruition. In this paper, we aggregate the 5G-related information coming from the various stakeholders, in order to i) have a comprehensive overview of 5G and ii) to provide a survey of the envisioned 5G technologies; their development thus far from the perspective of those stakeholders will open up new frontiers of services and applications for next-generation wireless networks.

1. Introduction

The fast development of electronic devices has brought about the advent of various emerging applications (e.g., big data analysis, artificial intelligence and 3-Dimensional (3D) media, Internet of everything, and so on), which requires significant amount of data traffic. While mobile networks are already indispensable to our society for "anywhere anytime connection," one main characteristic of 5G and Beyond (B5G) mobile networks is the huge amount of data, which requires very high throughput per device (multiple Gbps) and per area efficiency (bps/km^2). For instance, it is predicted that the worldwide monthly data traffic in smartphones will be about 50 petabytes in 2021 [1], which is about 12 times the traffic in the year 2016. From these figures, we can also estimate that the traffic will continuously increase at a very rapid pace. Other characteristics include low delay communications, high reliability, and large heterogeneous connected devices.

Among the various kinds of data traffic, video data is more dominant. Video traffic already constitutes a significant fraction of the mobile traffic volume and is expected to reach 67% of the total traffic by 2017 and more in the future. Video traffic has already presented very severe challenges to mobile networks, including the forthcoming 5G mobile networks. For instance, it is expected that at least 10 Gbps traffic is needed for one Virtual Reality (VR) device. Moreover, full High-Definition (HD) video is becoming increasingly important for mobile devices; further, devices Using Ultra HD (UHD) (4K and 8K) and 3D rendering are expected to become widely available in the not so distant future. An uncompressed UHD video may reach a rate of 24 Gbps, and an uncompressed 3D video with UHD can reach 100 Gbps [2].

Based on the above observations, the main technical objectives for 5G systems will be

- Extremely high data rates per device (multiple tens of Gbps).
- High data rates per area and massive a large number of connected devices. Thus, the interference among transmitters should be minimized.
- Ultra-low latency (round time of less than a microsecond), especially for multimedia and interactive 3D video/VR applications.
- Ultra-reliable support for various critical applications such as Vehicle-to-Vehicle (V2V) communications, industrial control, and healthcare.

From the list of technologies developed in recent years [3] by the stakeholders (standardization, regulatory bodies and industrial organizations), we briefly describe the ones that are most promising for 5G. To the best of our knowledge, this is the first attempt to summarize 5G technologies from industrial, standardization, and regulatory perspectives.

This paper is organized as follows. Section II provides a brief overview of the most anticipated 5G technologies. Section III presents the 5G use cases and key performance indicators (KPI). Sections IV and V describe novel radio development and field trials for 5G, respectively. Finally, the paper is concluded in Section VI.

* Corresponding author.
E-mail address: smumtaz@av.it.pt (S. Mumtaz).

https://doi.org/10.1016/j.dcan.2017.09.010
Received 5 August 2017; Received in revised form 16 September 2017; Accepted 19 September 2017
Available online 20 September 2017

2. Envisioned technologies for 5G by regulation and standardization bodies

2.1. Radio Access Network (RAN)

2.1.1. Millimeter-Wave (mmWave)

The distinctive feature of 5G is its intrinsic flexibility, which will allow it to support several use cases in an optimized way, either using low-band spectrum below 1 GHz, mid-band frequencies from 1 GHz to 6 GHz, or high-band spectrum above 6 GHz.

The low-band spectrum is deemed essential for use cases that require seamless coverage and high mobility, as is the case with ultra-Reliable Low Latency Communications (uRLLC) and massive Machine Type Communications (mMTC). The mid-band spectrum is going to be utilized by the first 5G networks to support enhanced Mobile Broadband (eMBB), which is vital to demonstrate the 5G business case and promote investment in 5G networks. When 5G networks become mature, eMBB will have to offer peak data rates of 20 Gbps and experienced user data rates of 100 Mbps to a very high number of users. With the feasible spectral efficiencies, such transmission speeds can only be delivered using channels with bandwidths in the order of several hundred megahertz, which are available only in the high-band at mmWave [52] frequencies.

International Telecommunication Union (ITU) has already allocated several bands from 450 MHz to 6 GHz for IMT (International Mobile Telecommunications) as indicated in Table 1 [4]. In principle, 5G may be used in any of these bands, although some preferences are being defined:

- The USA is willing to use the recently cleared 600 MHz licensed band (617–652/663-698 MHz), as well as the 3.5 GHz shared band (3550–3700 MHz) [5]. The Advanced Wireless Services (AWS-3) bands, i.e., 1695–1710 MHz, 1755–1780 MHz, and 2155–2180 MHz can also be used if desired [5]. It should be noted that although the 600 MHz band is not an IMT band, ITU has already decided to review the situation of TV broadcasting band (470–694/8 MHz) in the year 2023, in view of releasing more spectrum for mobile systems if necessary.
- Europe selected 700 MHz (694–790 MHz) as the band below 1 GHz for 5G, while the leading pioneer 5G band should be 3.4–3.8 GHz. It is in this band that each European country is expected to deliver 5G services at least in one city by 2020. The 1.5 GHz band (1427–1452/1492-1518 MHz) is being studied to provide supplementary downlinks [6–8]. 5G may also be used in any other band harmonized at the European level for mobile services and licensed under technology neutrality paradigm (800 MHz, 2 GHz, 2.3 GHz and 2.6 GHz).
- Japan is trialing 5G in the 3600–4200 MHz and 4400–4900 MHz bands [9].
- China is testing 5G in the 3300–3600 MHz and 4800–4990 MHz bands [9].

Regarding the high-band, 11 mmWave bands, between 24.25 GHz and 86 GHz, were indicated as candidate 5G bands during the last 2015 World Radio Conference (WRC-2015), as can be seen in Resolution 238 of [4]. As indicated in Table 2, three of these candidate bands may be available only in the long term, as currently they are not allocated to mobile communications on a primary basis.

Although the decision on globally harmonized 5G millimeter wave bands will only take place at WRC-2019, the regulatory bodies of the countries with strong 5G initiatives are already trying to influence the final decision:

- In the USA, the Federal Communications Commission (FCC) selected 3.85 GHz of the licensed spectrum in the 27.5–28.35 GHz and 37–40 GHz bands (37–37.6 GHz is allocated to 5G on a shared basis), along with 7 GHz of the unlicensed spectrum in the 64–71 GHz band [10]. Although these choices are not fully aligned with ITU plans, FCC is analyzing the possibility to open up to 18 GHz of additional spectrum in all ITU candidate bands, except 42.5–47.2 GHz [10].
- The European Union followed ITU guidelines and designated 3.25 GHz of spectrum in the 24.25–27.5 GHz band as a pioneer 5G band. Europe also considers the bands 31.8–33.4 GHz and 40.5–43.5 GHz as promising bands in the future [6,8].
- South Korea intends to offer 5G in time for the 2018 Winter Olympics, for which they have decided to use the 27.5–28.35 GHz and 37.5–40 GHz bands, i.e., very similar choices to those of the USA [9].
- Japan intends to commercially roll out 5G in time for the 2020 Summer Olympics, using the spectrum from 27.5 to 29.5 GHz [9].
- China is adopting 24.25–27.5 GHz, which ensures compatibility with Europe, and 27.5–29.5 GHz, which also ensures compatibility with USA, South Korea, and Japan [9].

These high-band frequencies have higher path losses, and therefore, the coverage will be limited. This drawback can be mitigated by the use of high power gain antennas or antenna arrays. However, these antennas exhibit very narrow beam widths (a few degrees), a feature that is both desirable, as it allows to confine interference over limited regions, as well as challenging because it requires precise beam steering algorithms and a careful planning of the number of beams that would be necessary. Due to path-loss constraints, millimeter waves are best suited for use in indoor hotspots and outdoor small cell scenarios.

2.1.2. Spectrum sharing

In an urban environment, 5G will rely on dense networks with reduced cell sizes, which may share the same band with other services operating in different territories [11]. 5G can perfectly use the spectrum sharing schemes developed in the last fifteen years, getting additional

Table 1
Low and mid-band frequencies.

ITU-R (IMT bands) [4]
450–470 MHz
698–960 MHz
1427–1518 MHz
1710–2025 MHz
2110–2200 MHz
2300–2400 MHz
2500–2690 MHz
3300–3400 MHz
3400–3600 MHz
3600–3700 MHz
4800–4990 MHz

Table 2
Candidate high-band frequencies.

ITU-R (IMT-2020 candidate bands) - Resolution 238 of WRC 2015 [4]	Allocated to mobile on primary basis?
24.25–27.5 GHz	Yes
31.8–33.4 GHz (Shared with the fixed service)	No
37–40.5 GHz (Shared with fixed-satellite service in 39.5–40 GHz in Region 1 and in 40–40.5 GHz worldwide. Shared with fixed service in 37–40 GHz)	Yes
40.5–42.5 GHz (Shared with fixed-satellite service in 40.5–42 GHz in Region 2. Shared with fixed service in 40.5–43.5 GHz)	No
42.5–43.5 GHz	Yes
45.5–47 GHz (Shared with space radio comm. in 43.5–47 GHz)	Yes
47–47.2 GHz	No
47.2–50.2 GHz (Shared with fixed satellite service in 47.5–47.9/48.2–48.54/49.44–50.2 GHz in Region 1, and in 48.2–50.2 GHz in Region 2. Band 48.94–49.04 GHz is forbidden for airborne stations.)	Yes
50.4–52.6 GHz (Shared with fixed service in 51.4–52.6 GHz)	Yes
66–76 GHz (Shared with space radio comm. in 66–71 GHz)	Yes
81–86 GHz	Yes

spectrum when and where needed.

