5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice

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***Abstract*— There is considerable pressure to define the key requirements of 5G, develop 5G standards, and perform technology trials as quickly as possible. Normally, these activities are best done in series but there is a desire to complete these tasks in parallel so that commercial deployments of 5G can begin by 2020. 5G will not be an incremental improvement over its predecessors; it aims to be a revolutionary leap forward in terms of data rates, latency, massive connectivity, network reliability, and energy efficiency. These capabilities are targeted at realizing high-speed connectivity, the Internet of Things, augmented virtual reality, the tactile internet, and so on. The requirements of 5G are expected to be met by new spectrum in the microwave bands (3.3–4.2 GHz), and utilizing large bandwidths available in mm-wave bands, increasing spatial degrees of freedom via large antenna arrays and 3-D MIMO, network densification, and new waveforms that provide scalability and flexibility to meet the varying demands of 5G services. Unlike the one size fits all 4G core networks, the 5G core network must be flexible and adaptable and is expected to simultaneously provide optimized support for the diverse 5G use case categories. In this paper, we provide an overview of 5G research, standardization trials, and deployment challenges. Due to the enormous scope of 5G systems, it is necessary to provide some direction in a tutorial article, and in this overview, the focus is largely user centric, rather than device centric. In addition to surveying the state of play in the area, we identify leading technologies, evaluating their strengths and weaknesses, and outline the key challenges ahead, with research test beds delivering promising performance but pre-commercial trials lagging behind the desired 5G targets.**

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***Index Terms*— 5G, massive MIMO, beamforming, trials, testbeds, waveforms, cloud ran, next generation core.**

I. Introduction

THE mobile access technology is going through a revolutionary change every ten years. Each generation of mobile technology has also provided significant performance enhancements. These rapid changes are in response to the capacity demands resulting from the massive data growth over the last ten years, posed mainly by video. The video resolution capability is also increasing and handsets supporting 4K video will need a data rate of 15.4 Mbps per user (using H.265 profile 5.1, 4K resolution at 64 fps and Chroma ratio 4:4:4) [1]. The viewing time of users is also increasing; it is becoming the norm for users to watch full-length TV programmes and movies via streaming video. There seems to be no saturation in sight to this trend. The demand for content will continue to grow at extreme rates, outstripping forecasts. Annual mobile traffic is expected to increase to 291.8 exabytes by 2019 [2].

However the usage patterns of 5G (IMT 2020) are not just limited to mobile broadband. In fact, IMT 2020 is envisaged to support a diverse variety of usage scenarios/use cases in three broad categories:

- Enhanced mobile broadband (eMBB): This is more of what we have today but with improved performance and an increasingly seamless user experience. This usage scenario covers a range of cases, including wide-area coverage and hotspots. For the wide area case, seamless coverage and high mobility are desired, with much improved user data rates compared to that offered today. For hotspots, the support of high user density, and very high traffic capacity is needed, but the requirement for mobility is at pedestrian speeds only. Note that the required user data rate is much higher than that of wide area coverage.
- Ultra-reliable and low latency communications (URLLC): Here we have stringent requirements for reliability, latency and availability. Some examples are tactile internet applications [3], intelligent transport systems, vehicle-to-everything (V2X), transportation safety, remote medical surgery, smart grids, public protection and disaster relief, wireless control of industrial manufacturing, etc.
- Massive machine type communications (mMTC): A family of applications for which the traffic patterns are not even fully characterised. However, we do know that an

TABLE I

MINIMUM TECHNICAL PERFORMANCE REQUIREMENTS OF IMT 2020

KPI	Key Use Case	Values
Peak Data Rate	eMBB	DL: 20 Gbps, UL: 10 Gbps
Peak Spectral Efficiency	eMBB	DL: 30 bps/Hz, UL: 15 bps/Hz
User Experienced Data Rate	eMBB	DL: 100 Mbps, UL: 50 Mbps (Dense Urban)
5% User Spectral Efficiency	eMBB	DL: 0.3 bps/Hz, UL: 0.21 bps/Hz (Indoor Hotspot); DL: 0.225 bps/Hz, UL: 0.15 bps/Hz (Dense Urban); DL: 0.12 bps/Hz, UL: 0.045 bps/Hz (Rural)
Average Spectral Efficiency	eMBB	DL: 9 bps/Hz/TRxP, UL: 6.75 bps/Hz/TRxP (Indoor Hotspot); DL: 7.8 bps/Hz/TRxP, UL: 5.4 bps/Hz/TRxP (Dense Urban); DL: 3.3 bps/Hz/TRxP, UL: 1.6 bps/Hz/TRxP (Rural)
Area Traffic Capacity	eMBB	DL: 10 Mbps/m^2 (Indoor Hotspot)
User Plane Latency	eMBB, URLLC	4 ms for eMBB and 1 ms for URLLC
Control Plane Latency	eMBB, URLLC	20 ms for eMBB and URLLC
Connection Density	mMTC	1,000,000 devices/km^2
Energy Efficiency	eMBB	Capability to support high sleep ratio and long sleep duration to enable low energy consumption when there is no data
Reliability	URLLC	$1{-}10^{-5}$ success probability of transmitting a layer 2 protocol data unit of 32 bytes within 1 ms in channel quality of coverage edge
Mobility	eMBB	Up to 500 km/h
Mobility Interruption Time	eMBB, URLLC	0 ms
Bandwidth	eMBB	At least 100 MHz; Up to 1 GHz for operation in higher frequency bands (e.g., above 6 GHz)

mMTC deployment could consist of a very large number of devices with a relatively low (or relatively high) volume of non-delay-sensitive data. Devices are required to be low cost, and have a very long battery life.

A. 5G Requirements

The minimum technical performance requirements for 5G were recently approved in [4]. There are a number of key performance parameters (see [4] for their definitions). The values are given in Table I along with the use case for which they are relevant.

B. Spectrum Regulation

5G is likely to be introduced in multiple frequency bands. The existing bands are lower than 6 GHz (referred to as microwave bands) have limited bandwidth and are currently heavily used. To meet growth, WRC-15 also approved a number of candidate frequency bands in the mm-wave range from 24 - 100 GHz. Specifically, the following bands were approved for study (in GHz: 24.25 - 27.5; 31.8 - 43.5; 45.5 - 50.2; 50.4 - 52.6; 66 - 76; 81 - 86). These bands provide a considerable amount of new bandwidth. A final list of the bands will be approved by WRC-19. In addition to the above licensed bands, spectrum in the unlicensed bands (60 GHz) may also be used. A judicious combination across all bands is likely to be important for 5G. This could include: lower frequencies for wide area coverage, high rate mm-wave links for local and personal area communications, and short range indoor links in the unlicensed spectrum range of the mm-wave bands [5].

The new spectrum, especially in the mm-wave bands, may be managed via a licensed access mechanism, as is the case now, or via new approaches being considered in [6]. There are existing satellite and fixed services in the mm-wave bands which would need to co-exist with future services (mobile access, fronthaul and backhaul). A licensed approach amongst multiple operators may result in congestion [7]–[9] so that novel forms of spectrum access [6], beamforming and coordination [10] may be required. These rely on:

- beamforming (analog, digital and hybrid) see Sec. IV;
- coordination (information sharing);
- extent of shared spectrum (partial or full).

Co-existence and cooperation between cellular and WiFi systems in the unlicensed 2.4 GHz and 5 GHz bands (where up to 500 MHz is available) was proposed in [11]. This work suggests that a combined licensed and unlicensed approach to spectrum management may be more beneficial for the public good. While the study in [11] was only for the two particular bands, the principles could also apply to the mm-wave bands.

C. Standardisation for 5G

The standards for 5G are to be approved by the ITU-R. Working Party (WP) 5D is currently preparing evaluation criteria [4] to be followed by submissions of proposals and evaluation of candidate technologies. This process is expected to be completed by late 2019, leading to the first certified 5G standards. ITU-T has recently completed a study into networking innovations required to support the development of 5G systems through a Focus Group on IMT-2020 as part of Study Group 13. This study takes a system-wide view of 5G architectures and also encompasses Proof-of-Concepts.

