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Visions Towards 5G: Technical Requirements and Potential Enablers

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Abstract Compared to the previous generations of mobile networks, 5G will provide a significant paradigm shift by including beyond state of the art technical solutions, like very high carrier frequencies with massive bandwidths, extreme base station and device densities, and very high number of transceiver antennas. However, unlike the previous generations, it will also be highly integrative and backward compatible: combining the novel 5G air interface and spectrum together with legacy wireless systems like LTE/LTE-A and WiFi, in order to facilitate an umbrella of high-rate coverage and a seamless user experience. In order to support this advances in the radio interface, the core network will also have to reach unprecedented levels of elasticity and intelligence. Spectrum regulation will need to be rethought and significantly improved, whereas energy and cost efficiencies will become one of the key parameters that will steer the 5G design and development. This paper elaborates on the 5G related topics, identifying the key challenges for future research and preliminary 5G standardization activities, as well as providing a comprehensive survey of the current literature.

Keywords 5G · mmWave · Massive MIMO · D2D communication · NFV/SDN · C-RAN

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1 Introduction

The ongoing societal development and the requirement of novel ICT technologies and services has started to change the way mobile and wireless communication systems are exploited. By introducing the aspect of: *Always on*, *Always connected* and *Always with you*, the computing paradigm and research is shifting form the personal computers and fixed network devices towards cloud computing and the mobile devices. Novel and advanced networking paradigms like, cloud computing, smart grids, etc. as well as the user personalization concepts will require fundamental system level innovation, in order to facilitate the development and utilization of user experience oriented services and applications. For example, it is expected that by the year 2018 there will exist around 10 billion mobile connections [1] generating more than 15EB of mobile data traffic [2]. Moreover, it is largely anticipated that todays leading scenarios of human-centric communication will, in the near future, be complemented by the Internet of Things (IoT) and Machine-to Machine (M2M) communication concepts, which will result in a significant increase in the number of communication capable devices/machines. These IoT and M2M communication concepts will introduce more than 50 billion online devices until the year 2020, and most of them will utilize wireless connections in order to provide ease of access and cost-efficient deployment [3]. The coexistence of human-centric and machine-type of applications and services impose additional and very diverse *requirements* on the future mobile and wireless communication systems, such as [4]:

- *Rigorous latency and reliability* that will facilitate applications related to healthcare, security, logistics, automotive applications, and mission-critical control.
- *Wide plethora of access data rates* varying from sessions with several hundreds of Kbps that provide instantaneous and reliable access to thousands of online devices, up to sessions with peak cell rates of multiple Gbps intended for future mobile broadband services, like holograms, immersive experience, etc.
- *Network scalability and flexibility* designed to facilitate large number of low complexity devices that require high energy efficiency (e.g. sensor devices/networks for M2M and IoT scenarios, device-to-device (D2D) communications, etc).

These requirements will trigger and leverage fundamental advances in future wireless systems [5]. The synergy of these envisioned technical advances will provide the next, i.e. the 5th, generation (5G) of wireless and mobile networks. 5G is forecasted to roll out by the year 2020 and from a system level design as well as technological concepts, it will drastically defer from the legacy cellular technologies. 5G will introduce a novel paradigm shift (denoted as mmWave), which will shift the RAN communication on the higher spectrum bands, i.e. above 10 GHz, in order to exploit the vast and unoccupied spectrum bands and leverage ultra broadband communications. The mmWave concept will subsequently initiate and trigger the development of other beyond the state of the art technological advances as massive MIMO, non-orthogonal modulation, ultra-dense cells, software defined networks, etc.

This paper provides a generalized vision concept of what 5G will/should represent, and gives a thorough and in-depth survey of the 5G technical requirements and potential enablers. The structure of the paper is as follows, Sect. 2 elaborates on the 5G vision, generic services models and technical challenges. Section 3 elaborates the possible technical enablers and solutions, from the Radio and Core network perspective, and discusses the underlying research issues and future directions. Section 4 presents the current

Research and Development (R&D) activity related to 5G and discusses the ongoing standardization initiatives. Section 5 provides the concluding remarks of the survey.

2 The 5G Vision: Service Models and Technical Challenges

Although, the rapid increase of mobile data volume is mainly driven by the video related content, it is expected that many innovative and unconventional services and applications will materialize in the near future. The ongoing research activities have already identified a set of generic *service and application models* that will be the main consumers of the 5G technology, i.e.:

- *Immersive experience* The immersive experience, enriched by *context information*, *ultra high definition (UHD) video*, *augmented reality* as well as the concept of *anything as a service* and *user personalization* will be the main driver for the massive adoption of the 5G technology components and its envisioned market uptake, which will evolve beyond the current *Client–Server* service models. In order to facilitate the requirements of the immersive like applications, the future 5G technologies will have to be capable of providing fiber-like peak access data rates, i.e. access data rates in the magnitude of Gbps.
- *Ubiquitous connectivity of smart objects* The IoT and M2M networking and communication concepts are foreseen to accommodate massive number of machine type devices and smart connected objects that will usher the automation process in nearly all fields of the modern society, enabling advanced applications like smart grids, smart cities, intelligent transportation systems, etc. The goal of 5G will be to employ novel access protocols and techniques that will be capable of achieving 100-fold

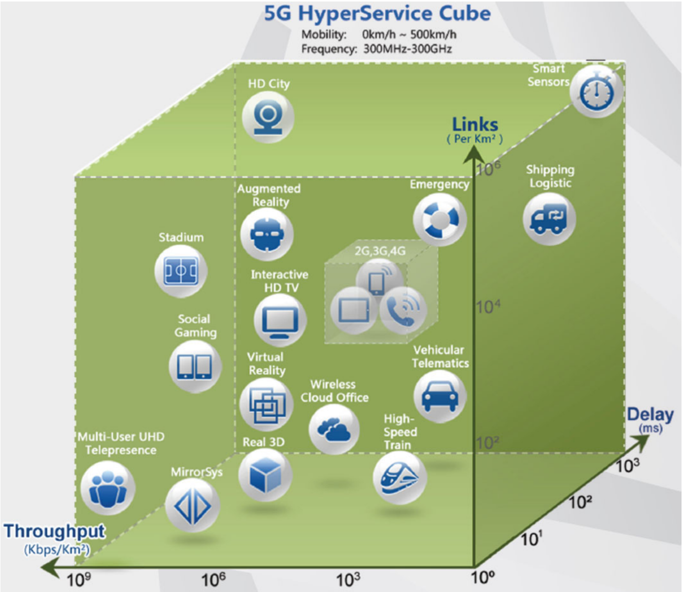

Fig. 1 5G service and scenario requirements [7]

increase in the number of simultaneously connected devices compared to legacy wireless systems (e.g. LTE) [6] and to reduce the energy consumption-per-bit usage by a factor of a thousand [7].
- *Mission-critical remote access* Mission-critical applications such as smart grids, telemedicine, industrial control, public safety, vehicle communications etc., have strict communication requirements in order to ensure uninterrupted and reliable operation. Full support for mission-critical machine-type applications will require that 5G should provide ultra-reliable connectivity with guaranteed availability and reliability-of-service, as well as end-to-end delays that will range in the magnitude of several milliseconds.
- *Everything on cloud* The cloud services and cloud computing, will facilitate the opportunity for the end users to experience desktop-like services (i.e. services that require high computational power and storage) while utilizing mobile devices. This, concept opens the possibilities for novel applications that will substantially increase the volume of the mobile traffic due to the frequent and massive exchange of data between the cloud and mobile devices and will necessitate all of the previously mentioned technical requirements, i.e. very high data rates, massive multiple access and minuscule end-to-end delays.