2.1.2.1. TV White Spaces (TVWS). In the last two decades, several measurement campaigns demonstrated that spectrum licensing methods had to be changed as they resulted in inefficient use of radio resources. While the appearance of software-defined radio and cognitive radio technologies provided the tools to adopt dynamic spectrum access schemes, the digital dividend, resulting from the migration to digital TV, provided an excellent first real-life test environment for introducing more efficient spectrum usage methods.

One such method, TV white spaces, originated in the USA in 2002. It was proposed by the FCC [12,13] for the sharing TV frequencies that were not used in certain areas (TV white spaces) by unlicensed low-power devices. In TV white spaces, the TV receivers are called primary users, and they have higher priority to transmit and are protected against interference. The unlicensed low-power devices are called secondary users, and they have lower priority to transmit and are not protected from the interference coming from the primary or secondary users (i.e., several secondary users may use the same frequencies in the same place at the same time). To avoid interference with the primary users before transmitting, the secondary users must consult a geolocation database to determine which spectrum is left available by the primary users at their current locations. In the USA, the final TV white space rules were published in 2010 [14] and updated in 2012 [15]. TV white spaces are commercially available to the public since the first database was approved by FCC in January, 2012 [16].

In 2007, the UK also decided to regulate the use of TV white spaces by unlicensed devices [17]. After a period of preliminary studies, in 2009, the UK selected geolocation databases as a more reliable method to protect primary users [18], and in 2013, it proposed the complete TV white spaces rules [19], which were updated in 2015 [20]. TV white spaces are commercially available in the UK since this regulation came into force, i.e., since December, 2015 [21].

Europe started looking into TV white spaces in 2008 as part of the digital TV switchover [22]. As in the UK, several studies were conducted [23,24], which culminated in the definition of regulatory guidelines very similar to those of the UK. These guidelines intended to harmonize the use of TV white spaces in European countries also using geolocation databases [25,26].

Although the USA and UK/Europe follow identical approaches, the implementation of geolocation databases is very different in the USA and UK/Europe. The USA geolocation databases draw exclusion zones around the protected stations to define a region where no unlicensed devices, which are assumed to be always transmitting at the maximum power, are allowed. On the other hand, the UK/European geolocation databases divide the territory into squares of 100 m $\times$ 100 m, called pixels, and compute the maximum power that the unlicensed device may use so that the protected TV service is not degraded beyond a predefined threshold.[1] To avoid different results from different databases, the UK regulator pre-computes the maximum power that may be used by a single unlicensed device in each TV channel in each pixel, and sends this information to all database operators. Although more complex, the UK/European geolocation database allows the sharing of spectrum resources by a higher number of secondary users than the USA database.

2.1.2.2. Licensed Shared Access (LSA). Since TV white spaces do not offer the required quality of service to secondary users, mobile telecom operators do not see this spectrum sharing scheme as a viable option to get additional spectrum. Therefore, in 2011, a different method called Authorized Spectrum Access (ASA) appeared in Europe specially; this method was tailored for mobile operators [27]. The idea of ASA was that the spectrum owners, i.e., the incumbents, of underutilized bands could allow a limited number of mobile telecom operators to share the spectrum when the incumbent is not using it. The sharing conditions should be previously agreed between the spectrum owner (incumbent) and the new licensees (mobile operators), probably defining a monetary compensation paid by the new licensee to the incumbent. Initially, it was thought that the sharing agreement should also include a pre-defined channel plan to allocate specific parts of the band to each mobile operator, thus avoiding the need for coordination among mobile operators. After signing the sharing agreement, whenever the new licensee needs spectrum, it should contact a database to see if the incumbent is planning to use the spectrum in a specific period in a given location. If it is not, the new licensee may exclusively use that spectrum.

Meanwhile, the Radio Spectrum Policy Group (RSPG) and the European Conference of Postal and Telecommunications Administrations (CEPT) decided that this concept should not be restricted to mobile networks, and therefore, they extended it to all radio services. The extended sharing scheme was called Licensed Shared Access [28–30]. Unlike TVWS, in LSA, the new licensees are protected against interference and thus can access the spectrum with a predictable quality of service. LSA is beneficial both for the LSA licensee (because it can access an underutilized band cost-effectively while the band cannot be cleared/reformed), and for the incumbent who can be authorized to stay longer in the band and eventually receive monetary compensation. The first band allocated to LSA in Europe was the 2300–2400 MHz band [31–33].

2.1.2.3. Spectrum access system (SAS). In the USA, another sharing scheme, called Spectrum Access System, was proposed in 2012 for the 3550–3700 MHz band, as a means to provide additional spectrum for mobile broadband [34,35]. Unlike LSA, SAS shares the spectrum among two types of users (i.e., incumbents and LSA licensees). In addition, SAS is a three-tier sharing scheme that allows three types of users to share the spectrum inside each administrative region (census tract): federal users, Priority Access Licensed (PAL) users, and General Authorized Access (GAA) users. The federal users take precedence over all the others and are protected against all types of interference, either through the definition of exclusion zones or by using the Environment Sensing Capability (ESC) networks that detect emissions from the federal users and inform the SAS, which will then instruct all other users to abandon the band. The PAL users will apply to geographic licenses through auctions. They may use the spectrum exclusively when the federal users do not use it and are protected from interference from the other PAL and GAA users, but not from the federal users. In the last priority level are the general authorized access users, which are unlicensed devices that use the spectrum opportunistically and are not protected against any interference. The final regulations of SAS were approved in April, 2016 [36].

2.1.3. Carrier aggregation

Carrier aggregation is a technique introduced in 4th Generation (4G) mobile systems, more specifically in Release 10 of the 3rd Generation Partnership Project (3GPP) specifications. It allows the aggregation of up to five Long-Term-Evolution (LTE) carriers, a.k.a. Component Carriers (CC), thus allowing the increase in system bandwidth up to 100 MHz (5 $\times$ 20 MHz). The mobile terminal of the user may receive one or more CCs depending on its capabilities. It is also possible to aggregate a different number of CC, eventually of different bandwidths, in the uplink and downlink, with the constraint that the number of aggregated CC in the uplink is not higher than the number of aggregated CC in the downlink. The CC being aggregated may belong to the same band (intra-band carrier aggregation) or different spectrum bands (inter-band carrier aggregation). Within intra-band carrier aggregation, it is possible to aggregate contiguous component carriers (contiguous carrier aggregation) or non-contiguous component carriers (non-contiguous carrier aggregation).

When using carrier aggregation, in each direction (uplink, downlink),

[1] The white space device power may only cause a rise of 1 dB in the noise-plus-interference floor at the edge of TV coverage. Greater rise in the noise plus interference floor is allowed in areas within TV coverage.

one of the CC must be selected as the Primary Component Carrier (PCC), while the others are called Secondary Component Carrier (SCC). There is one serving cell associated with each component carrier, eventually with different coverage areas due to propagation issues. The serving cell associated with the PCC is called the Primary serving Cell (PCell), whereas the serving cells associated with the SCC are called Secondary serving Cells (SCell). The signaling traffic is exchanged only in the PCell, whereas data traffic is exchanged in both the PCell and SCell.

Carrier aggregation was introduced to the Third Generation Partnership Project (3GPP) specifications using a stepwise method: in Release 10, only two CC could be aggregated in the DownLink (DL) and there was no carrier aggregation in the UpLink (UL); in Release 11, carrier aggregation was improved by allowing up to two CCs in the uplink; Release 12 added Time Division Duplex (TDD)/Frequency Division Duplex (FDD) carrier aggregation. In Release 13, the number of 20 MHz component carriers that can be aggregated was increased from 5 to 32. This will be of great value, especially for using large blocks of unlicensed spectrum in the 5 GHz band.

Although a powerful technique, the hardware circuitry behind carrier aggregation is complex, not only because the number of components is higher in carrier aggregation, but also because the reception of multiple signals with different frequencies generates intermodulation products that may interfere with the desired signals.

2.1.4. *Dual connectivity*

Dual connectivity is a feature recently added to 4G systems to improve the performance of heterogeneous networks. It involves the establishment of several parallel bearers associated with the same mobile, thus allowing extension of the bandwidth allocated to that terminal. The different bearers are combined in the mobile terminal and the core network. For dual connectivity, the mobile is connected with several base stations, one Master eNB (MeNB), and at least one Slave eNB (SeNB), each using different carrier frequencies and controlled by a different Medium Access Control (MAC) entity. The control traffic is transmitted solely by the master eNB, while the user data is split between the MeNB and several SeNBs.

This behavior is implemented using a protocol stack, which includes the control-plane, Radio Resource Control (RRC) entities (only in the MeNB), and the mobile terminal. Therefore, only the MeNB may send the RRC signals and control the RRC procedures.