3GPP is following a process of standardisation [12] that aligns with the ITU-R timeline [13]. 3GPP publishes major releases roughly once per year and is currently conducting study items for both RAN and Core aspects of 5G within the Release 14 window which is due to complete in March 2017. Standardisation of 5G technology is broken into two phases. The goal of this phased standardization approach is to complete initial specifications to allow deployments in the 2020 timeframe. Phase 1 will be completed by September 2018 in Release 15. Phase 2 will incorporate more functions to extend the capabilities of 5G to progressively support more services, scenarios and much higher frequency bands (e.g., above 40 GHz). Phase 2 will be completed around the end of 2019 in Release 16.

Some key decisions have been reached in the Release 14 study phase such as the focus on eMBB and URLLC use cases, non-standalone operation of the New Radio, interworking back to the existing EPC (enhanced packet core) through the eNodeB acting as the anchor cell (which in turn is based on the Dual Connectivity principle - see Fig. 1).

IEEE has recently begun a 5G track to oversee the roadmap of enhancements that will occur for numerous existing and new IEEE technologies such as: 802.11ax and 802.1 lay (WLAN), 802.15 (short range technologies), 802.22 (Fixed Wireless Broadband), P1914.3 (fronthaul solutions to support Cloud RAN), P1918.1 (tactile and haptic Internet). Timelines for completion vary for the individual specification groups.

D. Key Contributions

In this paper we provide an extensive discussion and summary of key 5G issues at a time where the race to 5G deployment is accelerating and many pre-commercial trials are being performed around the world. The introduction sets the scene with 5G targets, spectrum regulation and standardization progress. Section II outlines the key technologies that are becoming widely accepted as the route to 5G performance. New developments in channel models with a 5G focus are discussed in Sec. III. Here, the focus is on both models and measurements which attempt to capture some of the increasingly important aspects of 5G channels, such as massive distributed arrays, mm-wave propagation and small cells. Signal processing methods at both ends of the link are surveyed in Sec. IV. Here, an emerging consensus is discussed where linear processing on multi-user links dominates, with a focus on low-complexity structures such as hybrid beam-forming. The importance of massive MIMO brings antenna layouts to the fore and these are discussed in Sec. V. It is noteworthy that fundamentals such as waveforms and channel access are agreed for phase 1 and Sec. VI provides an overview of the leading contenders and their merits. The current state of play in terms of achievable performance with current trials and test-beds is outlined in Sec. VII. Here it is shown that while test-bed results are promising, the tests remain very limited and the technology trials are not yet attaining all 5G targets. New core network and cloud RAN architectures are essential for 5G to satisfy the simultaneous requirements of diverse use cases. Also, densification and small cells using mm-wave are driving a change to deployments using HetNet concepts and dual connectivity. These are discussed in Secs. VIII and IX.

II. Key Technologies for RF Interface(s) of 5G

The requirements in Table I are hugely challenging. There are diverse capacity and quality of service requirements to be met and one size (access and core technology) may not fit all. For example, the peak rate, even though it is a marketing

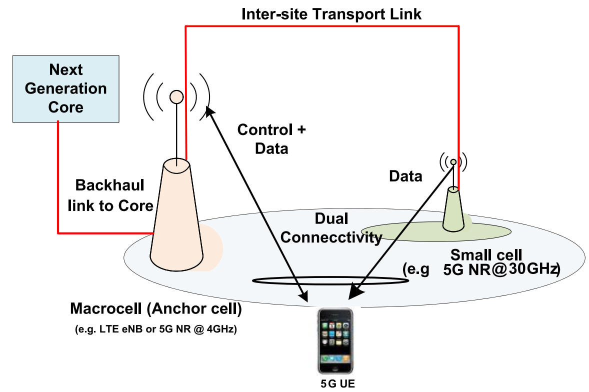

Fig. 1. Dual Connectivity Deployment Architecture.

number and is for ideal conditions, determines the maximum bandwidth and spatial degrees of freedom, modulation and coding supported by the radio access technology. The user experienced data rate (the 5% point of the CDF of user data rate), influences cell sizes and the need to support interference mitigation techniques (as cell edge SINRs are quite low). The high area capacity points to network densification via small cells. The low latency requirement requires the need of smaller transmit time intervals. The requirement of high energy efficiency requires low power consumption when there is no data to transmit. All this and more points to new radio access technologies and a new core network (as described in Secs.VI and VIII).

The capacity gains may be achieved from the aspects listed below. Taken together they are expected to provide a 1000 times gain relative to what is achievable today.

- **Increased bandwidth**. Mobile systems today are widely deployed in the microwave bands (less than 6 GHz), and the bulk of the deployments use frequencies below 3 GHz. This spectrum is hugely congested. In contrast, there is plenty of spectrum available in the centimeter and mm-wave bands (28-300 GHz) and wide carrier bandwidths of the order of 1 GHz are possible. However, some 5G deployments may have two layers: a macro layer in the microwave bands that provides user plane traffic and control plane signalling and a micro layer in the mm-wave band that carries user plane traffic (see Fig. 1). The control plane for both layers is carried over the macro layer.
- **Massive MIMO antenna arrays at the base station** [14], [15]. The use of higher frequencies makes it possible to deploy large scale antenna arrays at the base station, which are used to provide array gain to overcome higher path loss and provide spatial multiplexing gain. Typical antenna numbers under consideration for the base station vary from 256 to 1024 for the mm-wave bands. The antennas consist of cross polarized elements arranged in a two dimensional array (2D). The array may also consist of constituent sub-arrays [16]. The antenna elements may further consist of groups of dipoles or patch antennas in order to achieve the desired gain. (For example, two dipoles per element are required to offer a gain of 5.2 dBi/element).

- **Advances in MIMO**. The use of 2D arrays and multi-user precoding enables simultaneous transmission to multiple users distributed both in azimuth and elevation. The number of simultaneous users is limited by the maximum number of spatial streams the base station and environment can support. This is in turn dependent upon the user locations and signal processing methods deployed [17]–[23]; see also Sec. IV.
- **Network densification**. This will result in traffic offloading to small cells [24] (with coverage in the tens of meters) especially for indoor hotspots and dense urban micro cells. High density deployments of small cells will off load the user plane traffic but will still need macro cell coverage (in the microwave bands) to carry the control plane traffic. Increasing cell density may also result in increased other cell interference that will in turn affect any capacity gains. In fact, there is a belief [25] that, dependent on the short range pathloss scenario, an unlimited increase in the number of small cells may be counterproductive due to other-cell interference (OCI). However, interference mitigation techniques such as cooperative scheduling, COMP [24], [26], etc., will also combat OCI and therefore contribute to improved spectrum efficiencies especially for the cell edge rates [27]. These techniques are already in use in IMT Advanced systems [28]. Furthermore, 5G antenna arrays will have a much narrower beamwidth than existing sectoral antennas and the interference levels may be reduced.
- **New waveforms**. 5G will require a new radio interface as discussed in Sec. VI and in [29] and the references therein. The use of OFDMA in LTE is suitable for large data transmission. However, for mMTC, the packet size is usually quite small. The overhead associated with orthogonal transmission such as scheduling, resource request/grant and time alignment signaling is very large when large numbers of devices are connected. In addition, scheduled data transmission usually has a large latency due to the request and grant mechanism. A new multiple access scheme is desirable to overcome the above issues.

III. Channel Characteristics

The performance of 5G systems is ultimately limited by the propagation channels they operate in. It is thus vital to investigate the channel characteristics that are relevant for 5G systems, in particular those that have not already been explored for earlier-generation systems. In this section we provide a very brief review of channels for massive MIMO, distributed systems, and mm-wave systems. Other important aspects such as device-to-device (including vehicle-to-vehicle) communication are omitted due to space reasons, see, e.g., [30] for a more comprehensive overview.

A. Massive MIMO Channels

In principle, a double-directional channel model [31] describes the propagation channel for any array, whether a MIMO system is massive or not. However, several important exceptions exist:

1) Spatial Nonstationarities: When MIMO arrays become very large, it is possible that the strength (not just the phase) of the multipath components (MPCs) varies over the array [32]. When this occurs, channel hardening, as well as the possible diversity gain, reduces compared to the values one would expect in an ideal scenario. Furthermore, when the array becomes very large, the wavefront curvature (and - depending on the bandwidth of the system - even the runtime across the array) can become relevant and has to be incorporated into the model (these latter effects can be handled by a geometric modeling approach, see Sec. III-D).