The diverse nature of the discussed service models will leverage the development of many novel services and applications like, multi-user UHD telepresence, augmented reality, virtual reality and social gaming, vehicular telematics, wireless cloud office, smart monitoring, etc. Figure 1 delineates the requirements of these novel (5G specific) applications and services, with respect to the 5G system performance and capabilities, and compares them to the existing capabilities of legacy wireless systems and services.

From Fig. 1, it is evident that 5G will provide significant performance improvement compared to existing legacy systems, and thus faces a major design challenge in order to simultaneously meet all of the underlying requirements. These requirements can be divided in four *key technical challenges*, which necessitate the development and utilization of non-conventional and beyond state of the art solutions:

- *Ultra fast data transmission* In order to provide ultra fast data transmissions, with peak data rates that reach more than 50 Gbps, the 5G system will have to combine several innovative solutions like, mmWave technology, massive MIMO, advanced modulation and coding approaches, two-way wireless communication, etc.
- *Superior user experience* Compared to the legacy systems, like 4G, where the quality of experience endure high degradations on the cell edges, future 5G systems will provide uniform Gbps data rates and superior user experience throughout the whole cell, by introducing solutions like, massive MIMO aided beamforming and small cells. The 5G user experience will be also enhanced as a result of the smaller network latencies (that are expected to decrease by a factor of ten compared to 4G), by utilizing advanced solutions like software defined networking.
- *Massive multiple access* It is expected that 5G will provide up to 100 times higher number of simultaneously connected devices, compared to legacy systems. In order to facilitate the massive multiple access requirements 5G systems will exploit solutions like, massive MIMO aided interference alignment, D2D communication, Cloud RAN etc.
- *Cost effectiveness* One of the biggest technical challenges that 5G faces, is to provide cost effective system deployment and increased operator revenue. Legacy systems like, 4G induce high traffic volume in the network that increase the running operators cost, while

providing almost negligible increase in the operator's revenue. The 5G systems are envisioned to provide up to 50 times more cost effective operation by utilizing solutions like small cells, network function virtualization, multi-RAN interworking, etc.

Table 1 summarizes the generic 5G technical requirements and gives a quantitative comparison with legacy systems, like 4G.

The following section presents and elaborates on the identified 5G technical solutions. It gives an in depth discussion on their technical aspects as well as their main issues and ongoing research advances.

3 5G Technical Enablers

As already discussed, 5G will introduce many cutting edge and beyond state of the art solutions in order to facilitate the wide plethora of performance requirements, which span from ultra fast data rates and low cost up to massive multiple access and increased energy efficiency. These solutions, i.e. technical enablers, can be divided in two distinct groups in dependance of their network location and technical background i.e. Radio Access Network (RAN) technical enablers and Core network technical enablers. This section will give a thorough overview of the key RAN and Core network technical enablers and will pinpoint their main research focus and issues.

3.1 RAN Technical Enablers

The generic focus of the RAN technical enablers is to improve the system capacity in order to cope with the advanced traffic models and user behavior. The system capacity can be determined by three distinct features, i.e. the underlying system *bandwidth*, *spectral efficiency* and *areal reuse*. The bandwidth increase is the most straightforward approach for improved system capacity, however the overcrowded spectrum below 3 GHz limits the possibility for an ultra broadband 5G implementation (e.g. 1 GHz of continuous band dedicated purely for 5G [8]) and represents a significant design challenge.

3.1.1 mmWave Communications

Although the bellow 3 GHz bandwidth utilization can be made more efficient by novel spectrum policies and regulatory procedures, they cannot free the envisioned quantities of

Table 1 5G generic technical requirements

5G technical requirement	Performance improvement compared to 4G
Supported mobile data traffic	1000 times higher
Number of connected devices	10–100 times higher
Peak cell data rates	10–100 times higher
Network latency	10 times lower
Energy efficiency	Up to 10 times higher
Operational cost	Up to 50 times lower

spectrum band required for optimal 5G operation. The only viable solution for utilizing vast amounts of bandwidth is to traverse to, and exploit the unoccupied higher end of the spectrum, i.e. above 10 GHz. The technical solution that leverages the possibility for mobile communications to operate on frequencies above 10 GHz is denoted as the millimeter wave (mmWave) communication. Until recently, it had been considered that the mmWave band is unusable for mobile communications, due to its hostile propagation characteristics. However, recent advances in hardware design and channel/propagation modeling have proven that the main obstacles related to this band, like the *pathloss effect*, *atmospheric absorption* and *specular propagation*, might be resolved in the nearest future [9–13].

Pathloss Effect The main mmWave design issue with respect to the pathloss, is the significant increase of signal attenuation when transmitting on higher frequencies. For example, increasing the central frequency for an order of magnitude will add an additional 20 dB of signal attenuation. Nonetheless, if the antenna design can provide constant aperture, in dependance of the central frequency, the wireless system will introduce higher antenna gains, as presented in the following equation:

$$G = \frac{4\pi f_c^2 A_{eff}}{c^2}, \tag{1}$$

where G denotes the antenna gain, f_c is the central i.e. carrier frequency, A_{eff} is the antenna aperture and c is the speed of light. From Eq. 1, it is evident that antenna designs with constant aperture can counter both, the pathloss induced by the higher carrier frequency and the higher noise floor due to the higher antenna gains. Maintaining the aperture constant is possible by introducing antenna arrays in the communication chain.

Atmospheric Absorption The signal absorption due to atmospheric phenomena like rain, mist, oxygen etc. can have substantial impact on the signal attenuation if focusing on macro-cell scenarios. However, for dense urban scenarios like the small cells, the atmospheric absorption does not degrade the communication performances due to the smaller cell radius and can even be of benefit since it attenuates the signals from the neighboring cells. Moreover, the signal absorption effectively mitigates the inter-cell interference [12–14], and provides better cell coverage and improved user experience, Fig. 2. Additionally,

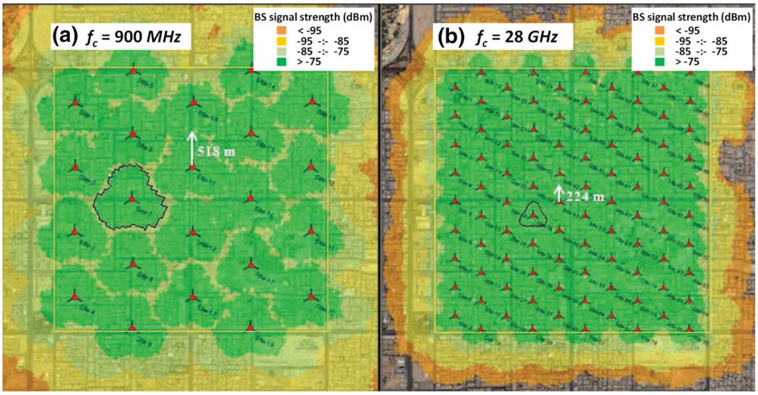

Fig. 2 RF coverage prediction for microwave and mmWave based networks: **a** microwave networks, fc = 900 MHz, **b** mmWave networks, fc = 28 GHz [13]

by utilizing directional antennas between the transmitter and receiver stations, the coverage range of the underlying cell can be considerably extended [13], and can provide applicability of the mmWave technology for concepts like backhauling as well as simultaneous mobile access and backhauling [15, 16].