In the user-plane, there are two protocol-stack alternatives to implement dual connectivity:

- SeNB connects directly to the Serving Gateway (S-GW) in the core network. Each Evolved Packet System (EPS) bearer is directed entirely to a different base station, so that there is no split of EPS bearers among different base stations. See Fig. 1, which illustrates the downlink direction.
- SeNB connects to the S-GW in core network through the MeNB. Therefore, some EPS bearers (marked in green in Fig. 2) are split between the MeNB and an SeNB. This is depicted in Fig. 2, taking the downlink direction as an example.

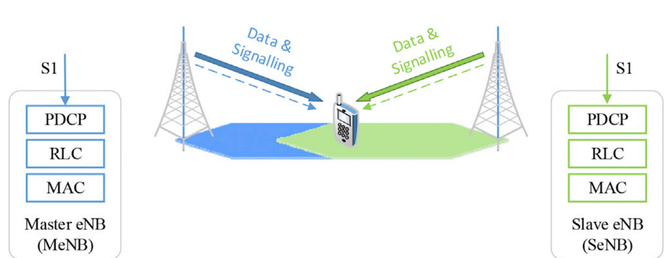

Fig. 1. Dual connectivity between MeNB and SeNB (downlink direction) without splitting EPS bearer.

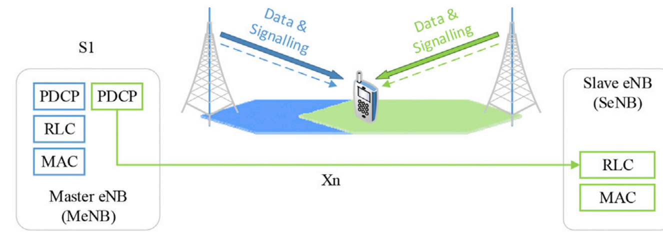

Fig. 2. Dual connectivity between MeNB and SeNB (downlink direction) with EPS bearer splitting.

Although dual connectivity has similarities with carrier aggregation, dual connectivity is different from carrier aggregation, because carrier aggregation has only one MAC entity due to the use of a signal base station, whereas dual connectivity has many MAC entities as a number of base stations are employed.

Dual connectivity is different from Coordinated MultiPoint (CoMP) transmission because several base stations transmit different information simultaneously to a specific mobile. Another difference is that dual connectivity assumes that the base stations are connected using non-ideal backhaul, which is not the case in CoMP.

2.1.5. *Unlicensed spectrum*

Licensed spectrum should be the core 5G spectrum; however, unlicensed spectrum can play a complementary role [11]. Therefore, the two different ways of using unlicensed spectrum developed for 4.5G (LTE--Pro) should also be useful for 5G.

2.1.5.1. Licensed Assisted Access (LAA). LAA is a new spectrum sharing scheme defined in 3GPP Release 13. Instead of alleviating radio network congestion by offloading cellular LTE traffic to Wireless Local Area Networks (WLAN), LAA proposes to deploy inter-band carrier aggregation using a primary LTE carrier component from a licensed band and a secondary LTE carrier component from an unlicensed band. LAA proposes to use the 5 GHz unlicensed band opportunistically to boost data rate, ensuring coexistence with Wi-Fi devices already deployed in the band by adopting a listen before talk scheme. LAA also proposes to use dynamic frequency selection in some regulatory domains, and ensure coexistence with radar, which is also deployed in the 5 GHz band. In 3GPP Release 13, the secondary LTE carrier component in the unlicensed band can only be used in the downlink. In Release 14, LAA is being enhanced to allow the use of the secondary LTE carrier component from the unlicensed band in the uplink also. In Release 13, the number of 20 MHz component carriers that can be aggregated increased from 5 to 32. This will be of great value, especially for LAA to use large blocks of unlicensed spectrum in the 5 GHz band.

2.1.5.2. LTE-WLAN Aggregation (LWA). LWA is a new spectrum aggregation scheme defined in 3GPP Release 13. LWA proposes to connect a mobile terminal simultaneously to an LTE base station and a WLAN access point. In the downlink, packets going to a specific User Equipment (UE) are split in the eNB. Some of them are transmitted through the LTE air interface, while the others are directed to the Wi-Fi access point, and these packets are then reordered and combined in the UE. Due to the unlicensed nature of Wi-Fi, the packets going through Wi-Fi use a secure IP (IPSec) tunnel. In Release 13, Wi-Fi Access Point (AP) can be used for the downlink only. In Release 14, LWA is going to be extended to allow the use of Wi-Fi AP in the uplink also.

2.1.6. *New waveforms for 5G*

Due to the high diversity of services that need to be supported in 5G, with very different requirements regarding throughput, delay, robustness, and energy consumption, the 5G air interface should be flexible enough so that it can be adjusted to the specific service being delivered, the band in use, and the maximum terminal velocity.

We consider that the 5G system should have a unified and flexible frame structure, in which the number of resources allocated to uplink and downlink is allowed to vary. It should also be scalable, in both the frequency and time domains, so that the number of subcarriers and the length of the time transmission interval allocated to a given user can be adjusted to achieve the required throughput and latency. Taking into account that 5G may have to be used in very different frequency bands, from 450 MHz to 86 GHz, and support a wide range of terminal speeds, from 0 to 500 km/h, the subcarrier spacing should be configurable in order to avoid inter-carrier interference caused by the Doppler effect.

The air interface should also support orthogonal and non-orthogonal multiple access schemes (e.g., Orthogonal Frequency Division Multiple Access (OFDMA), Interleave Division Multiple Access (IDMA), Non-Orthogonal Multiple Access (NOMA) [53–55], Sparse Code Multiple Access (SCMA), etc.), as well as synchronous and asynchronous traffic (e.g., Carrier Sense Multiple Access (CSMA)). Regarding the waveforms, most of the candidates for the 5G interface are of the filtered multicarrier type. These waveforms help maintain the InterCarrier Interference (ICI) and InterSymbol Interference (ISI) below an unrecoverable level, to relax the synchronism requirements and increase spectral efficiency.

In Europe, several research projects have been working on the 5G air interface. For example, 5GNOW [37] proposes a unified frame structure combining orthogonal and non-orthogonal multiple access, as well as synchronous and asynchronous traffic. This frame structure may have several signal layers superimposed using IDMA. 5GNOW also studies several filtered multicarrier waveforms (Generalized Frequency Division Multiplexing (GFDM), Filter Bank Multicarrier (FBMC), Universal Filtered Multicarrier (UFMC), and Bi-Orthogonal OFDM (BFDM)) to be used in 5G and identifies the pros and cons of each waveform. In order to support asynchronous traffic in uplink, which would be advantageous for machine type communications, the project proposes an uplink random access scheme where the base station uses the joint sparsity of the message, propagation channel, and user activity, to fully recover the random access packet just by decoding a reduced number of samples.

Prior to 5GNOW, the project FANTASTIC-5G [38] considered a unified multi-service air interface where the frequency-time resources are grouped into elementary blocks called tiles. Each tile can be independently configured in terms of forward error coding, modulation, subcarrier spacing, time transmission interval, and waveform. For Forward Error Correction (FEC), FANTASTIC-5G proposes the use of enhanced turbo codes, which exhibit superior performance when compared with other solutions like Low-Density Parity-Check (LDPC) and Polar codes. Regarding waveforms, FANTASTIC-5G studies several OFDM-based waveforms belonging to two families:

- Subband-wise filtered waveforms:

- Universal Filtered OFDM (UF-OFDM) - one filter is used to filter each group of adjacent subcarriers. The length of the filter/number of subcarriers in each group is equal to the length of the cyclic prefix.
- Filtered OFDM (F-OFDM)– similar to UF-OFDM; however, the subband filter can have lengths higher than the cyclic prefix length
- Block-filtered OFDM (BF-OFDM).

- Subcarrier-wise filtered waveforms:

- Flexibly Configured OFDM (FC-OFDM) – this waveform can be configured to become multi-carrier, DFT-spreading, zero-tail DFT-spreading, etc. These different formats can be multiplexed in the frequency or time domain.
- Pulse-shaped OFDM (P-OFDM): identical to conventional OFDM, except that pulse shapes other than the rectangular pulse may be used.
- Frequency Spreading Filter-Bank Multicarrier/Filter-Bank Multicarrier (FS-FBMC/FBMC): similar to FBMC-OQAM, except in the method used to implement the prototype filters. They are generated by applying a frequency sampling technique instead of using a polyphase network implementation. This is advantageous for channels with large delay spread or when there are synchronization errors.
- FBMC with Quadrature Amplitude Modulation (QAM) signaling (QAM-FBMC): an FBMC system using QAM symbol mapping instead of offseting QAM (OQAM). This reveals the advantage of increasing the transmission rate at the expense of reduced orthogonality.
- Zero-Tail-spreading OFDM (ZT-DFT-S-OFDM): similar to Single-Carrier Frequency Division Multiple Access (SC-FDMA) waveform, with zeros in the borders of the Discrete Fourier Transform (DFT).

FANTASTIC-5G concludes that none of these waveforms is ideal for all kinds of situations; therefore, it makes some recommendations on the criteria to follow when selecting a waveform for a specific situation. FANTASTIC-5G made numerous contributions to standardization bodies regarding the specification of the 5G air interface to be used in bands below 6 GHz, while mmMAGIC [39] proposes the specification of air interface for bands above 6 GHz using millimeter wave bands.