2) Elevation Characteristics: Due to constraints on the form factor, massive MIMO arrays will almost certainly be 3D (planar or cylindrical arrays), and separate users in both azimuth and elevation domains. Thus, channel models that provide elevation characteristics are important for 5G [33] Elevation spectra at the UE show a larger spread than at the BS [34], but are more difficult to exploit, since large arrays are usually not present at the UE. Elevation spreads at the BS are typically less than 5° in outdoor environments [35]–[37]. The main propagation is usually over rooftops; other contributions can come via far scatterers, or waveguided through street canyons [38]. The 3GPP channel model has been generalized to include the elevation of MPCs at the BS [16].

3) Model Simplifications: While not a new physical effect, several modeling simplifications made for standard MIMO systems lead to unacceptable errors in massive MIMO systems; a very important case in point is the number and amplitude distribution of the MPCs.

With arrays that can form beams that are significantly narrower than a cluster, the correct modeling of intra-cluster parameters becomes a significant issue. In the EU-project MAMMOET, a massive MIMO channel model based on the COST 2100 approach was developed taking the first steps in this direction [39].

B. Channels for Distributed Systems

5G systems will encompass multi-user MIMO as well as distributed BSs, be it in the form of cloud RAN systems or cooperative multipoint (CoMP). For multi-user MIMO, the joint channel conditions for multiple users have to be provided - under many conditions this is equivalent to modeling the evolution of the channel as a single UE moves on a trajectory to different locations in the cell. This "spatial consistency" has been modeled in geometry-based stochastic channel models and quasi-deterministic models in the past (3GPP models are currently being modified to incorporate it as well).

A bigger challenge is the modeling of links from a single UE to multiple BSs. Much earlier work concentrated on the correlation of shadowing between different links. More recent measurement campaigns [40], [41] have quantified the correlation of other parameters, such as angular spreads, delay spreads, and mean directions. Significant correlation can exist even if the BSs are far away from each other; Correlation of BSs can be modeled through the concept of common clusters, i.e., clusters that interact with MPCs from different users [42]. If those clusters are, e.g., shadowed off, it affects the power (and angular and temporal dispersion) of multiple users simultaneously, a concept adopted in the COST 2100 model.

C. Millimeter-Wave Channels

Millimeter-wave (mm-wave) channels experience some fundamentally different propagation effects, such as noticeable atmospheric absorption for longer links, reflection on surfaces with a roughness that is comparable to the wavelength, and poor diffraction. We can thus anticipate that attenuation and dispersion characteristics, which determine system performance, will also be significantly different. Due to the large number of publications, the following sections can only cite a few representative examples; and while many important mm-wave channel measurements have been done over the past 30 years, we mostly cite here recent papers.

1) Basic Propagation Phenomena:

a) Free space pathloss: While there is a widespread assumption that mm-wave channels suffer from high free-space pathloss, textbooks (e.g., [43, Ch. 4]) have long pointed out that this is true only if the antenna *gain* is assumed to be independent of frequency. Pathloss becomes independent of frequency when the antenna *area* at one link end is kept constant (and actually decreases when the antenna area at both link ends is constant), since at higher frequencies higher antenna gain (for a constant area) is possible. Equivalently, one can say that for the same geometrical aperture, a mm-wave antenna array can accommodate a larger number of antenna elements, and thus provide narrower beamwidth and higher gain than a cm-wave antenna.

b) Atmospheric attenuation: At mm-wave frequencies, the atmosphere can become absorbing, attenuating the received signal as $\exp(\alpha_{atm} d)$, where d is the distance between TX and RX. The attenuation coefficient, α_{atm}, depends on the frequency as well as atmospheric conditions such as fog, rain, etc. [44], [45]. For the cell sizes anticipated for 5G systems at mm-wave frequencies (less than 200 m), atmospheric attenuation will not contribute more than a few dB to the pathloss except in the most severe conditions, such as tropical rainstorms.

c) Vegetation attenuation: Mm-waves are much more sensitive to blockage by foliage. The attenuation usually increases with the "length of the path traveled through foliage", though this attenuation saturates for long distances as the paths around the canopies become dominant [46]. Dependence of the attenuation coefficients on the type of trees, season, BS elevation, etc., is an ongoing topic of research [47], [48].

d) Outdoor to indoor penetration: A large number of cellular users are located indoors, and coverage by outdoor base stations would be a major goal for 5G systems. However, penetration through windows and house walls is more attenuated at higher frequencies. The actual values of the attenuation strongly depend on the material. While "post and drywall" dwellings have less than 10 dB attenuation, steel concrete or brick buildings, in combination with energy saving windows, can impose 20-40 dB loss (see Fig. 2).

e) Shadowing by objects: Since mm-waves do not effectively penetrate, or diffract around, human bodies and other objects, shadowing by these objects is an important factor in the link budget and the time variance of the channel. We can distinguish the following main effects: (i) the person holding the UE induces an effective antenna pattern that has nulls in the directions in which the torso or head is located; in combination with the angular spectrum of the propagation channel at the UE, this will determine the overall channel [50]. (ii) a person or object blocking the line of sight between a BS and a UE can cause an attenuation typically around 20 dB [51], with similar values for trucks [52], [53]. (iii) people (or other objects) moving in the vicinity of the target UE can increase the received power, since radiation is scattered off them, and thus can enhance the overall received power [51].

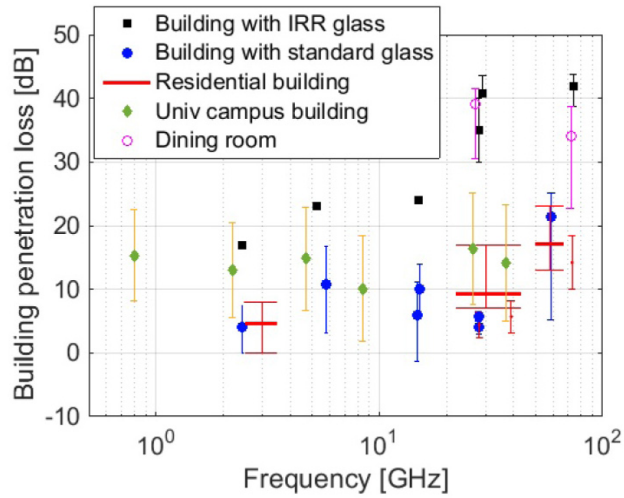

Fig. 2. Effective building penetration loss; bars indicate variability for a given building. From [49].

f) Channel sparsity: It is widely believed that mm-wave channels are "sparse". However, determination of the actual number of MPCs in outdoor experiments is challenging due to the limited resolution of the horn antennas used in most experimental setups. On the other hand, a lower bound on the channel sparsity can be established from those measurements, and in many environments the percentage of delay/angle bins with significant energy is rather low, though not necessarily lower than at cm-wave frequencies [2].

2) Measurement and Evaluation Techniques: Measurement of the characteristics of mm-wave channels is complicated by the cost of equipment as well as the sensitivity to nonidealities. Due to the short wavelength, the impact of phase noise, as well as errors in distance between antenna elements of an array, is an order of magnitude larger than for cm-wave systems.

For these reasons, outdoor measurements either lack directional resolution (i.e., with either directional or omnidirectional antennas at both link ends, but in any case the angular distribution of the radiation was not measured) [54], [55], or directional resolution was obtained by mechanically rotating a directional (horn) antenna, and measuring the impulse responses for each horn orientation (these measurements then have an angular resolution essentially determined by the beamwidth of the antenna), e.g., [2], [56], [57]. This is in contrast to sub-6GHz measurements, where directional evaluations using switched arrays in conjunction with superresolution techniques provide accurate directional information.

For indoor measurements, rotating horn antennas or virtual arrays (in combination with vector network analyzers to provide phase stability) have been used. In the latter case, evaluation of the measurements with superresolution algorithms, such as SAGE, can be made [58]; the same can be achieved with electronically switched horn arrays [59]. This allows to evaluate the number of MPCs and obtain insights into the intra-cluster characteristics.