Specular Propagation Because of the higher carrier frequencies, mmWave communication exhibits more emphasized specular propagation , smaller diffraction and penetration compared to legacy microwave communications. The mmWave's sensitivity to blockages from large scale obstructions requires novel propagation models that can reflect the real behavior of the propagation effects. To better understand the radio propagation in the mmWave environment, extensive measurements have been carried out to portray these bands for future cellular and backhaul systems and for both indoor and outdoor environments [11–13, 17, 18]. These propagation models have been already utilized for system performance evaluation and simulation studies [13, 19–21]. Initial conclusions from these papers highlight that the mmWave channels have low number of multipath components an hence can provide the development of simpler estimation and precoding algorithms. Additionally, because of the low multipath, the mmWave communications are more suitable for LOS transmissions [19–21].

Figure 3 presents the results from a tangible study of the mmWave channel advantages compared to micro wave channels in terms of the achieved capacity. It is evident that mmWave concept provides significant performance gains, with respect to the channel capacity, compared to legacy system solutions, mostly due to the exploitation of vast amounts of unoccupied spectrum bands.

3.1.2 Massive MIMO and Beamforming

Improving the spectrum efficiency is another approach to provide higher system capacities in the radio interface of the wireless systems. One of the most prominent solutions related

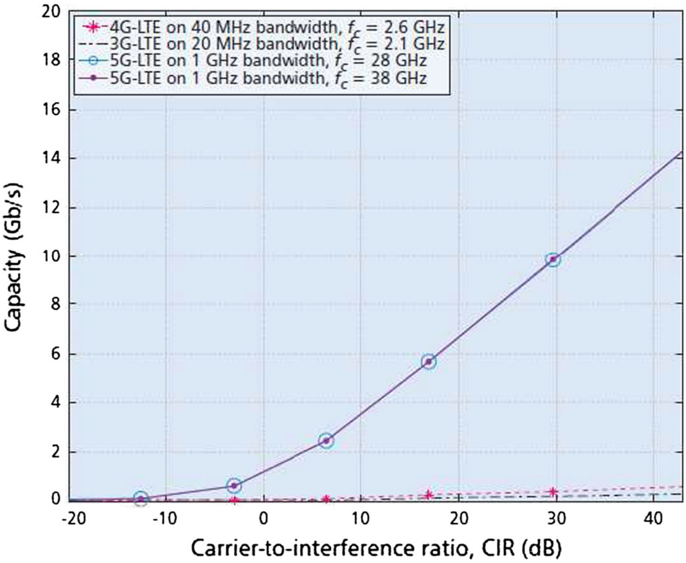

Fig. 3 Channel capacity in dependence of carrier to interference ration [13]

to increased spectrum efficiency is the Multiple Input Multiple Output (MIMO). MIMO as a technical enabler exploits the spatial dimension i.e. spatial diversity, which arises from the multiplicity of antennas available at transmitter and receiver. Hence multiple orthogonal spatial dimensions become available for data transmission resulting in improved spectral efficiency [22–24]. The latest advances in MIMO technology, propose to equip the cellular base stations (BS), with very large number of antennas that can potentially increase the spectral efficiency, compared to legacy MIMO, possibly for several orders of magnitude [25]. More specifically, this emerging technical enabler, also denoted as massive MIMO, provides several advantages as, significantly improved spectral efficiency, improved channel response and simplified transceiver designs. So far, most of the research work related to massive MIMO has been purely theoretical, mostly because of its practical limitation regarding the hardware design and the huge and bulky antenna array dimensions. However, for very high carrier frequencies, i.e. in the mmWave band, the antenna array dimensions scale down significantly, providing practical and small scale designs (e.g. on an area of 8 cm^2 practical mmWave massive MIMO designs can accommodate antenna arrays consisted of up to 256 elements [26]). The ongoing research on massive MIMO for 5G, focuses on several distinct technical and design related aspects such as, *channel estimation*, *full-dimension MIMO and beamforming*, *channel correlation* and *channel modeling*.

Channel Estimation For very large antenna arrays, *channel estimation* errors due to uncorrelated noise and interference are less problematic since the impact of such errors diminishes as the number of antennas approach infinity. In massive MIMO, the primary source of channel estimation errors is considered to be the pilot contamination, where the training sequences transmitted in a given cell are correlated with those from the neighboring cells [27–29]. However, pilot contamination is relatively negligible for practical massive MIMO systems where the number of antennas is large but finite [30]. Moreover, several works have proposed methods to reduce and even eliminate pilot contamination via low-intensity BS coordination [31, 32]. Still, an efficient pilot structure design is required in order to avoid introducing significant overhead in the network. Some of the ideas being considered for efficient pilot design include exploiting spatial correlations, as well as separating the pilots into classes where each class should be transmitted at a different data rate [33].

Full-Dimension MIMO Legacy BSs equipped with MIMO, are mostly consisted of 1D i.e. horizontal arrays that only utilize the azimuth dimension, and which are restricted to a small and limited number of antennas due to form factors. By introducing 2D planar arrays [26] and further exploiting the elevation dimension, the so-called *full-dimension MIMO (FD-MIMO), i.e. 3D-MIMO,* can incorporate higher number of antennas within the same form factor [26, 34]. Moreover, utilizing the 2D antenna arrays can provide increased signal power and reduced interference to inter-cell users. The main consumer of the massive MIMO antenna arrays is the directional, i.e. adaptive, beamforming process that provides improved array gains, which can be exploited to alleviate high pathlosses and achieve sufficient link margins. The main objective of adaptive beamforming is to shape the beam patterns (e.g., by beamsteering) so that the received signal-to-noise ration (SNR) is maximized [12]. The requirement for low cost and low-power hardware has pushed the massive MIMO research towards utilization of analog architectures that contain only digitally controlled constant modulus phase shifters [26]. However, in order to increase the degrees of freedom in the system, novel beamforming/precoding algorithms, like the hybrid precoding have been proposed, which divides the required precoding between the analog and digital domains, and hence facilitates better beam shaping [35]. The main performance advantage of the hybrid beamforming can be exploited in multi-stream and multi-user (MU) scenarios in which the digital precoding facilitates the inter-stream and inter-user interference management [36].

Channel Correlation Because of the large antenna array in massive MIMO, under favorable propagation conditions and low channel correlation, the distinct user channels become spatially decorrelated i.e. pairwise orthogonal. Most frequently, the theoretical studies regarding massive MIMO typically assume independent Rayleigh fading, which is a phenomena that rarely occurs on mmWave frequencies. This suggests that user scheduling could be a critical component of mmWave massive MIMO systems in order to eliminate co-channel users with highly correlated channels [29]. Moreover, several works have shown that combining schemes like maximum ratio combining (MRC), can have a reasonable performance, with knowledge of Channel State Information (CSI) for the entire combining branches [37, 38]. Due to the significantly increased implementation overhead and complexity introduced by the combining schemes, recent research advances have argued that cost-efficient antenna selection strategies can be employed to reduce the complexity and implementation overhead [39], as well as to effectively maintain the reasonably high performance [40].