2.1.7. Non-Orthogonal Multiple Access (NOMA)

Thus far, multiple access schemes multiplex the users' signals orthogonally, so that when they reach the receiver, the interference among them is low, which allows robust detection with simpler receivers. With the computational power available in the current generation of mobile chipsets, a substantial amount of interference can be allowed as it can be removed at the receiver.

In NOMA, non-orthogonality is deliberately introduced in the transmitter by superimposing the signals in the power domain, thus allowing the reuse of the same radio resources by more users, and improving the network capacity. If the power of each signal is reasonably different from the powers of the other signals that are superimposed, it is possible to recover the weaker signals through successive interference cancellation. The stronger signals will also be recoverable because they will be much stronger than the interference.

By allowing more users to share the same radio resources at the same time, NOMA improves the system capacity, although requiring more complex receivers. NOMA does not require instantaneous Channel State Information (CSI) at the transmitter, although the information on the expected path loss could be used to optimize the power allocation.

2.1.8. Massive MIMO

The 5G radio access network will use massive MIMO in "*macro-assisted small cells*," where the macro cell uses the lower bands to provide control-plane traffic omnidirectionally, and the small cells use the mmWave band to carry user-plane traffic delivered using highly-directive massive-MIMO beams [40].

Massive MIMO is a fundamental technology for 5G, especially when deployed at millimeter wave bands. At such frequencies, arrays with several hundred elements can be feasible. Such a high number of elements can be used to produce very narrow high-power beams to counteract the mmWave high path loss or open the possibility to implement higher-order MultiUser MIMO (MU-MIMO) to boost small cell capacity.

Recent trials in Japan using a base station with up to 8 arrays of 64 elements spaced 0.7λ (at 15 GHz) could achieve the transmission of eight spatial streams for MU-MIMO. In another trial, at a frequency below 6 GHz, a base station with 192 elements was able to maintain a connection with 23 mobile terminals, each of them having a linear array with 8 elements. In this trial, by using MU-MIMO, the base station could deliver up to 24 spatial streams to different terminals, and each terminal could receive up to 3 streams [44].

Another possibility brought about by massive MIMO is the use of distributed MIMO, i.e., the use of several beams that are transmitted simultaneously to the same mobile terminal from base stations at different locations, which reduces the correlation among the antenna panels and improves throughput [44]. In addition, when the terminal is moving, the reflections from nearby obstacles help in achieving the lowest beam correlation by different beam combinations along the trajectory of the terminal. Therefore, instead of selecting the beams received with the highest power, higher throughputs are obtained in larger parts of the cell when beam selection is done based on the channel state information sent from the mobile to the base station during transmission [44]. In this way, the beams with the lowest correlation can be reselected as the mobile moves. In another experiment in Japan, it was demonstrated that beam reselection every 10 ms is feasible when using massive MIMO, which helps in maintaining a 28 GHz link with a terminal moving at 150 km/h [44].

A question that frequently arises in massive MIMO scenarios is that when the beams do not overlap, the throughput delivered to each mobile is high; however, when the beams overlap, they interfere and the throughput reduces tremendously. One of the techniques that may be used to avoid inter-beam interference is to deploy orthogonal beams, e.g., using Eigen-Zero-Forcing (EZF) precoding [44].

In short, when massive MIMO is deployed in higher frequency bands (e.g., mmWave), the performance is improved when the transmission to a specific terminal uses beams from base stations at different locations, or when beams are continuously reselected (based on CSI) so that the beams reflected from buildings can be used to obtain lower inter-beam correlation. Beam selection every 10 ms is feasible.

2.1.9. Separation of control and data planes in the RAN

Traditionally, the traffic that circulates in the radio access network is classified as belonging to either the user plane or the control plane. Each base station in every cell always processes both planes.

During the specification of 3GPP Release 12, a concept called “phantom cell” was proposed. This concept involves splitting the control plane and user data plane between the macro cell and small cells using different frequency bands. The small cells handle traffic for high-throughput user data sessions, while the macro cellular layer controls signaling (e.g., RRC). The macro and small cells form a master-slave relationship, through which the macrocell sends control information relevant to the user connected to the small cells [40].

As signaling traffic requires reduced bandwidth when compared with user traffic, the macro cell can “control” a large number of small cells, which allows an easier implementation of reconfiguration, self-optimization, and mobility management algorithms. At the same time, the user traffic can use much larger channel bandwidths because the small cells allow a higher frequency reuse and will have fewer users than the macro cells.

2.1.10. Cloud RAN (C-RAN)

C-RAN [41,59], uses centralized BaseBand Units (BBU) connected to Remote Radio Units (RRU) via fiber fronthaul [56–58]. The RRU acts as a repeater, transforming the optical signal into radio waves and vice-versa, while the BBU is in charge of implementing all features of the base station and interfacing with the core network. In Fig. 3, we present a C-RAN architecture.

As the RRU just contains a compact antenna and an optoelectronic converter, it does not need a large space to be installed; it does not require high amount of energy to operate, and also does not need air conditioning. This makes C-RAN very appealing to be deployed for Ultra-Dense Networks (UDN), e.g., installing an RRU on every lamp post 20 m apart. C-RAN can also be used to deploy heterogeneous networks, so that the macro cells ensure basic connectivity and the small cells provide additional capacity in specific areas using dual connectivity and higher frequency bands.

Another merit of C-RAN comes from the fact that, as several BBUs are centralized in the same location, it is possible to use a single backhaul link to connect several BBU to the core network. Moreover, the BBUs can exchange traffic among themselves when required, thus reducing the amount of traffic exchanged with the core network.

As a final remark, the need for fiber fronthaul makes this solution tailored for urban networks where fiber is already available; however, it may not be adequate for rural networks where fiber cannot be installed or is simply too expensive.

2.1.11. Device to Device (D2D)

D2D [42,59] is also a promising technology for 5G, in the sense that it will be fundamental to support, e.g., applications associated with the vertical automotive sector, which traditionally has reduced range and requires very short latency. In Fig. 4, we depict a network architecture with D2D system. D2D proximity services (ProSe) were introduced in 4G (3GPP Release 12) to allow the deployment of non-traditional cellular services, initially focusing on public safety applications.

From the perspective of radio communication, one of the essential requirement is that the network is always in control of the uplink radio resources assigned to the communication path of ProSe, enabling it to change these assignments adaptively among ProSe and other RAN services whenever required (i.e., dynamic resource allocation must be possible). It is assumed that ProSe uses the uplink spectrum and uplink sub-frames of the cell providing coverage. It is also desirable that the eNB exchange information on resources used for D2D in neighbor cell are transmitted directly through the X2 interface.

The coexistence between device-to-device ProSe and uplink cellular communications using the same carrier frequency is done in the time domain, i.e., when ProSe uses a sub-frame, it cannot be shared with cellular communications, and vice-versa. In the case of collision, the uplink cellular transmissions are always prioritized. The ProSe mobile terminals use SC-FDMA with normal or extended cyclic prefix.

To provide device-to-device proximity services, three procedures might be necessary: synchronization (time and frequency), discovery, and direct communication between devices.

- D2D synchronization: ProSe-enabled devices under cellular coverage use the cell's primary and secondary synchronization signals broadcasted by the eNB, to obtain ProSe time and frequency

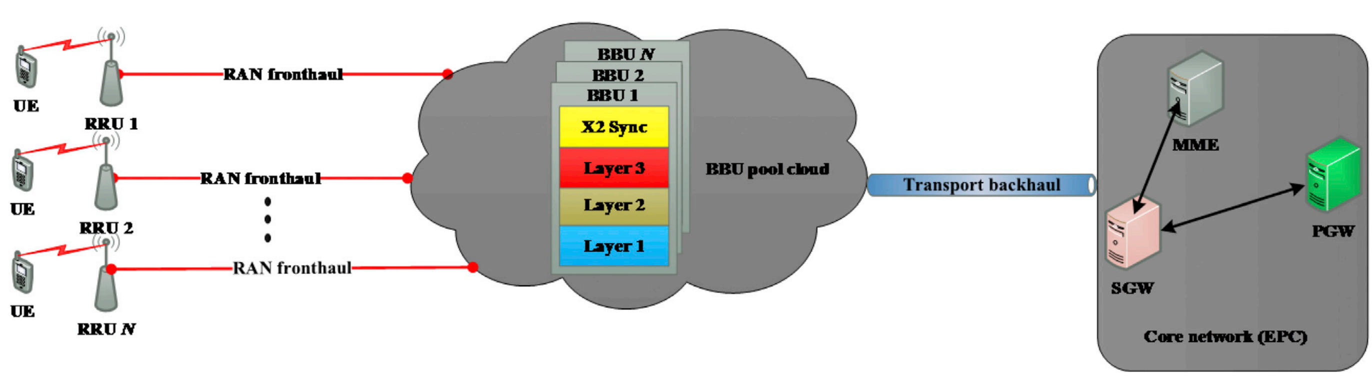

Fig. 3. C-RAN communication network.