3) Key Outdoor Results: A key result of outdoor measurements is that the pathloss coefficient at mm-wave frequencies is similar to that of below-6 GHz spectrum in many situations. Specifically, for LOS situations, the pathloss coefficient is in the range of 1.6-2.1 (it would be 2 for pure freespace) For NLOS situations, the pathloss coefficient is typically between 2.5 and 5 (e.g., [2,56,62]). There often is no strong frequency dependence beyond the f^2 dependence of free-space pathloss [60], [61].

However, the variance of the pathloss around the distance-dependent mean is considerably larger at mm-wave frequencies. Thus the probability of outage is higher, and appropriate countermeasures have to be taken. The standard deviation of the pathloss is also a strong function of distance, increasing from typically 5-10 dB at 30 m to more than 20 dB at 200 m [62]. Recent work shows that this effect may not actually be due to shadowing, but rather that different streets (and different cells) have different pathloss coefficients (ranging from 0 to more than 10), so that very different power levels are experienced in different streets [63].

A large range of delay spreads have been measured or simulated by ray tracing in outdoor environments [2], [56], [57], [64], [65]. Astonishingly, the reduction of the delay spread by beamforming, while noticeable, is not overwhelming - a factor of 2 or 3 is typical [66]. Another important issue is the frequency dependence of the delay spread: various papers in the literature show different results, which are strongly related to the use of different dynamic ranges and post-processing methods. This throws in doubt whether rms delay spread is the best measure for quantifying delay dispersion for these systems (delay windows, i.e., the window that contains $x\%$ of the energy of the power delay profile), might be better suited.

The angular dispersion is critical because it determines the type of beamforming, and the achievable gain. For many outdoor environments, the rms angular spread at the BS is on the order of 10°, and only a single cluster can be observed, e.g., [56], [67]. However, a number of measurements have observed multiple clusters, which provides the possibility of beam-switching to enhance robustness, when the main direction becomes blocked by a moving obstacle [2]. At the UE, angular spreads are considerably larger, often in the range 30-70° [2], [56], [67], [68]. While ray tracing generally predicts the angular spreads at the BS well, it tends to significantly underestimate the angular spreads at the UE, because many scattering objects such as street signs, parked cars, etc., are not included in geographic databases used for ray tracers [62].

For fixed wireless access, the temporal Rice factors describe the relative importance of time variations compared to the fixed component. Rice factors of the order of 20 dB at shorter distances, decreasing to a few dB at large distances, have been measured. This indicates the importance of compensating for and/or exploiting temporal fading even in these scenarios [69].

4) Key Indoor Results: Results in indoor environments are largely for office environments and hotspots such as lobbies, malls, train stations, etc. The pathloss coefficient is on the order of 2-3 in NLOS, and 1.2-2 in LOS [70], [71]; some results in office environments suggest a two-slope model, as propagation to larger distances involves either penetration through multiple walls, or at least one diffraction [72]. Again, these values are similar to what is observed at lower frequencies, but with a higher outage probability (due to shadowing by persons blocking the LOS, as well as highly absorbing steel-concrete walls). The frequency dependence of the pathloss is more pronounced in indoor environments than outdoor; f^κ with $\kappa \approx 2.5$ was observed in [73].

Delay spreads in offices are often less than 5ns in LOS, and 10 - 50 ns in NLOS [74]–[76]. For hotspots, the NLOS delay spreads can range up to 150 ns [75]. The power delay profile is often described by a Saleh-Valenzuela model, though with the important modification that the PDP of each cluster is not a single-exponential decay $exp(-\alpha t)$ for $t \geq 0$ and 0 otherwise (when the cluster start at $t = 0$), but rather exhibits pre- and post-cursors of the strongest component [77]. The directional characteristics can be described by an extended SV model, with azimuth angles of the cluster centers typically described as uniform and intra-cluster azimuth dispersion with a Laplacian distribution, while elevation angles also have a Laplacian distribution with a spread of about 5° [78].

Another interesting characteristic is the number of MPCs observed in the measurements. High resolution evaluations tend to find larger number of MPCs and clusters than nondirectional or rotating-horn measurements [78], [79]. Also, Ref. [80] used Fourier beamforming with a very large virtual array ($25\times25\times25$ elements) and found that a significant part of the multipath energy is diffuse (or can be explained as a large number of discrete components), in contrast to the common assumption of sparsity in mm-wave channels.

D. Modeling Methods

Turning the measurement results into suitable models has been pursued mainly along three avenues: (i) 3GPP-type spatial channel models (ii) geometry-based stochastic channel models (GSCMs) [16][1] such as in COST 259/273/2100 [81], [82], and (iii) quasi-deterministic models. The main issues that such models aim to solve are (i) incorporation of shadowing by humans and objects, including the effect of nonstationarities induced by them, (ii) spatial consistency both with respect to multiple UEs and distributed BSs.

1) 3GPP-SCM: 3GPP, the standardization body for 5G cellular systems, is establishing a channel model that is to be used for the whole frequency range between 1 and 100 GHz.

[1]3GPP-type models are sometimes called GSCMs (even by 3GPP itself), but this is not in line with the definitions of GSCMs established since the 1990s, which model scatterer locations (instead of tap angles and delays, as in the 3GPP SCM).

There is currently an ongoing debate about whether the model should exhibit discontinuities at 6 GHz, or whether all parameters should have a smooth frequency dependence (in many cases, the parameters would actually be frequency-independent). In either case, the fundamental structure of the model would not change compared to the existing one used for LTE standardization. This implies that, e.g., the MPCs in each cluster have the same amplitude. Attempts are being made to introduce spatial consistency of the angles of arrival/departure, by defining the rate of change of these angles as a function of the movement of the UE (this is similar to fixing the location of the first/last scatterer an MPC sees, compare the "twin cluster" model of COST 273). Attenuation by humans/objects is described by a double-knife-edge diffraction model [83].

Irrespective of the final results of the ongoing deliberations, it must be emphasized that the 3GPP model is intended to *compare different systems under reproducible channel conditions*. It is *not suitable* for an absolute system performance evaluation; specifically it does not predict accurately how well a final 5G deployment will work. While this is true for most standardized models, it is especially valid for 3GPP models, which have to consider backwards compatibility, and fast simulation times that allow companies to produce results within the very short time between meetings of the system standardization groups such as 3GPP RAN 1. It is anticipated that the 3GPP model will also strongly impact the standardization of the ITU.

2) Geometry-Based Stochastic Channel Models (GSCM): In a GSCM, the geometric position of scatterers is determined by a probability density function, and the actual double-directional impulse response is determined from simplified ray tracing. This principle has been used (at least for the inter-cluster properties) in the COST modeling framework (COST 259, COST 273, COST 2100) for the past 15 years, and is able to inherently provide spatial consistency. The appearance/disappearance of clusters as the UE moves through the cell is governed by visibility regions (a cluster is "active" if the UE is in the visibility region of the associated cluster) [81]. The directions of the MPCs are derived from the location of the "first" and "last" scatterer cluster an MPC sees on its way from the TX to the RX. All propagation effects between those "twin clusters" are subsumed into a black box delay and attenuation, since the details of those aspects are not relevant for the overall effects [84].

GSCMs do not need any significant modifications for describing 5G systems - as mentioned above, spatial consistence and spherical wavefront effects are inherently provided, and shadowing by humans or objects can also be easily provided by introducing geometrical shapes of the shadowing objects (similar to the double-knife edge diffraction model in 3GPP).

3) Quasi-Deterministic Models: The quasi-deterministic models choose a deterministic geometry, from which they derive the "main MPCs" through a simple ray tracing or waveguiding (either restricted to single reflections, or incorporating multiple reflections). Each of these main MPCs is associated with a cluster of MPCs whose directions and delays are spread around the main MPC. Furthermore, additional smaller MPCs may exist that have completely stochastic distributions. This principle, first suggested more than 15 years ago [85], [86], was recently adopted by the EU projects METIS [65] and MiWeBa [57], and has been widely used by the companies involved in these projects. Just like GSCMs, these models provide inherent spatial consistency.

IV. Signal Processing Techniques for 5G

As discussed in Sec. I, the drivers of 5G signal processing techniques are highly diverse. Clearly, no single approach will handle such disparate needs and elements of 5G signal processing are being proposed from a wide range of recent technologies and algorithms.