Channel Modeling The channel modeling also represents a key aspect in the development of future massive MIMO solutions, which require extensive field measurements in order to provide reliable data. Antenna correlations and couplings for massive arrays, with respect to the system topology of interest, are one of the crucial goals related to this aspect that must be solved. In particular, these models have to verify the actual degree of channel correlation due to the nonidealities of the channels and antenna design. Additionally, for FD-MIMO solutions, the modeling also needs to incorporate the elevation dimension [41–43], which is a dimension on which very little data and knowledge exists, in terms of parameters like power spectra and angle spreads. 3GPP has recently initiated a 3D channel modeling study that is currently under way, and it is expected to address most of the massive MIMO channel modeling features [44].

As elaborated in this section, it is evident that there exist a correlation between the mmWave and the massive MIMO technical enablers. More specifically, massive MIMO significantly improves the performances of mmWave communication and provides it with the possibility for practical implementation in LOS and NLOS cellular scenarios. Additionally, mmWave facilitates massive MIMO with simple and cost effective hardware, i.e. antenna array design due to the significantly lower wavelengths introduced on the higher operating frequencies, i.e. above 10 GHz. Table 2 delineates and compares the performance of conventional MIMO techniques on microwave channels, with the massive

Table 2 Comparison of cell throughput for MIMO and massive MIMO solutions [36]

Transmission strategies	Average rate per user (Mbps)	Average cell throughput (Mbps)
Microwave SISO	31	31
Microwave MIMO	77.2	77.2
mmWave single-user beamsteering	451.2	451.2
mmWave multi-user beamsteering	450.9	901.7
mmWave multi-user hybrid precoding	464.0	928.0

MIMO concept on mmWave channels, utilizing either standard beamsteering or advanced hybrid precoding, based on the simulation analysis performed in [36].

The results provided in Table 2 clearly show that the combination of mmWave and massive MIMO provides drastic increase of system capacity that meet the 5G requirements. The forthcoming research activities related to the mmWave and massive MIMO coexistence will focus on finding the optimal tradeoff between the power gain required for efficient mmWave operation and the interference tolerance margin required for optimal spatial multiplexing performance, in order to attain the maximal system capacity.

3.1.3 Advanced Modulation and Coding

Spectrum efficiency can be also improved by novel waveform designs. Although OFDM has proven to be the dominant waveform for SoA wireless communication systems, there exist numerous weak points, like peak-to-average-power ratio (PAPR), cyclic prefix (CP) redundancy, requirement of complex amplifiers for mmWave communication, etc., which are not inline with the 5G technical requirements. Although, there have been attempts to modify the OFDM design, (e.g. GFDM [20] and tunable OFDM [45]), in order to address its underlying disadvantages, the research community has been focusing on several alternatives that provide significantly improved performances, such as the *Faster-than-Nyquist signaling*, *filterbank multicarrier* and *single carrier* concepts.

Faster-Than-Nyquist Signaling Faster-than-Nyquist (FTN) signaling [46–48] and multicarrier FTN i.e. Timefrequency packing (TFS) [49] have been recently proposed to circumvent the OFDM limitations regarding the strict orthogonality requirement and CP design. Opposite to OFDM, where the product of the symbol interval and the subcarrier spacing equals one, in FTN and TFS can accommodate signaling products smaller than one. This novel signaling approach can provide the underlying waveform with up to 25 % improved spectral efficiency.

Filterbank Multicarrier Recently there has been growing interest in developing and exploring novel non-orthogonal multicarrier formats, like filterbank multicarrier (FBMC). FBMC is an OFDM-like modulation format where the subcarriers are filtered in order to suppress the signals sidelobes, making them eventually strictly bandlimited. FBMC can provide improved spectral efficiency compared to OFDM, while still being implemented through FFT/IFFT blocks or polyphase filter structures [49, 50] that are common for OFDM implementation. The utilization of FBMC for 5G networks is mainly endorsed due to its, ability to cope with network asynchronicity that arises in the uplink or in the downlink with coordinated transmission [51], greater robustness to frequency

Table 3 Comparison of possible 5G modulation formats [55]

Modulation formats	Ease of hardware implementation	Low latency	Immunity to PAPR	Robustness to sync. errors	Coupling with massive MIMO	Compatibility with mmWave
OFDM	Yes	No	No	No	Yes	Yes
TFS	No	No	No	No	Yes	No
FBMC	No	No	No	Yes	Yes	Yes
Single carrier	No	Yes	Yes	No	Yes	Yes

misalignments among users [52], and more flexible exploitation of frequency white spaces in dynamic spectrum access and cognitive radio networks [49]. FBMC is usually either coupled with QAM or with Offset-QAM (OQAM) modulation formats.

Single Carrier In legacy wireless systems, the multicarrier approach has been the dominant modulation format and waveform, because optimal equalization can be efficiently carried out in the frequency domain, where as optimal equalization of a single carrier system is much more complex and essentially requires the use of a Viterbi algorithm. However, single-carrier transmission has also been attracting renewed interest as a possible 5G waveform, mainly because of the development of high-performance and low-complexity equalizers operating in the frequency domain [53, 54].

Table 3 summarizes the capabilities of the possible 5G waveforms i.e. modulation formats with respect to the 5G technological requirements. The information provided in the table shows that the preferable modulation format specifically depends on the considered scenario in terms of channel characteristics, hardware and processing requirements, as well as compatibility with envisioned 5G solutions, like massive MIMO and mmWave. In this sense, RAN virtualization and implementation of cloud radio access networks, see Sect. 3.2, may pave the way towards a tunable and adaptive modulation design, where the waveform parameters can be chosen based on the specific scenario requirements.

3.1.4 Small Cells

In order, to simultaneously provide ultra high throughputs and facilitate access to massive number of users, apart form the bandwidth and spectral efficiency, 5G must also exploit the areal reuse. The most auspicious technical solution that facilitates the areal reuse, are the small cells. In legacy systems like 3G and 4G, the deployment of macrocells mainly provides wide coverage, where the transmit power is generally utilized to mitigate the path loss. By deploying dense small cells, the 5G high data rate demand of indoor and hotspot users could be easily met. Concurrently, the macrocell load could be decreased, through re-routing the mobile device traffic to the small cells, providing the possibility for massive multiple access. The ongoing research on small cells, focuses on several technical and design related issues as, *synchronization*, *carrier selection*, *inter-cell power control*, *access type* and *decoupled access*.

Synchronization Network synchronization among multiple neighbor access points (APs) is considered as an important enabler for interference management techniques, whose usage can significantly boost the cell throughput in dense scenarios like small cell deployment. In current cellular networks, time synchronization among multiple base stations is typically achieved by locking onto the timing signals from the GPS system. However, penetration losses due to inside location may significantly reduce the accuracy of such timing reference. Hence, recent works have identified several synchronization approaches like, Physical-layer-based timing and Packet-based timing that support frequency synchronization [56], distributed primary reference time clock and Packet-based time synchronization approaches, which facilitate time/phase synchronization [57], as well as distributed solutions where the small cells synchronize in a stand alone fashion [58, 59].