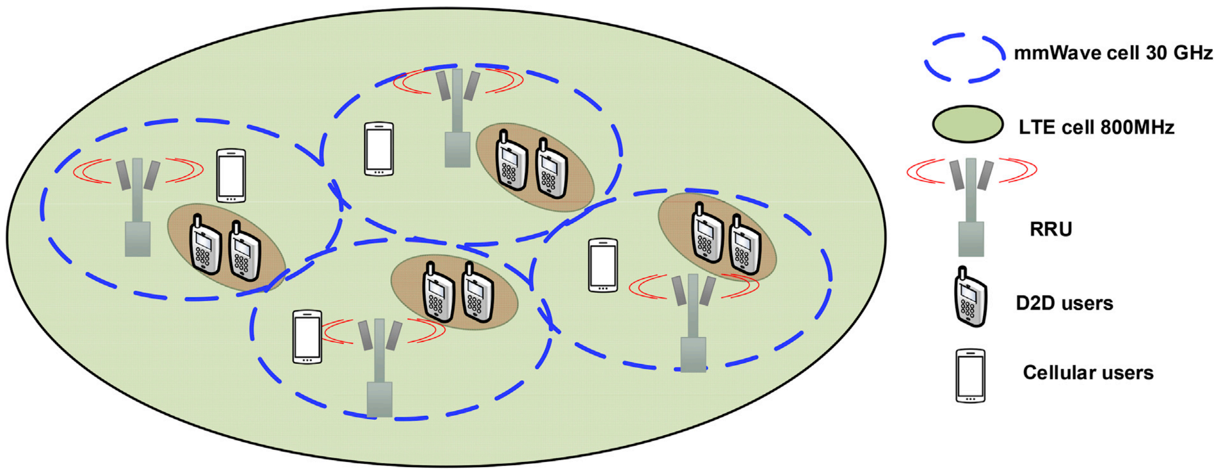

Fig. 4. D2D system.

synchronization. ProSe-enabled devices may also transmit synchronization signals for synchronizing with neighboring ProSe devices, e.g., when there is no cellular network coverage. When a mobile terminal detects multiple synchronization signal sources, it should give priority to the eNB synchronization signal, then to the synchronization signal from the terminals under cellular coverage, and then to terminals out of cellular coverage.

- D2D Discovery: the discovery of ProSe terminals is needed for point-to-point D2D communication; however, it is not required for group-cast or broadcast D2D communications. When required, the discovery procedure is implemented through the transmission of a discovery signal by each ProSe terminal that has information to send. The discovery resources[2] that may be used by ProSe terminals, under cellular coverage, to transmit discovery signals, are allocated by the eNB in a "semi-static manner" and included in the system information broadcasted in the cell. Then, the ProSe terminal randomly selects one of the available discovery resources to transmit its discovery signal. It is assumed that the IP layer is not used, and therefore, Robust Header Compression is not needed, and security is not applied in the access stratum.
- D2D communication: radio resource allocation and scheduling assignments for D2D communication may be performed by the eNodeB when the mobile terminal wishing to transmit is under good cellular coverage, or by the mobile terminal itself when it is in the cell-edge or not under cellular coverage. A UE operating in the "scheduled mode" (Mode 1) needs to have an active signaling connection with an eNB in order to transmit the D2D communication. Before transmitting, the UE sends a scheduling request to the eNodeB followed by a Buffer Status Report (BSR) based on which the eNodeB can understand that the UE intends to perform a D2D transmission and determine the required amount of resources. The eNodeB then schedules radio resources for transmission. A UE under cellular coverage may also be allowed by the eNodeB to operate in the "autonomous mode" (Mode 2). Out-of coverage UE operates necessarily in the "autonomous mode" (Mode 2). In this mode, the UE is provided with a resource pool (time and frequency) from which it chooses the resources required for transmitting the D2D communication. All the ProSe enabled terminals need to be aware of the resource pools (time/frequency) to be used in the reception of D2D communications and scheduling assignments.

In Release 14, 3GPP is already expanding the D2D communications to support vehicle-to-everything (V2X) applications, adding enhancements for high speed, high user density, improved synchronization, and low latency (e.g., through shortened processing time, and shortened Time Transmission Interval (TTI) using one timeslot with 2 or 4 OFDM symbols).

[2] specific resource blocks within specific subframe(s) within a specific discovery period.

2.1.12. Machine to Machine (M2M) and Internet of Things (IoT) communication

One of the use cases that have to be addressed by 5G is the massive machine type communications. In this scenario, a very large number of sensors and actuators will be connected to the Internet. They will send low amount of information during short periods of time using low data rates and reduced bandwidth channels. The transceivers must be as simple as possible, so that they are low-cost and low power consuming, capable of operating with the same battery for several years.

In the last few years, several M2M standards have appeared. Some of them are proprietary and use the unlicensed band, while the others are extensions of cellular mobile technologies that support M2M communications efficiently in the licensed spectrum.

In 3GPP, three cellular M2M/IoT standards were defined for use in the licensed spectrum bands: Machine Type Communication (MTC), Narrowband – IoT (NB-IoT), and Enhanced Coverage GSM–IoT (EC-GSM-IoT). Compared to proprietary solutions, 3GPP solutions offer the benefits of being supported by a huge number of companies, interoperability across vendors, and reliable performance.

To achieve reduced power consumption, all the 3GPP M2M technologies include a Power Saving Mode (PSM), which enables the terminals to enter deep sleep mode when they do not need to transmit or receive. During the sleep time, they remain registered in the network, so that when the terminals decide to become active again, they do not need to re-attach or re-establish the connection. While the terminals are in deep sleep mode, they are not reachable by the network.

Another technique for reducing power consumption involves using discontinuous reception with an extended sleeping cycle in the idle-mode, during which the circuits are turned off to save power. During the sleeping period, the terminals are not reachable by the network; however, they become reachable periodically during the on cycle.

2.1.12.1. MTC. In 3GPP, M2M communications are available for both LTE and GPRS/EDGE networks. M2M communications using LTE technology have been supported since Release 8 by Category 1 mobile terminals, which are full-featured LTE devices with two receiver chains, supporting full duplex operation (FDD, TDD) and achieving 5 Mbps in the uplink and 10 Mbps in the downlink.

In 3GPP Release 12, a Category 0 device is specified in order to reduce LTE device complexity to a level similar to GPRS devices. Category 0 devices operate with only one Rx chain, support half-duplex operation, and have reduced peak rates of 1 Mbps both in uplink and downlink [45].

In 3GPP Release 13, a low-cost Category M1 device is added, which has reduced bandwidth (1.4 MHz, 6 physical resource blocks), reduced transmission power (23 or 20 dBm), and ultra-long battery life (more than 10 years), and is capable of supporting half-duplex and full-duplex FDD and TDD transmissions and extended coverage operation. The goal is to reduce the sensitivity level of these devices by 15 dB, so that the network operators can reach these devices in poor coverage conditions such as in basements (155 dB link budget). It adopts in-band LTE deployment (i.e., MTC selects any physical resource block from a conventional LTE carrier), uses OFDMA in the downlink and SC-FDMA in the uplink, and utilizes 16QAM symbols to achieve a peak data rate of 1 Mbps in both UL and DL.

2.1.12.2. NB-IoT. NB-IoT reuses various principles and building blocks of the LTE physical layer. However, the new physical layer signals and channels, such as synchronization signals and physical random access channel, have been added to the LTE platform to meet extended coverage and ultra-low device complexity required by the lower end of the market. NB-IoT allows in-band, guard band, or standalone deployments. Standalone deployment uses any available carrier only for M2M connections. In-band deployment allows multiplexing M2M services together with other services in a conventional LTE carrier. Guard-band deployments select physical resource blocks from the guard bands of the conventional LTE carrier to deliver M2M services.

NB-IoT uses LTE Category 0 devices, signal bandwidths of 180 kHz (in-band, guardband) or 200 kHz (standalone), and maximum transmitter power of 23 dBm, and supports half-duplex FDD transmissions. It uses OFDMA in the downlink, although in the uplink it may use a single tone with 3.75 kHz spacing or SC-FDMA with 15 kHz spacing. NB-IoT achieves peak data rates of around 60 kbps in the downlink and around 20 kbps (using single tone) or around 50 kbps (using SC-FDMA) in the uplink. It was designed to support a link budget of 164 dB.

2.1.12.3. EC-GSM-IoT. EC-GSM-IoT [45] was introduced in Release 13 as an additional M2M standard to make GPRS/EDGE markets prepared for IoT. It provides enhancements based on EDGE technology, and is designed for high capacity, long range, low energy, and low complexity cellular systems that can be used for IoT communications in challenging radio coverage conditions.

EC-GSM-IoT adopts in-band GSM deployment, uses 200 kHz channels, admits two transmission powers classes (23 dBm, 33 dBm), and supports 164 dBm (33 dBm power class) or 154 dBm (23 dBm power class) link budgets. It is a Time-Division Multiple Access (TDMA) system, uses half-duplex FDD transmissions, uses Gaussian Minimum Shift Keying (GMSK) or 8PSK (Phase Shift Keying) waveforms, and achieves a peak data rate of around ~70 kbps (using 4 TDMA time slots and GMSK waveform) or around 240 kbps (using 4 time slots and 8PSK). This technology is backward compatible with previous GSM releases, which allows it to be introduced to existing GSM networks as a software upgrade on the radio and core networks.