A. The Big 3

As mentioned in the introduction, the big 3 technologies forming the backbone of 5G are densification [87]–[95], massive MIMO [15], [87]–[89], [92], [96]–[98] and mm-wave [17], [87], [88], [92], [99]–[105]. Densification brings with it increasing opportunities for small cells and HetNets [24], [89], [91], [106] and a corresponding increase in the importance of signal processing based on cooperation, coordination, interference cancellation and management, smart receivers and distributed arrays [87], [88], [106]–[108]. A combination of massive MIMO and mm-wave is also driving a change of focus of signal processing methods towards low complexity techniques with limited hardware, operating over potentially sparse, 3D channels with an increasing emphasis on TDD [17], [87], [88], [92], [99], [100], [102], [105], [109]. Essentially, these big 3 directions create signal processing challenges which are variations on long-established MU-MIMO problems. For this reason, the research community has made rapid progress in this area, but a close look at any particular technology reveals the associated challenges and trade-offs.

B. Other Contenders

Outside the big 3 and their associated signal processing methods, full duplex communications [89], [95], [110]–[112] continues to emerge as a serious option in 5G and aspects of CR (cognitive radio) are also envisaged as a possibility [92], [107], [113]. Of course, many other directions will play a role in 5G, notably D2D (device to device), V2V (vehicle to vehicle), M2M (machine to machine) and the whole range of IoT communications [88], [89], [94], [111], [114]–[116]. Signal processing approaches for these scenarios are not discussed here in order to focus the study on user-centric rather than device-centric communications.

C. MU-MIMO Downlink (DL) Processing

1) Linear Precoding: The workhorse of 5G DL signal processing is likely to be linear precoding [15], [87], [88], [97], [117] as it gives a good balance between complexity and performance [118]. Consider K users, with channels $\mathbf{H}_1, \mathbf{H}_2, \ldots, \mathbf{H}_K$, where N_s streams of data are sent to a total of N_r receive antennas at the K devices and $K \leq N_\mathrm{s} \leq N_\mathrm{r}$. The transmitter has N_t antennas and forms the precoded signal, $\mathbf{s} = \mathbf{F}\mathbf{x}$, where $\mathbf{F}$ is the precoder and $\mathbf{x}$

is the data. The global received vector at the K devices is $\mathbf{r} = \mathbf{HFx}+\mathbf{n}$, where $\mathbf{H} = [\mathbf{H}_1^T \mathbf{H}_2^T \ldots \mathbf{H}_K^T]^T$ is the global channel. The precoder is usually based on established techniques such as matched filtering (MF, $\mathbf{F} = \mathbf{H}^H \mathbf{D}_{\mathrm{MF}}$), zero-forcing (ZF, $\mathbf{F} = \mathbf{H}^H(\mathbf{HH}^H)^{-1}\mathbf{D}_{\mathrm{ZF}}$), regularized ZF [119] (RZF, $\mathbf{F} = \mathbf{H}^H(\alpha\mathbf{I} + \mathbf{HH}^H)^{-1}\mathbf{D}_{\mathrm{RZF}}$), signal to leakage based precoding (SLNR) and block diagonalization (BD), where the diagonal matrices, $\mathbf{D}_{(\cdot)}$, perform transmit power normalization. There remains interest in more powerful non-linear techniques, such as dirty paper coding, but it remains an open question whether such techniques will emerge as practical alternatives.

2) Hybrid Precoding: In traditional MU-MIMO systems, DL processing is performed digitally with CSI made available at the transmitter. With the advent of massive MIMO, especially at mm-wave frequencies, the need for large numbers of RF chains and the corresponding ADC/DACs means increasing power consumption, cost and complexity at the base station [19], [20], [87], [88], [120], [121]. As a result, hybrid beamforming (HBF) architectures (first suggested and analyzed in [122]) involving $N_{\mathrm{RF}} << N_{\mathrm{t}}$ RF chains are becoming popular, especially for mm-wave systems, where the processing is spread over both digital and analog domains [87], [88], [122]. A typical "fully connected" structure [17], [19], [20], [120] breaks the precoder down into $\mathbf{F} = \mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}$, where the $N_{\mathrm{t}} \times N_{\mathrm{RF}}$ analog precoder, $\mathbf{F}_{\mathrm{RF}}$, links the N_{t} antennas to the N_{RF} chains and performs analog phase shifting, while the $N_{\mathrm{RF}} \times N_{\mathrm{s}}$ precoder, $\mathbf{F}_{\mathrm{BB}}$ operates digitally (see Fig. 3).

Design strategies for HBF can maximize some performance metric over the feasible space of $(\mathbf{F}_{\mathrm{RF}}, \mathbf{F}_{\mathrm{BB}})$ which is limited by transmit power and phase shifting constraints (elements of $\mathbf{F}_{\mathrm{RF}}$ must have unit magnitude [19], [120]). Another common approach is to select a target precoder and minimize $||\mathbf{F}_{\mathrm{target}} - \mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}||$ over the feasible space [19], [123], [124].

A restricted version of this HBF approach occurs when the RF chains are not connected to all N_{t} antennas, but to a subset or sub-array (a partially connected architecture [17], [124]). Note that most arrays now envisaged are 2D or 3D in order to capture angular diversity in the channel over both azimuth and elevation domains [87], [125]. Many variations of sub-array design are possible, including both static and dynamic sub-array selection [18] and panel structures, but the motivation is the same: simplified circuitry and reduced RF losses. The impact on the design methodology is to add more constraints on the analog precoder as certain blocks of $\mathbf{F}_{\mathrm{RF}}$ are zero due to the lack of a connection from an RF chain to a set of antennas [124] (see also Sec. V).

Despite the constraints on HBF, it has been shown that fully digital performance can be obtained if $N_{\mathrm{RF}} \geq 2N_{\mathrm{s}}$ [23], [122]. Furthermore, the viability of HBF in mm-wave is supported by physical arguments as the envisaged sparsity of the mm-wave channel increases the importance of a few dominant ray directions which are well captured by analog processing. For this reason, many HBF algorithms use individual ray directions as well as global channel information in precoder design [19], [120]. In addition, many of the traditional DL precoders (eg. ZF: $\mathbf{F} = \mathbf{H}^H(\mathbf{HH}^H)^{-1}\mathbf{D}_{\mathrm{ZF}}$) essentially perform two-stage processing involving power inflation (in ZF this is $\mathbf{H}^H$ corresponding to MF) followed by diagonalization (in ZF this is $(\mathbf{HH}^H)^{-1}$). Hence, the basic hybrid structure is aligned with its digital counterpart. Note that in sparse channels, the number of streams that can be utilized will depend not only on N_{RF} but also on the number of clusters in the channel, which gives an indication of the inherent dimensionality.

Driving these techniques is the recognition that simple precoding is increasingly efficient as the system dimensions grow [15], [97], [98]. Despite this, many difficulties are still attached to these approaches. For example, a combination of massive MIMO with mm-wave results in the highly directional beams required to counter the high mm-wave pathloss, but these beams then pose challenges in attaching users, sensitivity to misalignment, adaptation and interference which is somewhat binary (ON or OFF) [87], [88].

D. MU-MIMO Receiver Processing

In the UL, linear processing is again dominant, especially for massive MIMO where even MRC becomes a possibility as well as interference mitigating receivers such as MMSE/ZF [15], [98], [117]. However, reduced complexity non-linear methods are still being considered [15], [126]. In the DL, lack of user coordination tends to mean that users concentrate on their own channels and MRC or SVD type receivers are common to maximize the power of the desired signal streams. Furthermore, the complex nature of 5G networks makes interference avoidance critical increasing the role for smart receivers in 5G [88], [90], [106], [108].

E. Other Important Approaches

1) Low Resolution Hardware: In addition to HBF, the use of low resolution or 1-bit ADC/DACs is another technique to improve power efficiency. Most current proposals for these systems [127]–[130] adopt standard linear processing techniques. However, the hardware limitations can be built into the signal processing methods [128] and this approach may grow in importance.

2) NOMA: NOMA [131]–[133] could be described as two-stage beamforming where a MU-MIMO technique (usually ZF) transmits beams in K directions and users in the same beams are separated using SIC receivers in the power domain.