Carrier Selection Since small cells can be turned on/off and are deployed by the end user without any prior network planning, new challenges of interference management and carrier selection emerge. In this user deployed network, central control mechanisms will lead to more signaling overhead and implementation complexity with the increasing number of small cells. Therefore, such centralized methods are impractical for this small cell network deployment, and solutions like cooperative distributed algorithms are more favorable [60, 61]. Most of the works in carrier selection, focus on exploiting graph theory, and in combination with approaches like binary criterion [62], coalitional games [63], cooperative fairness [64] and stochastic geometry [65] provide efficient solvers of the underlying small cell interference management and carrier selection optimization problem.

Inter-Cell Power Control Due to the random deployment issues of small cells, discussed previously, the development of inter-cell power control algorithms are required in order to efficiently maximize the performance of the small cell networks. Although, centralized algorithms can obtain a global optimal solution, they cannot be adopted for a multi-cell scenario, which limits their applicability. Therefore, distribution in the optimization process is required in order to address the multi-cell scenario issues [66, 67]. Additionally, several works have theoretically shown [66, 68] and practically demonstrated [68] that introducing cooperation in the power control process can increase the overall system capacity.

Access Type One of the main research topics related to the small cells, is the evaluation of the open and close cell access type. A closed access small cell has a fixed set of subscribed home users that, for privacy and security, are licensed to use the given small cell. Opposite to the closed access, the open access small cells provide service to macrocell users if they are in the coverage area of the small cell. Although open access reduces the macrocell load, the higher numbers of users communicating with each small cell will strain the backhaul to provide sufficient capacity and raise privacy concerns for home users [69]. Several recent works have proposed a hybrid access in which a fraction of resource is allocated to macrocell users [70, 71]. By doing so, the macrocell users near a small cell may handover into it in order to avoid high interference. This access is the most efficient and provides the best performances in terms of areal reuse and overall system capacity [69–73].

Decoupled Access A key issue in small cell scenarios is how devices select the most suitable small cell among the plethora of available ones in the network. If a device employs different association policies for downlink and uplink access, it may choose one base station for downlink and another for uplink access. This type of access is called the decoupled access [74, 75]. The key advantage of the decoupled access is the improved uplink capacity of the cellular system. For example, the authors in [76] compare the uplink capacity with and without decoupled access in theory and simulations. The results in the paper show that the decoupled access improves the uplink capacity by more than 600 %. Moreover, the decoupled access can leverage joint improvements of both energy efficiency in uplink capacity [77] that represent crucial parameters in future 5G systems.

3.1.5 Device to Device Communication

The areal reuse in future 5G systems can be even further improved, by providing novel technical solutions as the D2D communication. The D2D solution in cellular networks is defined as point-to-point communication between two mobile users that do not utilize the BS as a communication anchor point. D2D communication is generally non-transparent to the cellular network and it can operate on licensed cellular spectrum (i.e., *inband*) or unlicensed spectrum (i.e., *outband*).

Inband D2D Communication The inband D2D communication, proposes to use the cellular spectrum for both D2D and cellular links. The motivation for choosing inband communication is usually related to the possibility to control the interference on the licensed spectrum bands, whereas the interference in the unlicensed spectrum is uncontrollable and can impose significant constraints for the QoS provisioning, [78, 79]. Inband

D2D communication can be further divided into underlay and overlay. In underlay D2D communication, cellular and D2D devices share the same radio resources [80, 81]. In contrast, D2D devices in overlay communication are given dedicated cellular resources [82, 83]. The key disadvantage of inband D2D communication is the interference caused by D2D devices to cellular users and vice versa. This interference can be mitigated by introducing high complexity resource allocation methods, which increase the computational overhead of the BS and/or D2D devices [81, 84, 85].

Outband D2D Communication For the case of *outband* D2D communication, the D2D devices exploit the unlicensed spectrum bands. The incentive behind using outband D2D communication is to eliminate the interference generated towards the cellular users. Using the outband D2D communication requires an additional communication interface such as WiFi Direct, ZigBee or Bluetooth. Some of the work on outband D2D, [86–88] suggest to provide control of the D2D interface/technology to the cellular network (denoted as controlled outband D2D). This type of outband D2D communication provides more efficient operation and introduces additional complexity in the resource management of the cellular system. In contrast, the authors in [89, 90] propose to leave the D2D communications autonomous and independent of the cellular network management (denoted as autonomous outband D2D), and thus facilitate lower design complexity of the cellular system, compared to the controlled outband D2D communication. In order to improve the energy efficiency, outband D2D communication can utilize the aspects of wireless energy harvesting [91] and gather energy from outside sources, like the ambient interference that occurs in the unlicensed bands [92]. Although, outband D2D communication alleviates the interference between the D2D and cellular users and provides improved energy efficiency, it may frequently suffer from uncontrolled interference that resides in the unlicensed spectrum and degrade the D2D performance.

3.2 Core Network Technical Enablers

As already discussed, it is unlikely that one standardized model of network deployment will be able to fit all use cases and scenarios envisioned for 5G. Moreover, it is foreseen that the core network and hardware equipment will poses a flexible (i.e. “liquid”) design in order to provide optimal performance for variety of scenarios, which can vary in space and time. This fundamentally redefines the network design and requires that the 5G core be much swifter, more flexible and more scalable. As such, three technological solutions have been identified as the main facilitators of the 5G core network design: *network function virtualization (NFV)*, *software defined networking (SDN)* and *cloud RAN (C-RAN)*. Combining both *network function virtualization (NFV)* and *software defined networking (SDN)* solutions, will provide the possibility for dynamicity and swiftness of the network and thus fundamentally change the way network services are provided. For example, when a given data center is unable to cope with a flash crowd scenarios (e.g., due to a local disaster or public mass events), additional capacity can be borrowed from other data centers. In addition, the resources within a data center can be dynamically shifted towards applications with higher user demand or processing power. More recently, the virtualization concept has started to also shift towards the network edges, i.e. towards the RAN. This technical solution is denoted as the *cloud RAN (C-RAN)* and it will be also discussed in more details in this subsection.

3.2.1 Network Function Virtualization/Software Defined Networking

NFV is a network architecture concept that proposes the facilitation of virtualization related technologies in order to virtualize the functionalities of the network nodes. NFV enables network functions, which are conventionally taut to the underlying hardware equipment, to be operated on virtual machines and cloud computing infrastructures. Foremost, NFV facilitates advanced network solutions like the separation of the data, control and management plane. Moreover, it provides the possibility for the separation of the network functions from the hardware infrastructure, which is identified as the cornerstone of future core network solutions. By introducing the NFV concepts in the networks, operators expect to achieve greater agility and accelerate new service deployments while driving down both operational (OpEx) and capital costs (CapEx) expenses [93, 94].