The following are some of the proprietary M2M standards:

- Weightless: proprietary technology using the TV white spaces or the unlicensed bands below 1 GHz. The base stations allocate a specific time and frequency for each device to transmit its data back to the base station.
- SigFox: proprietary technology that enables communication using the 868 MHz (Europe) and 915 MHz (USA) unlicensed bands. It utilizes “ultra narrowband” modulation technology.
- LoRa [46]: a proprietary, Chip Spread Spectrum (CSS) radio technology, using unlicensed spectrum bands below 1 GHz. Devices in the network are asynchronous and transmit when they have data available to send.

2.2. Core network

2.2.1. Software Defined Networks (SDN)

The basic idea behind SDN is the separation of the control and user data planes. Although this separation has existed in other network technologies, especially in legacy technologies that existed in the networks of telecom operators (e.g., Signaling System no. 7 (SS#7)), the adoption of IP technology in most of the current networks of telecom operators have brought both the planes together.

The splitting of the control and user data planes, which is proposed by SDN, allows centralization of the control plane functions in a single entity (the SDN controller). It is capable of providing a centralized view of the available resources and making the network more dynamic and reactive than it would be possible if the network had a distributed control plane. On the other hand, the SDN controller offers an abstraction layer that allows hiding the specific characteristics of the infrastructure, and makes the network programmable through a standardized Application Programming Interface (API), in a way that is independent of the technology.

2.2.2. Network slicing (multi-tenant networks, support to verticals)

5G networks will have to be multi-tenancy networks. 5G will have to support very different services, and these services should be created quickly, preferably by those who are interested in commercializing them. In other words, it would be suitable that mobile networks could be rented by different service providers, each of them offering a different service. This requires that mobile networks can be rapidly subdivided into several independent subnetworks, which are called network slices. Each network slice would then be configured according to the requirements placed by the service that it is going to deliver.

In network slicing, the roles of connectivity provider and service provider are separated. The mobile operator would be responsible for providing connectivity services, although it may continue to play both roles. Although not necessary, network slicing [51] can be implemented more easily when the network functions are virtualized. The network slices would also be more flexible if they are implemented using the SDN concept.

2.2.3. Network Function Virtualization (NFV)

Recently, the concepts of Network Function Virtualization and Software Defined Networking have gained much visibility within the telecom industry. Although the two concepts are independent and have distinct origins, they have a complementary relationship, which provides significant benefits when they are used jointly. Together, these two evolution trends have the potential to produce a radical change in the way of building, maintaining, and controlling telecommunication networks.

From a general perspective, NFV can be understood as the set of technologies that support the virtualization of network functions. This means that the functions that traditionally depended on specific and proprietary hardware platforms may migrate to a cloud infrastructure and have their lifecycle managed and controlled in a similar perspective, i.e., through self-service and with fast elasticity.

2.2.4. Multi-access Edge Computing (MEC)

MEC [47– 50] is a result of the convergence between Information Technology (IT) and telecom networks. It offers cloud-computing capabilities and IT services near the edge of the network to software developers and content providers. By doing so, applications may have real-time access to the radio network information, and innovative services with ultra-low latency and high bandwidth, addressing subscribers, enterprises, and vertical segments, can be implemented.

MEC has a fundamental impact on the design and manufacturing of base stations, which will have to include additional computing and storage hardware to extend the cloud infrastructure to the place where people and objects connect to the network. From the perspective of core networks, by deploying various services and caching content at the network edge, the core networks can also be relieved from congestion.

3. 5G use cases & KPI by regulatory body

ITU started its activities on IMT-2020, and beyond, the name ITU gives to the 5G mobile system in 2012. From 2012 to 2015, several studies have been performed in order to build ITU's 5G vision: updated technology trends have been investigated, traffic estimates for the year 2020–2030 have been collected, and studies on millimeter-wave channel models concluded that IMT-2020 is feasible on bands above 6 GHz. In September, 2015, the ITU vision on 5G was finalized; it established the key capabilities that 5G had to meet in three usage scenarios: enhanced Mobile BroadBand (eMBB), ultra-Reliable and Low Latency Communications (uRLLC), and massive Machine Type Communications (mMTC).

According to the draft report on "Minimum requirements related to technical performance for IMT-2020 radio interfaces", available in February, 2017 [60], the following performance indicators as shown in Table 3 have to be achieved in each 5G use case:

ITU-R will base its decision regarding the acceptance of the candidate technologies for IMT-2020, probably in the last quarter of 2019. It seems reasonable to consider that the production of the recommendation, which includes the accepted IMT2020 specifications, should be ready during the first half of 2020. The deployment of IMT2020 networks should occur during 2020.

4. Development of novel radio technology for 5G by standardization body

New Radio (NR) is the 5G radio technology developed by 3GPP. It uses Time-Division-Duplex (TDD) and OFDM-based waveforms.

4.1. Frame structure

The frame structure contains a flexible and non-uniform grid of time-frequency resources. In the frequency domain, the grid is divided into Physical Resource Blocks (PRB), always with 12 subcarriers each. The subcarrier spacing can assume any value of the form $2^m * 15$ kHz between 3.75 kHz and 960 kHz ($m = -2,-1,0,1,8$), so that the bandwidth occupied by a PRB may be adjusted. For each subcarrier spacing, multiple cyclic prefix lengths are available.

In the time domain, this grid is composed of subframes, and each subframe is divided into an integer number of slots and/or mini-slots. Although the duration of a subframe is fixed at 1 ms, the durations of the slots and mini-slots are adjustable, with the constraint that there cannot be slots/mini-slots crossing the time boundary of a subframe. The slots always have 7 OFDM symbols, and the mini-slots have a lower integer number ($z < 7$) of OFDM symbols. The slot/mini-slot can be freely allocated to the uplink or downlink, provided that a guard period is included when there is a change from uplink to downlink, and vice-versa. The first or last OFDM symbols of a slot/mini-slot may be used for control signals/channels. In NR, both the bandwidth of the PRB and the length of the mini-slots are adjustable. In Table 4, we describe the flexibility/degrees of freedom added in NR design. The basic scheduling unit is the PRB in the frequency domain and the slot/mini-slot in the time domain.

Although very flexible, the NR frame structure can easily be aligned with LTE (1 ms subframes, 2 slots per subframe, 7 symbols per slot, 15 kHz subcarrier spacing) allowing it to support LTE plus NR dual connectivity efficiently and reduce the complexity of dual-mode NR/LTE terminals.

Table 3
Key performance indicators associated with 5G use cases.

#	Technical performance requirement	Indoor hotspot		Dense urban		Rural	
		UL	DL	UL	DL	UL	DL
eMBB usage scenario							
1	Peak data rate (Gbit/s) NOTE: all resources allocated to a single user	10	20	10	20	10	20
2	Peak spectral efficiency (bit/s/Hz) NOTE: these values assume 8 × 8 MIMO in DL and 4 × 4 MIMO in UL, but this is not mandatory	15	30	15	30	15	30
3	User experienced data rate (Mbit/s) NOTE: 5% point of the CDF of the user throughput	–	–	50	100	–	–
4	5th percentile user spectral efficiency (bit/s/Hz)	0.21	0.3	0.15	0.225	0.045	0.12
5	Average spectral efficiency (bit/s/Hz/TXRX) NOTE: aggregate throughput of all users divided by channel bandwidth divided by number of TX-RX points	6.75	9	5.4	7.8	3.3	1.6
6	Area traffic capacity (Mbit/s/m^2)	10		–	–	–	–
7	User plane Latency NOTE: one-way time measured above layer 3, considering single user and IP packet with 0 bit payload	4 ms					
8	Control plane latency NOTE: idle to active transition	20 ms					
9	Energy efficiency	Support high sleep ratio (network) and long sleep duration (terminal). Other mechanisms can be proposed.					
10	Mobility (bit/s/Hz)	1.5 (10 km/h)	–	1.12 (30 km/h)	–	0.8 (120 km/h) 0.45 (500 km/h)	–
11	Mobile interruption time	0 ms					
12	Bandwidth NOTE: maximum aggregated system bandwidth	At least 100 MHz (In bands above 6 GHz, this should be higher, e.g. 1 GHz)					
uRLLC usage scenario							
1	User plane Latency NOTE: one-way time measured above layer 3, considering single user and IP packet with 0 bit payload	1 ms					
2	Control plane latency NOTE: idle to active transition	20 ms					
3	Reliability NOTE: probability of successful transmission of layer-2 Packet Data Unit (PDU) with 32 bytes, within 1 ms, considering cell- Edge channel quality	99.999% (Packet error rate less than 10^{-5})					
4	Mobile interruption time	0 ms					
5	Bandwidth NOTE: maximum aggregated system bandwidth	At least 100 MHz (In bands above 6 GHz, this should be higher, e.g., 1 GHz)					
mMTC usage scenario							
1	Connection density	1 000 000 devices/km^2					
2	Bandwidth NOTE: maximum aggregated system bandwidth	At least 100 MHz (In bands above 6 GHz, this should be higher, e.g., 1 GHz)					

Table 4
Flexibility/Degrees of freedom added in NR design.