3) SM: SM [134] is part of a broader class of index modulation techniques where various indices related to transmission (spreading code [135], sub-carrier [136], precoding matrix [137], etc.) also carry information in addition to data symbols. While these methods are not designed for large rate increases, they do allow some trade-offs inherent in 5G, by reducing RF chains and power consumption.

4) Cognitive Radio (CR): remains a possibility for 5G [92], [107], perhaps as a method to mop up the diverse traffic expected [113]. Current trends suggest that CR developments may be based more on efficient scheduling and interference management rather than on advanced sensing and signal processing.

5) Full Duplex Communications: is also important [89], but here the signal processing approaches are key to reduce self-interference, the dominant issue with FD. In addition to passive

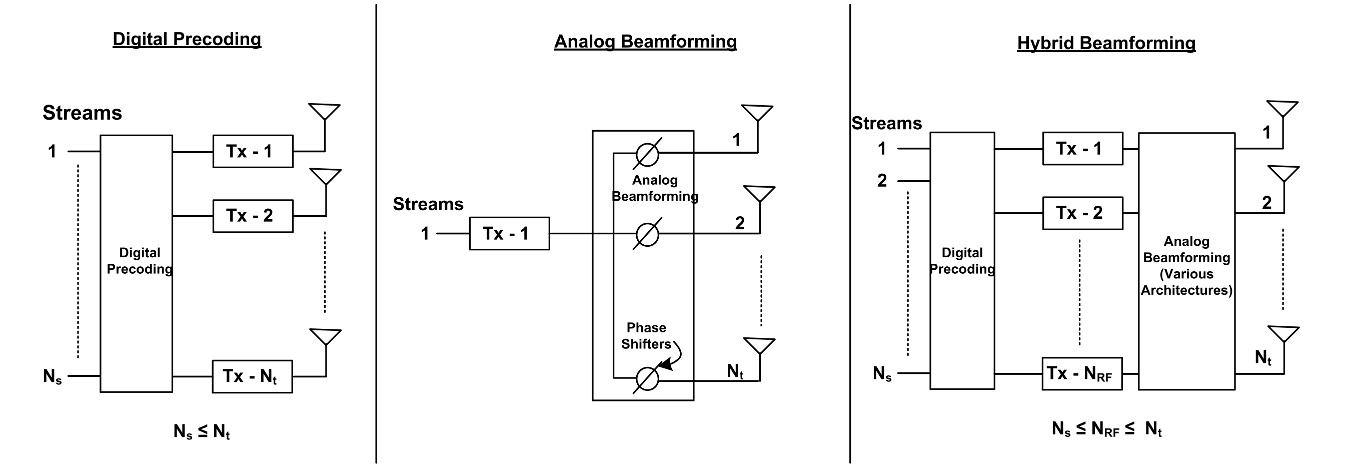

Fig. 3. Beamforming Architectures: A. Analog Beamforming, B. Digital Beamforming, C. Hybrid Beamforming.

methods such as directionality and antenna placement, signal processing is essential to further reduce self-interference both with RF and digital processing [110], [112].

V. Antenna Layouts

Large antenna arrays at the base station are envisioned for 5G systems and, for mm-wave systems, many antennas at the user equipment side are expected as well to guarantee minimum receive signal levels [88], [138], [139].[2] As the number of antennas increases it is advantageous to use 2D and 3D structures for the arrays [140]. This reduces the required space and also enables spatial separation and beamforming in two or three dimensions. For example, a 64 element uniform linear array with an inter-element spacing of half wavelength ($\lambda/2$) could occupy a horizontal span of 3 m at 2 GHz, which reduces to 1.5 m if dual polarized antennas are used [141]. In contrast, an 8×4 dual polarized array can be accommodated in a 0.6 m$\times$0.4 m space and can spatially resolve users and form beams in 3D [118], [142].

Antenna arrays may be arranged in a number of different ways, the most common architectures being uniform linear arrays (ULAs), uniform rectangular arrays (URAs), uniform circular arrays (UCAs) and stacked uniform circular arrays [143]–[145]. The system performance of these architectures is often measured in terms of beam gain and half power beam-width both in azimuth and in elevation.

For massive MIMO, in the sense of aggressive spatial multiplexing where no explicit beamforming is assumed, the antenna metric is a bit more involved. There, it is important to capture as many degrees of freedom of the channel as possible with a high number of effective antennas. For compact antenna arrangements this often leads to antenna structures that have shown to be effective for multidimensional channel characterization and parameter estimation, see [145] for an overview. However, massive MIMO used for aggressive spatial multiplexing also allows for fully or partially distributed arrays since no explicit beamforming is performed and antenna elements can be spread over a larger area without the limitations above. In the spatial multiplexing context, various antenna structures have been investigated in, e.g., [118], [146], [147]. The main conclusions from these investigations are that the performance improves as the array aperture increases, but the impact of the aperture is mainly visible when the users are closely grouped (i.e., they have high correlation). Furthermore, there is in general a good channel resolvability and the larger the aperture the larger the resolvability. One important aspect to remember, for physically large arrays, is that there can be large differences in received power levels over the array [148] which affects user resolvability.

For beamforming solutions the antenna elements in an array must be placed close together. All the analog components (phase shifters, low noise power amplifiers, etc) should be tightly packed behind the antenna elements (see Fig, 3(a) of [149]). The dense packing of antenna elements creates two main effects [150]: 1) spatial correlation, and 2) mutual coupling (see [143] for further discussion).

[2]The numbers of antennas on the UE will not be as large as the corresponding number at the BS, but could for mm-wave systems be much larger than what is used today.

VI. 5G New Waveforms and Channel Access

The large variety of 5G use cases and scenarios can be clustered into three major categories as discussed in Sec. I: eMBB, mMTC and URLLC. In addition, following [151], [152], 5G has to be flexible enough to meet the connectivity requirements of existing and future services to be efficiently deployable on a single continuous block of spectrum. Moreover, the new 5G air interface should target a unified framework addressing all requirements, usage and deployment scenarios [152] including V2X communication. Altogether, such heterogeneity requires a very high degree of flexibility which rules out any one-size-fits-all solution. Key enablers for a flexible 5G air interface are the applied waveform and the multi-user access scheme minimizing the risk of adopting costly and service-specific multiple radio interfaces.

A. Waveforms for the 5G Air Interface

Recent research (e.g. as part of the European projects 5GNOW [153], FANTASTIC-5G [154] and mmMAGIC [155]) has produced a plethora of waveform candidates depicted in Table III. A common theme among them is that they i) deliver reduced side-lobe levels relative to plain OFDM which uses the rectangular pulse shape, and ii) provide the degrees of flexibility for the envisioned service heterogeneity, forward compatibility, and future-proofing [154]. Many eMBB use cases target higher peak data rates, a higher per area capacity and the support a large number of users within a given area. Assuming synchronization in time and frequency, LTE OFDM is considered optimal from a capacity viewpoint, with a reasonable signal processing complexity when combined with MIMO and interference management. Yet, to support in-band coexistence of different services in a single 5G frame, OFDM suffers from a significant spectral efficiency loss due to the guard bands required to ensure sufficient signal isolation. OFDM is also known for its vulnerability to time and frequency offsets which can lead to severe inter symbol (ISI) and inter-carrier interference (ICI). Example scenarios are the highly asynchronous access of mMTC devices or the high Doppler shifts in V2X communication.

Another major aspect is that many URLLC use cases have very stringent requirements for successful packet delivery or demand very low end-to-end latencies requiring concerted latency optimization across all layers. Examples are wireless robot-to-robot communication in industrial automation which may allow/require a proactive and redundant resource allocation for an often a-priori known time and communication area/range. Therefore, the link establishment and control can be realized over a separated control plane while the Low Latency Communicatio (LLC) is performed directly in device-to-device (D2D) mode, avoiding an access point in-between [156]. Yet again, to support the flexibility and robustness for such advanced LLC coding and diversity schemes, as well as spectral containment, a flexible numerology in the frame structure is a key requirement for the 5G waveform. OFDM with its inflexible use of cyclic pre- and postfixes (CPs) as well as static configuration of physical layer parameters is not well suited to the such advanced frame structures. Hence, new waveforms based on advanced multi-carrier schemes equipped with filtering functionalities are widely seen as key for the design of a multi-service air interface. The requirements for numerology [157] and frame structure [158] for NR (New Radio) in 3GPP [159] consider mixed operations of eMBB, URLLC and mMTC and use the following design rules:

1) Subcarrier Spacing: It is proposed to be scaled as $\Delta_f \times 2^K$ (Δ_f = 15 kHz is the subcarrier spacing, K is some natural number). This is to achieve high multiplexing efficiency between different numerologies [157]. The subcarrier spacing varies with the frequency of the spectrum and/or maximum UE speed to minimize the impact of the Doppler shift and phase noise [160].