SDN is a new technical solution that has been designed to enable more agile and cost-effective core network architectures and managing. More specifically, SDN is a concept in core networking that facilitates network administration and network services management through abstraction of lower-level functionality. Much like NFV, SDN accelerates innovation by breaking the bond between proprietary hardware and control/application software. In the SDN architecture, network control is distributed and the network intelligence, i.e. decision-making is facilitated throughout the whole network, as opposed to conventional core network architectures, where the network nodes and devices are unaware of the overall state of the system. SDN networks are inherently controlled by software functionalities, which may be provided either by the vendors or the network operators and

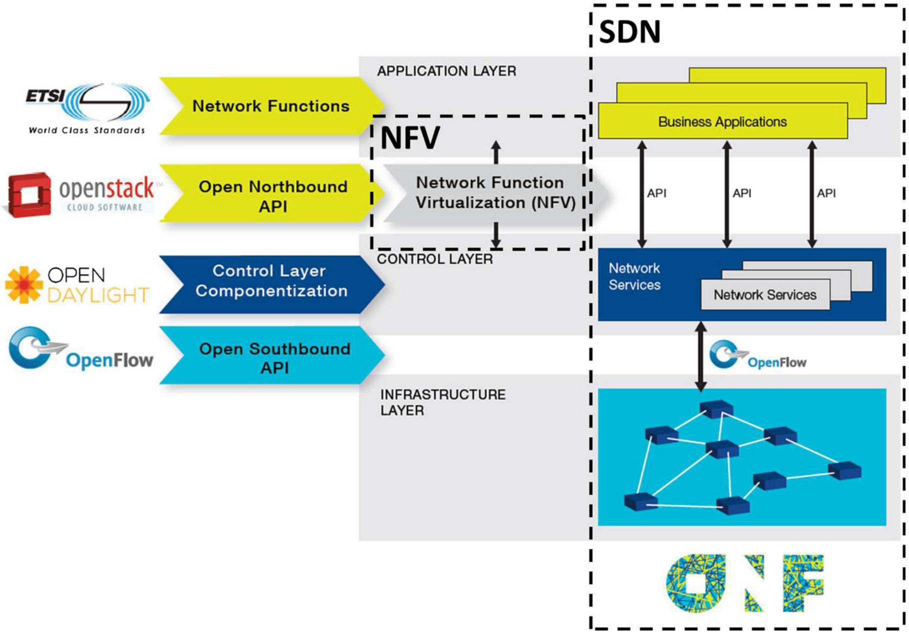

Fig. 4 NFV/SDN architectural design

providers. Such programmability enables automatic network configuration, and stipulates the adoption of the cloud concept [95].

Architectural Design Both NFV and SDN seek to leverage automation and virtualization to achieve improved agility and performance of the underlying core network while simultaneously reducing the operators expenses. Platform-wise, NFV is intended to optimize the deployment of network functions (such as firewalls, DNS, load balancers, etc.), while SDN is focused on optimizing the underlying networks. Figure 4 depicts the NFV/SDN architectural design as well as the main interfacing points and leading industry projects therein.

NFV/SDN Open Issues Although the combination of NVF and SDN represents the most prominent suitable technical solution for the 5G core network architecture, there exist several implementation and design challenges that still have to be addressed, such as dynamic network configuration and addressing, design of network management automation, NFV/SDN end-points scalability and mobility and NFV/SDN multi-tenancy [96–98]. More information regarding the technical challenges and open issues with respect to the NVF/SDN concept can be found in [99] and the references therein.

3.2.2 Cloud RAN

Because of the high areal reuse efficiency, densification of the RAN as well as exploiting the multi-RAN interworking concept, 5G intra-cell management scenarios become highly complex. A centralized approach can provide the implementation of efficient radio resource management (RRM) algorithms, which will facilitate radio resource coordination across multiple cells and RAN technologies. It can also allow optimization of the radio access performance at the signal level, like the joint multi-cell processing and inter-cell interference coordination and provide seamless transition between different RAN technologies. However, conventional network designs and architectures limit the applicability of a centralized solution for 5G scenarios. C-RAN has recently been identified as one possible technical solution capable of providing efficient centralized coordination and management of the dense RAN deployments [100]. The C-RAN solution, envisions a network topology where multiple sites are connected to a central data center that performs the complete baseband processing. Radio signals are exchanged over dedicated transmission lines (called front-hauls) between the remote radio heads and the data center.

C-RAN Open Issues At present time, only a fiber link technology is capable of supporting the required data rates. The high-capacity front-haul links and low latency requirements, significantly limit the C-RAN's implementation and applicability. Due to the necessity for optical fiber, current C-RAN deployments are characterized by poor flexibility and scalability because only sites with existing fiber access can be selected, in order to avoid costly fiber access deployment. Hence, there exists a trade-off between centralized processing that requires high capacity front-haul links, and decentralized processing that utilizes traditional backhaul to transport the user and control data to/from the BSs. Novel solutions like the RAN as a service (RANaaS), can address this trade-off issue, by dynamically managing the centralized RAN functionalities in dependance on the actual needs as well as network characteristics [100, 101]. More information regarding the technical challenges and open issues with respect to the C-RAN concept, can be found in [102] and the references therein.

3.3 Summary

5G will introduce many novel and beyond state of the art technologies in order to leverage the wide plethora of performance requirements. The foremost, and core 5G technological advance is the mmWave technology, which provides the utilization of unprecedented system bandwidths, on frequencies beyond 10 GHz that will substantially increase the RAN system capacity. However, the shift towards the mmWave spectrum band will require the development and use of advanced technical concepts as massive MIMO and cell densification, in order to cope with the underlying mmWave issues like significant signal attenuation, low object penetration, etc. Moreover, concepts like non-orthogonal modulation and D2D communication will additionally improve the underlying RAN system capacity in terms of the achieved user and cell throughput as well as the number of connected/served devices. From the core network perspective, it is highly questionable that single network solution will be capable to address the envisioned use cases and provide support to the novel 5G RAN. Instead, it is foreseen that the core network will incorporate several technological advances as NFV, SDN and Cloud-RAN that will facilitate the required flexible, i.e. “liquid” and adaptive network design that will deliver the optimal core network performance for variety of user and service specific scenarios.

Table 4 summarizes the main characteristics of the presented 5G technical solutions in this section. In order to facilitate all envisioned technical requirements, it is evident that 5G will have to rely on all of the presented cutting-edge solutions, once more highlighting the technological leap compared to legacy systems like 3G/4G.

4 Standardization and R&D Activities

After introducing the future mobile trends and vision of 5G, its functional requirements, as well as the foreseen 5G technical solutions regarding the state-of-the art advances in the respective areas, this section dwells into the 5G regulatory and standardization efforts. Moreover, the section presents the ongoing R&D activities related to ongoing 5G trials, testbeds and measurement campaigns.

Table 4 Performance advances of the possible 5G technical solutions

Technical solution	Peak data rate	Cell edge data rate	Cell spectral efficiency	Mobility	Cost efficiency	Massive access	Latency
mmWave comm.	Yes	Yes	Yes	No	Yes	Yes	Yes
Massive MIMO	No	Yes	Yes	No	Yes	Yes	No
Advanced modulation	No	Yes	Yes	No	No	No	No
Small cells	No	Yes	Yes	No	Yes	No	No
D2D communication	No	No	Yes	No	No	Yes	No
NFV	No	No	No	Yes	Yes	No	Yes
SDN	No	No	No	Yes	Yes	Yes	No
C-RAN	Yes	No	No	Yes	Yes	Yes	No

4.1 Standardization and Regulation

As already presented in this survey, the research activities on developing novel technologies that will form the foundation of 5G standards has been occurring for the last few years. However, the formal standards process is still at its initial phase. This subsection presents the already started standardization activities as well the ongoing spectrum regulation and allocation initiatives.