Network degrees of freedom	PHY problem	PHY degrees of freedom
Mobile terminal speed Frequency band	Inter-carrier Frequency (ICI)	Subcarrier spacing
Inter-site distance	Inter-Symbol Interference (ISI)	Cyclic Prefix length
Latency	Propagation Delay	Mini-slot Length

4.2. Multiple access

NR is more flexible in this respect than previous 3GPP technologies. It supports the use of orthogonal, non-orthogonal, synchronous, and asynchronous multiple access schemes. In the downlink, only an orthogonal synchronous multiple access scheme is supported. NR uses OFDMA to allocate an integer number of resource blocks and slots/mini-slots to a specific user. A non-orthogonal scheme was also studied, i.e., downlink Multiuser Superposition Transmission (MUST); however, at present, it is not included in the NR specifications, and is included only in the specifications. In uplink, both orthogonal/synchronous and non-orthogonal/asynchronous multiple access schemes are supported. Thus, NR may use OFDMA to support uplink services, which demand very high throughput (e.g., mobile broadband) or very high reliability (ultra-reliable low latency communications). Additionally, for services demanding an extremely large number of power constrained low-datarate links (uplink machine-type communications), a non-orthogonal asynchronous scheme will also be available in the uplink, which allows several users to share the same time-frequency resources. For the uplink, 3GPP currently considers the following non-orthogonal asynchronous schemes:

- Code Division Multiple Access (CDMA). As the transmissions would be asynchronous, the orthogonality of the spreading codes will be destroyed, and the receivers will need to deal with multiuser interference. Appropriate receivers are the Successive Interference Cancellation (SIC) or Message Passing Algorithm (MPA) receivers, among others.
- Sparse Code Multiple Access (SCMA).
- Multiuser Shared Access (MUSA).
- Pattern Division Multiple Access (PDMA).

5. Simulations and field trials for 5G technologies by operators and vendors

DOCOMO started working on a real-time 5G system simulator in 2012. Using this ray-tracing tool, they showed that 5G achieves a thousand-fold increase in system capacity when compared[3] with LTE macrocells, with 90% of the 5G users experiencing data rates above 1Gbps [40]. In late 2012, DOCOMO performed 5G uplink field trials using a base station and 2 mobile terminals in an outdoor environment, and each user obtained an uplink data rate of 10 Gbps with a 400 MHz bandwidth in the 11 GHz band, using 8 transmiting and 16 receiving antennas [43].

In December, 2014 and in October, 2015, Docomo & Nokia conducted indoor field trials to demonstrate super-wideband single carrier transmission and beamforming using the 1 GHz channel in the 73 GHz band, achieving a transmission speed above 2 Gbps. In May, 2016, this system was used to demonstrate 8K video transmission. The 48 Gbps 8K video signal was encoded into signals with speeds ranging from 85 Mbps to 145 Mbps and transmitted without any delay [43].

[3] The simulator simulated 7 LTE tri-sectored macro cells. Each sector of the LTE macro cell uses a 20 MHz channel in the 2 GHz band and two transmitting antennas. In each sector of the LTE macro-cell, the 5G system deployed 12 small cells, each using a 1 GHz channel in the 20 GHz band. The 5G system also used massive MIMO with 64 antennas in each small cell. The mobile terminals had 4 receiving antennas for both LTE and 5G.

In February, 2015, Docomo & Ericsson completed an outdoor field trial to demonstrate new air interface concepts and the massive MIMO technology, achieving 4.5 Gbps using 800 MHz bandwidth in the 15 GHz band. The field trial was improved in November, 2015, achieving 10 Gbps in the 15 GHz band at a distance of 10 m from the base station. This distance was increased to 70m in February, 2016. Further improvements were made in February, 2016, when 8 arrays with 64-antennas were used, achieving a cumulative throughput of 20 Gbps by using MU-MIMO to connect 2 mobile terminals to the base station simultaneously, each with 10 Gbps downlink bit rate [43].

In October, 2015, Docomo & Fujitsu conducted a field trial to demonstrate a cooperative transmission system, which achieved 11 Gbps in four mobiles, using the 4.6 GHz band [43].

In November, 2015, Docomo & Samsung conducted an outdoor field trial to demonstrate super-wideband hybrid beamforming and beam tracking, capable of transmitting 5G signals to a terminal moving at 60 km/h, and achieved 2.5 Gbps using 800 MHz bandwidth in the 28 GHz band. This was improved in November, 2016, when similar transmission speeds were maintained for a terminal moving at 150 km/h. The experiments used 2 arrays with 48 elements each in the base station and 2 subarrays with 4 elements each in the mobile terminal [43].

In November, 2015, Docomo & Huawei performed an outdoor field trial in China to demonstrate MU-MIMO technology, and achieved a spectral efficiency of 43.9bps/Hz/cell, which is 3.6 times higher than that of the previous outdoor MU-MIMO LTE-Advanced trials. In October, 2016, Docomo/Huawei performed a large outdoor field trial in Japan, where a 200 MHz system bandwidth in the 4.5 GHz band was used. In this trial, a base station maintained a simultaneous connection with 23 mobile terminals, distributed within 100 000 square meters, achieving an aggregated throughput of 11.29 Gbps and latency below 0.5 ms. The base station used 64 subarrays with 3 antennas each, and the mobile terminal used a linear array with 8 antennas. This allowed the base station to perform MU-MIMO, transmitting up to 24 streams at the same time, and achieved a spectral efficiency of 79.82bps/Hz/cell [43].

In February, 2016, Docomo agreed to form a global initiative with three other telecom operators (KT, SK Telecom, Verizon), called the *5G Open Trial Specification Alliance*, which aims to define a common trial platform and trial specifications. The focus will be on 5G air interface, both above and below 6 GHz band [43].

In May, 2017, Docomo opened “5G Trial Site” in Tokyo, operating in the 28 GHz band, using network equipment from Ericsson and handset chipsets from Intel. Additional trial sites will be developed later using the 4.5 GHz band [43].

Before June, 2018, Docomo will perform trials of 3GPP 5G air interface standard (Release 15), in the 4.5 GHz and 28 GHz bands, using base stations from Ericsson and mobile device prototypes from Qualcomm [43].

6. Conclusions

In this paper, we presented technologies that will be incorporated in the RAN and the core network of 5G systems. Regarding the RAN, we have described the technologies that intend to increase the system bandwidth (mmWave band, spectrum sharing, carrier aggregation, dual connectivity, operation in unlicensed spectrum); increase the spectral efficiency (unified air interface, improved waveforms, massive MIMO, non-orthogonal multiple access); and enhance the flexibility of the RAN (Phantom Cell, C-RAN, D2D, M2M). Regarding the network architecture, we assume the use of Network Slicing, NFV, SDN, and MEC to be essential.

The aforementioned 5G technologies represent an attempt to realize the prospects envisioned by the mobile industry through significant advancements in research and 5G field trials. Such technologies are being combined into worldwide 5G standards, capable of respecting the constraints imposed by the regulatory authorities of each country. This paper holistically presented 5G, by describing the requirements, regulatory frameworks, technologies, and standardization efforts in a single document.

Acknowledgment

The author, Kazi Mohammed Saidul Huq, would also like to acknowledge the Fundação para a Ciência e a Tecnologia (FCT) of Portugal; Reference No.: SFRH/BPD/110104/2015.