2) Number of Symbols per TTI: It is proposed to be scaled as 2^M (M: is some natural number) symbols per TTI. This is to ensure flexible TTI downscaling for URLLC from 2^M symbols to 1 symbol [157].

3) CP Length: CP length would be determined by deployment types (e.g. outdoor or indoor) that has different delay spread requirements, and/or determined by frequency bands, service type (e.g. unicast or broadcast) or determined by whether beam forming technology is used or not [160].

TABLE II

SUMMARY OF THE NUMEROLOGY CHOSEN FOR THE 5G PRE-TRIALS IN COMPARISON TO LTE [186]

Parameter	5G Pre Trial	LTE
Subcarrier Spacing	75 kHz	15 kHz
Sampling Time (Ts)	6.5 ns	32.5 ns
Sampling Rate	153.6 M sps	30.72 M sps
Subframe Length	0.2 ms	1 ms
Number of OFDM Symbols per subframe	14	14
Number of Subcarrier per RB	12	12
Max RB per Carrier	100 (per 100 MHz)	100 (per 20 MHz)
Length of Radio Frame	10 ms	10 ms
Number of subframes per Radio Frame	50	10

4) TTI Length: TTI length would be determined by service types that have different latency requirements, or determined by downlink vs uplink vs sidelink. Table II provides an example of the current 5G pre-trial parameterization compared to LTE Rel. 8-13.

In order to allow flexible deployment in the field for narrow band mMTC services, 3GPP LTE Rel.13 introduced NB-IoT deployable e.g. in-band or in guard band single-tone with a subcarrier spacing down to 3.75kHz.

3GPP decided that 5G New Radio (NR) phase 1 should stick to OFDM like waveforms as a base line with spectral confinement technologies such as filtering/windowing, keeping the forward option for combinations with use of other waveforms for phase 2. This includes, in particular, use cases beyond eMBB, which is the main focus in phase 1, which may require a more sophisticated selection and composition of physical layer components including waveforms. In particular this may becomes relevant for mm-wave communication and mMTC. The proposed candidates can be grouped into two categories, namely: subcarrier-wise filtered waveforms, comprising FBMC with OQAM [161] and QAM signaling [162], Pulse shaped OFDM (P-OFDM) [163], Flexibly Configured OFDM (FC-OFDM) [164] as well the Single Carrier (SC) family such as Zero Tail spreading OFDM (ZT-s-OFDM) [165], Continuous Phase Modulation Frequency Division Multiple Access (CPM-SC-FDMA) as well as Differential QAM (D-QAM) [155], Orthogonal Time Frequency Space (OTFS) modulation [211], and subband-wise filtered waveforms, comprising Universal Filtered OFDM (UF-OFDM) [166] and Filtered OFDM (F-OFDM) [167]. All these waveforms allow the flexible partitioning of the system bandwidth into separate subbands for a multi-service air interface. Flexible parameters include subcarrier number and spacing, pre- and postfix configuration, filter coefficients and the specific frame structure. They can be individually configured according to the requirements of a service, especially where OFDM reaches intrinsic limits like stable frequency confinement if e.g. transmit timing requirements cannot be fulfilled by timing advance (TA) compensation. Moreover, they all allow for typically high (or at least moderate for the SC family) spectral efficiency (SE) and low out-of-band (OOB) emission. Beyond these similarities, some specific properties, pros and cons are summarized in Table III. Among the subband-wise filtered solutions, UF-OFDM is fully MIMO OFDM compatible but can

TABLE III
SUMMARY OF WAVEFORMS FOR THE 5G AIR INTERFACE: PROS AND CONS

Scheme	Pros	Cons	Reference
FBMC OQAM	High SE, very low OOB, robust in asynchronous access	Not MIMO OFDM compatible, delay for short bursts	[161]
FBMC QAM	Subband wise configurability, asynchronous FDMA access support	Degredation due to non-orthogonality in some cases	[162]
P-OFDM	Robust to spectral and temporal offsets	Possible degredation due to time localization constraints	[163]
FC-OFDM	Co-existence of different waveforms in the same band	Not all features of each multiplexed waveform candidates can be maintained	[164]
ZT-s-OFDM	Low PAPR	Susceptible to temporal and spectral offsets	[165]
CPM-SC-FDMA	Low PAPR	Low SE	[155]
D-QAM	Low PAPR	Low MIMO compatibility	[155]
UF-OFDM	Subband wise configurability, coexistence with CP-OFDM	ISI in certain conditions with large delay spread	[166]
F-OFDM	Subband wise configurability, coexistence with CP-OFDM	ISI in certain conditions with large delay spread	[167]

introduce ISI for moderately large delay spreads. ZT-OFDM, with an adjustable zero tail, is robust to time and frequency offsets but its overhead scales with the tail. Among subcarrier-wise filtered multi-carriers, FS-FBMC as a derivative of FBMC has been shown to be more robust to large delay spreads in highly asynchronous mMTC scenarios at the expense of a highly reduced time localization and performance degradation for short bursts due to inter-symbol overlapping [168]. Moreover, it is not compatible with OFDM and has no intrinsic support for MIMO. QAM-FBMC offers a time-frequency localization trade-off with some performance degradation due to non-orthogonality. In P-OFDM the pulse shaping is a free design parameter with very good performance in large (symmetric) delay spreads but its length may be limited by delay constraints. FC-OFDM offers a flexible solution for multiplexing different waveforms in the same band, but not all features can be maintained.

Notably, while all OFDM/FBMC derivatives have considerably high PAPR values, the SC family has very low PAPR making it attractive for low-cost devices and wide-band beamforming in time domain. OTFS also offers robustness for fast UE movement and/or small packet sizes, and performance advantages for higher-order MIMO. Finally, it can be said that the overall complexity over the range of waveforms is controllable in all cases (but considerably higher for OQAM FBMC and P-OFDM) so that it is, in general, no show-stopper for the 5G use cases and scenarios.

B. Multiuser Access Schemes

While eMBB and URLLC can handle multi-user access (MA) in a scheduled manner, mMTC requires new MA schemes. Examples include battery driven sensors waking up to transmit data in a grant free fashion at minimum energy and with asynchronous channel access. Furthermore, contention based overloading may ask for new non-orthogonal MA schemes in the uplink. Here, [169]–[177] are proposed candidates considering parameters such as the support of contention based access, overloading capabilities and receiver complexity. The objective is to support data transmission at any time and everywhere, which can be efficiently achieved by macro cell deployments. Here, CP based OFDM imposes strict synchronization requirements [178], in particular, for uplink signals simultaneously transmitted by devices at different distances from the base stations. While for man-made communication the propagation delay can be continuously tracked and compensated during a session, for mMTC this is not possible due to the sporadic and rather short activity. In addition, MTC devices would need to run the entire connection setup procedure before sending data, which would result in a tremendous signaling overhead. Therefore, suitable combinations of waveforms and MA Schemes in the context of unified frame structure and agreed numerology are still subject to ongoing discussion in 3GPP.

VII. TRIALS, TEST-BEDS, AND DEPLOYMENT

Even though 5G standardization is still at an early stage, 5G prototypes, test-beds, and experimental technology trials have been in progress for several years, developed by universities, research institutes, vendors, operators and 5G related forums. Early 5G commercial deployments have been announced by various operators.