Standardization Activities Recently, several regional and international workgroups, as part of ITU, have been founded in order to shape the 5G vision and to identify its key enabling technologies [103–105]. Moreover, ETSI has also been actively exploring the possible 5G user requirements and plausible standardization directions [106]. The initial ETSI conclusions, are that an evolution of LTE may not be sufficient to meet the anticipated 5G requirements. Similar conclusions, have been also made by the 3GPP, which is currently in the phase of finalizing LTE Rel-12 and starting with Rel-13. The timing of 5G standardization has to be agreed yet, although it is tentatively expected to start in line with Rel-14, at the beginning of 2016. However, many ongoing and proposed study items for Rel-12 and Rel-13 are already closely related to 5G candidate technologies, such as massive MIMO, D2D communications, SDN etc. Whether an entirely new standards body will emerge for 5G is obscure, although the influence and affirmation of 3GPP gives it an early advantage.

Regulation Activities Spectrum regulation and harmonization efforts for 5G have also begun within the ITU, with respect to the ITU-R WP5D work group [107]. Their studies are under way on the feasibility of bands above 6 GHz [108], including technical aspects such as channel modeling, semiconductor readiness, coverage, mobility support, potential deployment scenarios and coexistence with existing networks. In addition to the ITU,

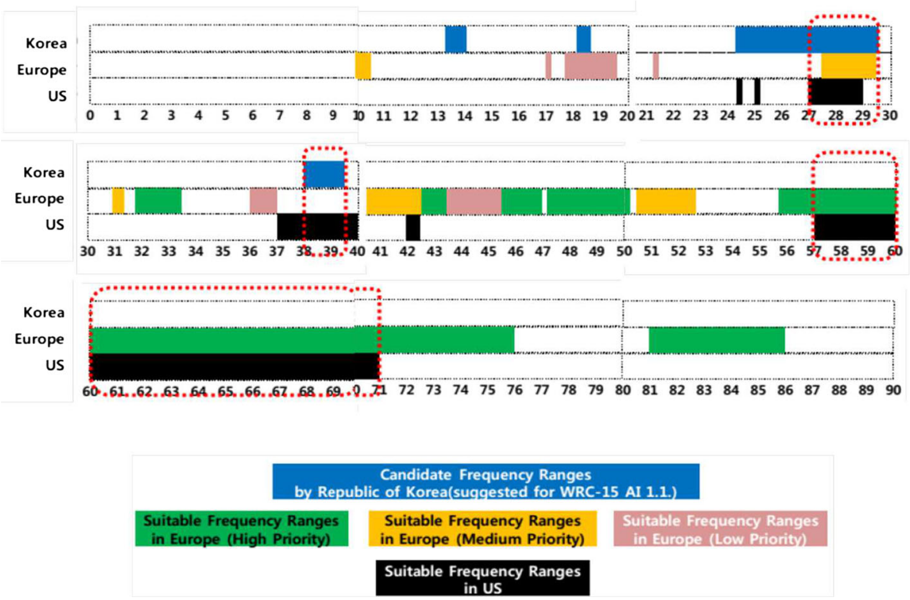

Fig. 5 Candidate mmWave frequencies in Korea, EU and US (GHz)

many national regulators have also started their own studies on mmWave spectrum for mobile communications. In the USA, the technological advisory council of the federal communications committee (FCC) has carried out extensive investigations on mmWave technology and recently has issued a notice of inquiry [109], which reflects the planed agenda of FCC towards allocating new frequency bands in the mmWave region. The document identifies several possible mmWave bands, LMDS Band (27.5–28.35 GHz, 29.1–29.25 GHz, and 31–31.3 GHz), 39 GHz Band (38.6–40 GHz), 37/42 GHz Bands (37.0–38.6 GHz and 42.0–42.5 GHz), 60 GHz Bands (57–64 GHz and 64–71 GHz), 70/80 GHz Bands (71–76 GHz, 81–86 GHz) and 24 GHz Bands (24.25–24.45 GHz and 25.05–25.25 GHz). The document also investigates possible licensing procedures as the *geographical* and *nonexclusive* licensing as well as the potential bandwidths, duplexing, modulation, and multiple access modes. Moreover, CEPT has also recently started to actively focus on the spectrum planning for 5G and has supported the initiative and agenda item for the ITU WRC'19 on additional frequency bands for IMT above the 24 GHz band, although the exact formulation and the target frequency bands are yet to be decided [110]. Figure 5 depicts the candidate frequencies for mmWave 5G communication in Korea, EU, and US.

Based on the provided information it is highly plausible, to expect that the first standardized 5G mmWave bands will be on 27–29 GHz, due to the mutual interest of EU, US and Korea, for this spectrum chunk. The band around 37–39 GHz is identified as suitable to both Korea and US, however, because of the small interest of EU, it can be expected that it will not be standardized on the international/global level. Moreover, the higher bands, 57–71 GHz, are of significant interest to the EU and US, and also pose a highly likable candidate for dedicated 5G spectrum as well, mostly due to the vast, continuous and unoccupied frequencies, which can facilitate ultra broadband communications and fiber-like wireless transmissions.

4.2 R&D Activities

The development of the next generation of mobile networks has triggered intensive global research and development activities with respect to the academia and the industry. This section discusses the most significant research activities and field trials.

4.2.1 Research Activities

Globally, there exist a number of research activities underway examining the candidate technologies and scenarios for the 5G mobile broadband system. This section provides a landscape of 5G-related research activities in the global regions of Europe, US and Asia.

EU Activities Under "A Digital Agenda for Europe" the EU has already launched several 5G related actions like the 5G-PPP (5G Infrastructure Public Private Partnership) as well as the Horizon 2020 initiative. The 5G-PPP is a 1.4 Billion Euro joint initiative between the European ICT industry and the European Commission (EC) to rethink the infrastructure and to create the next generation of mobile networks [111]. The 5G-PPP is tightly related with the Horizon 2020 action, which is the prime European research funding program related to 5G, with an overall budget of over 700 million Euros [112]. Additionally, EU has already initiated a set of research projects via the European Commission FP7 framework, adding up to over 50 million Euros for research, which are envisioned to explore the technological options that will pave the road towards 5G. Several of these projects are listed bellow:

- *METIS* [113]: The main objective of METIS is to lay the foundation for, and to generate a European consensus on the future global mobile and wireless communications system. METIS will provide fundamentally new solutions which fit the needs beyond 2020.
- *5GNOW* [114]: 5GNOW focuses on developing new PHY and MAC layer concepts that are better suited to meet the upcoming needs with respect to service variety and heterogeneous transmission setups in the next generation of mobile networks.
- *iJOIN* [115]: iJOIN introduces the concept of RANaaS, where RAN functionality is centralized through an open IT platform based on a cloud infrastructure. iJOIN aims for a joint design and optimization of access and backhaul, operation and management algorithms and architectural elements, integrating small-cells, heterogeneous backhaul and centralized processing.
- *TROPIC* [116]: The project aims at exploiting the convergence of pervasive small cells network infrastructure and cloud computing paradigms for virtualization/distribution of applications and services that would otherwise run in the user terminal under a framework that optimizes energy, communication and computation resources.
- *Mobile cloud networking (MCN)* [117]: The project aims at exploiting cloud computing for mobile network operations as well as investigating the possibilities and impact of a end-to-end mobile cloud solution.
- *COMBO* [118]: The project proposes and investigates new integrated approaches for fixed/mobile converged (FMC) broadband access/aggregation networks for different scenarios (dense urban, urban, rural). COMBO architectures are based on joint optimization of fixed and mobile access/aggregation networks that exploit the novel concept of next generation point of presence (NG-POP).
- *CROWD* [119]: The project targets very dense heterogeneous wireless access networks and integrated wireless-wired backhaul networks. CROWD pursues four key goals: (1) bringing density-proportional capacity where it is needed, (2) optimizing MAC mechanisms operating in very dense deployments , (3) enabling traffic-proportional energy consumption, and (4) guaranteeing mobile users quality of experience.
- *MOTO* [120]: The project develops a traffic offloading architecture that exploits in a synergic way a diverse set of offloading schemes, including offloading from cellular to other wireless infrastructures (such as WiFi), and also offloading to multi-hop ad hoc communications between users devices.
- *PHYLAWS* [121]: The project designs and proves efficiency of new privacy concepts for wireless communications that exploit propagation properties of radio channels. The project identifies the existing, and upcoming future systems, where these techniques might be implemented, without or with updates to the standards.
- *MiWEBA* [122]: MiWEBA is publicly supported research project between the EC and Japan, bringing Millimeter-Wave Technology into the mobile radio world, focusing on access links (overlay of millimeter-wave small cell base stations), front-haul links (connecting base stations to their controlling entity), backhaul links (connecting base stations to the core network).

US and Asia Activities In the US the activities gravitate around research done at the Polytechnic Institute of New York University (NYU-Poly) that is tightly collaborating with several industry partners. Researchers at NYU-Poly have assembled a consortium of government and business support to advance beyond todays fourth generation (4G) wireless technologies. The National Science Foundation (NSF) has awarded the team an Accelerating Innovation Research (AIR) grant of $800 thousand, matched by $1.2 million from corporate backers and the Empire State Development Division of Science, Technology and Innovation (NYSTAR). This project is envisioned to develop smarter and far less expensive wireless infrastructure by means of smaller, lighter antennas with directional beamforming to bounce signals off buildings using the uncrowded millimeter-wave spectrum. It will also focus on developing smaller, smarter cells with devices that cooperate rather than compete for spectrum. The 5G initiative in Asia spreads across several national and international actions, like Korea's 5G forum [123], Japan's ARIB2020 [124] and China's IMT-2020 group [125].

4.2.2 Field Trials

To prove the concepts and the technical functionalities of 5G, several industry and academic institutions have already started with a variety of experiments and field trials. Table 5 summarizes the ongoing 5G trials and the respective companies' competitive run towards the first deployable 5G system.

As discussed in this section 5G standardization and R&D activities are in their early stages. New 5G related spectrum is expected to be agreed upon for the World Radio Communication Conference (WRC) next year, in collaboration with 3GPP and FCC. After WRC-15, standardization entities will have a clearer path for determining network system and technology requirements. Figure 6 delineates the possible 5G evolution and road map, with respect to 3GPP and ITU, towards its initial deployment.

Initial forecasts, based on the ongoing standardization, research and trial activities (Fig. 6), predict that the first commercially deployable 5G system, should arrive no later than the year 2020 in the most technological advances countries, where as a global 5G deployment can be expected in the subsequent years.

Table 5 Ongoing 5G trials

Institution(s)	Trial scenario	Main achievements
Samsung [12]	5G mmWave mobile technology (carrier frequency: 27 GHz)	Adaptive array transceiver technology operating in mmWave frequency bands for outdoor cellular. Achieved NLOS communication up to 200 m
Ericsson Tokyo Inst. of Tech. [126]	Performance analysis of massive MIMO (carrier frequency: 11 GHz) (No. antennas: 24 × 24)	Achieved maximal data rate of 35.3 Gbps at an average mobility of 10 kmh
NYU [11]	Channel measurements for mmWave frequencies (carrier frequencies: [28,38,60] GHz)	Comprehensive analysis of the mmWave propagation and channel model for different scenarios
Ericsson Chalmers Univ. of Tech. [127]	5G mmWave communication (carrier frequency: 140 GHz)	Achieved a record braking data rate of 40 Gbps
Nokia Siemens networks [8]	Single carrier mmWave design (carrier frequencies up to 100 GHz)	Successfully achieved communication on 1 GHz bandwidth at 70 GHz frequency

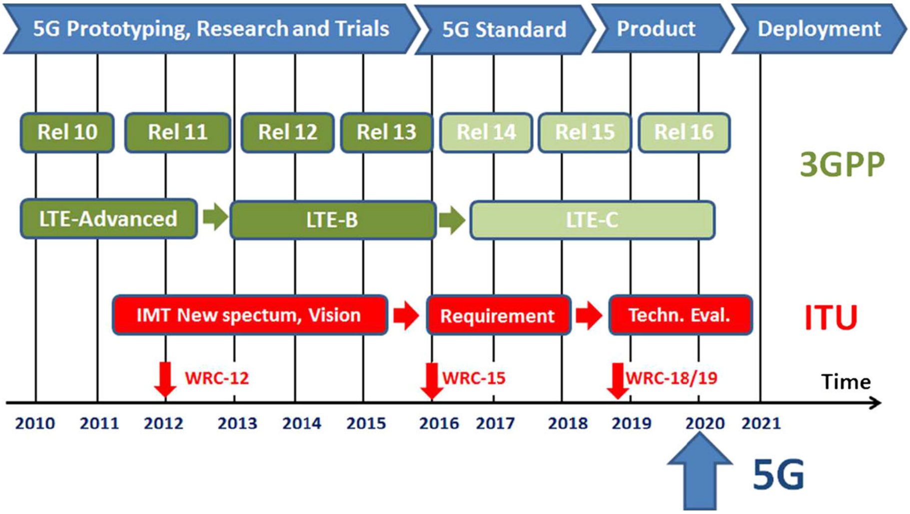

Fig. 6 5G roadmap and timeline

5 Conclusion

This paper provided an in-depth survey of the existing and most recent literature works that focus on the vision and requirements of 5G as well as the core 5G technical enablers. Moreover, the paper discussed and identified the key challenges for the future research directions and the ongoing 5G standardization and trial activities. As elaborated in the paper, 5G will require "out of the box" rationing and incorporate several cutting-edge technologies, like mmWave, massive MIMO, D2D, NVF/SDN etc., in order to provide the required performance improvements, compared to existing legacy systems. Early predictions, based on the current research, trial and standardization activities estimate that 5G will be commercially deployable, in the most developed countries, before the end of this decade. However, the roll-out of a complete and disruptive 5G system is still long way ahead, and necessitates resolution of many pending technical, standardization and design challenges.

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