References

[1] Ericsson AB, "Traffic Exploration Tool," Online tool. Available at: http://www.ericsson.com/TET/trafficView/loadBasicEditor.ericsson.
[2] H.J. Song, T. Nagatsuma, Present and Future of Terahertz Communications, IEEE Transactions on Terahertz Science and Technology, Aug. 2011.
[3] Int Telecom Union – Radiocom Sector (ITU-R), Report M.2320 – Future Technology Trends of Terrestrial IMT Systems, Nov. 2014.
[4] Int Telecom Union – Radiocom Sector (ITU-R), Final Acts - World Radiocommunication Conference (WRC-15), Nov. 2015.
[5] Tom Wheeler (FCC Chairman), "The Future of Wireless: a Vision for U.S. Leadership in a 5G World", Washington, D.C, Jun. 20, 2016.
[6] Radio Spectrum Policy Group (RSPG), Strategic Roadmap towards 5G for Europe - Opinion on Spectrum Related Aspects for Next-generation Wireless Systems, RSPG 16-32, Nov. 9, 2016.
[7] Radio Spectrum Committee (RSC), Mandate to CEPT to Develop Harmonised Technical Conditions for Spectrum Use in Support of the Introduction of Next-generation (5G) Terrestrial Wireless Systems in the Union, RSCOM16-40rev3, Dec. 7, 2016.
[8] Electronic Communications Committee (ECC), ECC(17)076-Annex 13: CEPT Roadmap for 5G, Jun. 28, 2017.
[9] Qualcomm, Making 5G NR a Reality – Leading the Technology Inventions for a Unified, More Capable 5G Air Interface, Dec. 2016.
[10] Federal Communications Commission (FCC), Report and Order And(ECC) Further Notice of Proposed Rulemaking in the Matter of Use of Spectrum Bands above 24 GHz for Mobile Radio Services (GN Docket No. 14-177), Doc. FCC-16-89, Jul. 14, 2016.
[11] GSM Association (GSMA), 5G Spectrum – Public Policy Position, GSM Association, Nov. 2016.
[12] Federal Communications Commission (FCC), Notice of Inquiry in the Matter of Additional Spectrum for Unlicensed Devices below 900 MHz and in the 3 GHz Band, (ET Docket No. 02–380), Doc. FCC-02-328, Dec. 11, 2002.
[13] Federal Communications Commission (FCC), Notice of Proposed Rule Making in the Matter of Unlicensed Operation in the TV Broadcast Bands (ET Docket No. 04-186), Doc. FCC-04-113, May 13, 2004.
[14] Federal Communications Commission (FCC), Second Memorandum Opinion And Order In the Matter of Unlicensed Operation in the TV Broadcast Bands (ET Docket No. 04–186), Doc. FCC-10-174, Sep. 23, 2010.
[15] Federal Communications Commission (FCC), Third Memorandum Opinion and Order in the Matter of Unlicensed Operation in the TV Broadcast Bands (ET Docket No. 04-186), Doc. FCC-12-36, Apr. 4, 2012.
[16] Federal Communications Commission (FCC), Approval for Spectrum Bridge's TV Bands Database System, Doc. DA-11–2044, Dec.2011.
[17] The Office of Comm (OFCOM), Digital Dividend Review - a Statement on Our Approach to Awarding the Digital Dividend, Dec. 13, 2007.
[18] The Office of Communications (OFCOM), Digital Dividend: Cognitive Access - Statement on Licence-exempting Cognitive Devices Using Interleaved Spectrum, Jul. 1, 2009.
[19] The Office of Communications (OFCOM), Consultation on TV White Spaces: Approach to Coexistence, Sep. 4, 2013.
[20] The Office of Communications (OFCOM), Statement on Implementing TV White Spaces, Feb. 12, 2015.
[21] The Office of Communications (OFCOM), Statutory Instruments No. 2066-White Space Devices Regulations, Dec. 31, 2015.
[22] Electronic Communications Committee (ECC), CEPT Report 24-A preliminary assessment of the feasibility of fitting new/future applications/services into non-harmonised spectrum of the digital dividend (namely the so-called "white spaces" between allotments), Jul. 1, 2008.
[23] Electronic Communications Committee (ECC), ECC Report 159-Technical and Operational Requirements for the Possible Operation of Cognitive Radio Systems in the 'White Spaces' of the Frequency Band 470-790 MHz, Jan. 2011.
[24] Electronic Communications Committee (ECC), ECC Report 185 (Complementary Report to ECC Report 159) - Further Definition of Technical and Operational Requirements for the Operation of White Space Devices in the Band 470–790 MHz, Jan. 2013.
[25] Electronic Communications Committee (ECC), ECC Report 186-Technical and Operational Requirements for the Operation of White Space Devices under Geo-location Approach, Jan. 2013.
[26] Electronic Communications Committee (ECC), ECC Report 236-Guidance for National Implementation of a Regulatory Framework for TV WSD Using Geo-location Databases, May 2015.
[27] Nokia/Qualcomm, Authorised Shared Access: an evolutionary spectrum authorisation scheme for sustainable economic growth and consumer benefit, in: Doc. FM(11)116 Presented at WG FM Meeting, May 17, 2011.
[28] Radio Spectrum Policy Group (RSPG), Report on Collective Use of Spectrum and Other Sharing Approaches, RSPG11–392, Nov. 2011.
[29] Radio Spectrum Policy Group (RSPG), RSPG Opinion on Licensed Shared Access, RSPG13–538, Nov. 2013.
[30] Electronic Communications Committee (ECC), ECC Report 205 – Licensed Shared Access (LSA), Feb. 2014.
[31] Electronic Communications Committee (ECC), CEPT Report 55-Technical Conditions for Wireless Broadband Usage of the 2300-2400 MHz Frequency Band, Nov. 2014.
[32] Electronic Communications Committee (ECC), CEPT Report 56-Technological and Regulatory Options Facilitating Sharing between Wireless Broadband Applications (WBB) and the Relevant Incumbent Services/applications in the 2.3 GHz Band, Mar. 2015.
[33] Electronic Communications Committee (ECC), CEPT Report 58-Technical Sharing Solutions for the Shared Use of the 2300-2400 MHz Band for WBB and PMSE, Jul. 2015.
[34] President's Council of Advisors on Science and Technology, Realizing the Full Potential of Government-held Spectrum to Spur Economic Growth, Jul. 20, 2012.
[35] Federal Communications Commission (FCC), Notice of Proposed Rulemaking and Order in the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band (GN Docket No. 12-354), Dec. 12, 2012.
[36] Federal Communications Commission (FCC), Order on Reconsideration and Second Report and Order in the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band (GN Docket No. 12-354), Apr. 28, 2016.
[37] 5GNOW, 5th Generation Non-orthogonal Waveforms for Asynchronous Signaling [Online]. Available: http://5gnow.com.
[38] FANTASTIC5G. Flexible Air Interface for Scalable Service Delivery within Wireless Communications Networks of the 5th Geneation [Online]. Available: http://fantastic5g.com.
[39] mmMAGIC. mmWave Based Mobile Radio Access Network for 5G Integrated Communications [Online]. Available: https://5g-mmmagic.eu.
[40] NTT DOCOMO, 5G Radio Access: Requirements, Concept and Technologies (5G White Paper), NTT Docomo Inc., Jul. 2014.
[41] China Mobile. C-RAN: the Road towards Green-RAN [online]. Available: http://labs.chinamobile.com/cran/wp-content/uploads/CRAN_white_paper_v2_5_EN.pdf.
[42] K.M.S. Huq, S. Mumtaz, J. Rodriguez, Outage probability analysis for device-to-device system, in: 2016 IEEE International Conference on Communications (ICC), Kuala Lumpur, 2016, pp. 1–5.
[43] NTT DOCOMO, News Releases, https://www.nttdocomo.co.jp/english/corporate/technology/rd/tech/5g (Jul. 28, 2017).
[44] Yoshihisa Kishiyama, Satoshi Suyama, Yukihiko Okumura, latest radio access technologies for 5G systems and field testing results, NTT Docomo Tech. J. 19 (1) (Jul. 2017) 15–29.
[45] GSMA, 3GPP Low Power Wide Area Technologies, White paper, Sep. 2016.
[46] Y. Yao, X. Chen, L. Rao, X. Liu, X. Zhou, LORA: loss differentiation rate adaptation scheme for vehicle-to-vehicle safety communications, IEEE Trans. Veh. Technol. 66 (3) (Mar. 2017) 2499–2512.
[47] ETSI, Mobile Edge Computing: a Key Technology towards 5G, White Paper, Sep. 2015.
[48] I. Morris, ETSI Drops 'Mobile' from MEC, LightReading, Sep. 2016.
[49] GSMA, Stakeholder Analysis and Feasibility Study for MEC, White paper, Jun. 2016, Version 1.0. .
[50] GSMA, Business Opportunities and Monetisation Options for MEC, White paper, Jun. 2016, Version 1.0. .
[51] NTT Docomo, 5G – Future Core Network", Presentation at GSMA Mobile World Congress 2016, Barcelona, Feb. 2016. Available at: https://www.nttdocomo.co.jp/english/info/media_center/event/mwc2016/pdf/about_future_core_network.pdf.
[52] M. Xiao, et al., Millimeter wave communications for future mobile networks (guest editorial), Part I, IEEE J. Sel. Areas Commun. 35 (7) (Jul. 2017) 1425–1431.
[53] L. Zhang, J. Liu, M. Xiao, G. Wu, Y.C. Liang, S. Li, Performance analysis and optimization in downlink NOMA systems with cooperative full-duplex relaying, IEEE J. Sel. Areas Commun. 35 (10) (Oct. 2017) 2398–2412.
[54] Z. Zhang, Z. Ma, M. Xiao, G. Liu, P. Fan, Modeling and analysis of non-orthogonal MBMS transmission in heterogeneous networks, IEEE J. Sel. Areas Commun. 35 (10) (Oct. 2017) 2221–2237.
[55] K.M.S. Huq, et al., Hybrid resource allocation for millimeter-wave NOMA, IEEE Wirel. Commun. Mag. 24 (5) (Oct. 2017).
[56] K.M.S. Huq, J. Rodriguez, Backhauling/fronthauling for Future Wireless Systems, John Wiley & Sons, Ltd, 2016.
[57] K.M.S. Huq, S. Mumtaz, J. Rodriguez, Communication Haul Design for 5G Radio: Challenges and Open Issues, Chapter in, Opportunities in 5G Networks: A Research and Development Perspective, Fei Hu, CRC-Taylor & Francis Group, New York, 2016.
[58] K.M.S. Huq, S. Mumtaz, J. Rodriguez, A C-ran Approach for 5G Applications, Chapter in, Backhauling/Fronthauling for Future Wireless Systems, John Wiley & Sons, Ltd, London, 2016.
[59] K.M.S. Huq, et al., Enhanced C-RAN using D2D network, IEEE Commun. Mag. 55 (3) (Mar. 2017) 100–107.
[60] Int Telecom Union – Radiocom Sector (ITU-R), Report M.2320 – Minimum Requirements Related to Technical Performance for IMT-2020 Radio Interface(s), Feb. 2017. https://www.itu.int/md/R15-WP5D-170214-TD-0300.