Test-beds for massive MIMO below 6 GHz have been developed and have successfully demonstrated that it is possible to achieve the gains predicted in theoretical studies in real-time real-life scenarios. The Argos test-bed [179] paved the way for fully digital solutions with 96 independent antennas and RF chains based on WARP boards. The Lund university massive MIMO test-bed, LUMaMi, encompassing 100 independent RF chains based on software defined radio units from National Instruments, demonstrated for the first time reciprocity based real-time massive MIMO operation [180] and later also reciprocity based operation in mobile scenarios with user movements of up to 50 km/h [181]. The same architecture is used for the test-bed at the University of Bristol encompassing 128 RF chains, where researchers from Lund and Bristol demonstrated a spectrum efficiency of 145.6 bps/Hz on a single 20 MHz radio channel with 22 simultaneous users. Facebook has developed a 96 antenna massive MIMO test-bed in the project Aries aiming to provide wireless connection in rural areas. In addition, Eurecom is working on a 64-antenna LTE compatible testbed based on their ExpressMIMO2 PCIe cards [182]. A detailed discussion of challenges, requirements, architectures and implementation issues for massive MIMO test beds can be found in [181].

Almost all major infrastructure providers, such as Huawei, Ericsson, Nokia, Samsung, ZTE, Datang Telecom, Qualcomm and Intel, have reported and showcased tests/trials with many-antenna systems. Multi-vendor trials have been announced by the China IMT-2020 promotion group (IMT-2020 PG) [183], CMCC [184], DOCOMO [185], the Verizon 5G Technology Forum (V5GTF) [186].

In January 2016, an IMT-2020 5G Promotion Group in China announced a three phase 5G network trial plan, spanning from 2016 to 2018, with the first phase test from September 2015 to September 2016. This phase was focused on key radio technologies and performance. The following building blocks of IMT 2020 were tested:

- Massive MIMO with different types of beamforming (analog, digital and hybrid) with fully and partially connected sub-arrays.

- Large bandwidths, ranging from 100 MHz to 1 GHz, with both single and multiple carriers.
- New multiple access techniques [187]: Sparse code multiple access (SCMA) [169], [188], multi-user shared access (MUSA), pattern division multiple access (PDMA) [189].
- New waveforms: Filtered OFDM (F-OFDM) [167], [190], universal filtered OFDM (UF-OFDM) [191], filter bank OFDM (FB-OFDM) [192].
- Higher frequencies: cm-wave. and mm-wave bands in the range 1.7 GHz −73 GHz.
- UDN: Ultra dense networks.
- New forward error correction: Polar codes.
- Single/multi-user scenarios with stationary/mobile users.

The phase 1 trial only demonstrated the feasibility of various building block technologies and showed that it is feasible to achieve some ITU 5G requirements such as a threefold increase in spectrum efficiency. The phase 2 trials of IMT-2020 PG will be conducted using a trial environment when more definitive conclusions can be obtained.

The joint trial organized by DOCOMO [193] includes major vendors' equipment. Table IV captures the main capabilities of the trial systems, where massive MIMO and mm-wave are two key technologies verified. The majority of the trials during 2015 and 2016 focused on eMBB scenarios over a wide range of frequencies ranging from 2 GHz up to 70 GHz. There are also trials targeting mMTC and URLLC and flexible numerology. More system trials with multi-cell interference are planned by DOCOMO for 2017 and 2018. A summary of the trials performed by DOCOMO is contained in [193].

Key observations on the trials conducted so far are:

- None achieved a single user peak rate of 20 Gbps DL: and 10 Gbps UL
- Most of the tests are for DL and only a few tests for UL.
- No tests are for a complete system where the impacts of other cell interference can be gauged or the benefits of the multiple layers determined.
- There is limited data on capacity distributions and they are conflicting. One test shows that maximum throughput is reached in the presence of LOS and the percentage of high throughput is therefore somewhat proportional to the LOS area. However, other tests showed that the presence of a dominant direct path decreases diversity, reduces throughput and this can only be mitigated by increasing antenna spacing at the base station.

In addition to the gaps and conflicting results contained in the trials, there are huge areas of 5G where even less is known. For example, there is limited information about any trials of mMTC, URLLC, and ultra dense networks. However, a simulation study of ultra dense networks was performed in [27] which shows that coordinated beamforming is needed to obtain an almost linear capacity increase with cell density. Increasing the cell density from 100 cells/km^2, the average throughput increased more than 500 times when co-ordination was performed over a 7 cell cluster. This is a spectacular increase in capacity! Without co-ordination the average throughput shows an asymptotic saturation at the cell density of 500 cells/km^2, but with co-ordination the throughput is doubled and shows no evidence of saturation.

TABLE IV

SUMMARY OF KEY CAPABILITIES TRIALLED (SEE [193])

	Huawei		Samsung		Ericsson		Nokia
Frequency	4.65 GHz	2.3 GHz	27.925 GHz	27.925 GHz	14.87925 GHz	14.9 GHz	73.5 GHz
System Bandwidth	200 MHz	100 MHz	800 MHz	800 MHz	730.5 MHz	400 MHz	1 GHz
Number of Component Carriers	10	5	1	1	8	4	1
Duplex (UL/DL)	TDD UL/DL Self Contained	TDD 4:4	TDD	TDD 4:34	TDD (UL/DL: 2:48)	TDD (UL/DL: 2:48)	TDD (UL/DL: 12:188)
Radio Access (DL/UL)	F-OFDMA	OFDMA	OFDMA	OFDMA	OFDMA	OFDMA	NCP-SC
Sationary/ Mobile	Mixed stationary and mobile users 30 km/h	Stationary	150 km/h	10-60 km/h	Mixed stationary and mobile users 3 km/h	3 km/h	Pedestrian
Single User/ Multi-user	SU/MU (12)	MU (24)	SU	SU	MU (2)	SU	SU
Peak Rate	11.27 Gbps (MU), 1.5 Gbps (SU)	–	3.77 Gbps	1.27 Gbps	21.6 Gbps (MU), 14.5 Gbps (SU)	5.5 Gbps	2 Gbps
Peak Spectral Efficiency (bps/Hz)	79.82 (MU)	43.9 (MU)	–	–	–	–	–
Coverage	500 m	75m	800 m (outdoor)	200 m (outdoor)	500 m LOS	30-100 m	60 m
Number of Antenna Elements at BS	192	64	48×2 = 96	48×2 = 96	64×4 = 256	8	64 switched beams
Number of Transceivers at BS	64	64	2	2	4	4	1
Number of Antenna Elements at UE	8	2	4×2 = 8	4×2 = 8	8	4	4
Beamforming Algorithm - Analog / Digital / HBF	HBF	Digital	HBF	HBF	Analog	No BF	Analog
References	[193]	[194], [195], [196], [197], [198]	[199]	[200]	[193], [201]	[200]	[202]

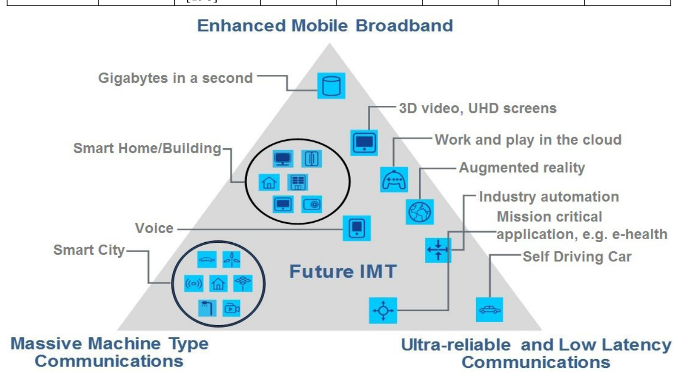

Fig. 4. IMT 2020 Use Case Categories [203].

VIII. 5G CORE NETWORK AND CLOUD RAN ARCHITECTURES

There are significant challenges for 5G in the core. These are discussed in this section.

The use cases driving the redesign of the packet core for 5G have been captured in the ITU-R document M.2083 [203], and are referenced in Fig 4. Within the 3GPP RAN architecture study item, there are currently two categories each with two variants for how to interconnect the RAN to the EPC or Next Generation Core (NGC) [204]. These can be summarised as:

- Stand-alone: a) RAN consist of New Radio (NR) only; b) RAN consists of Evolved E-UTRA only.
- Non-standalone: a) RAN consists of Evolved E-UTRA and NR with Evolved E-UTRA as the anchor RAT; b) RAN consists of Evolved E-UTRA and NR with NR as the anchor RAT.

The current view in 3GPP is to prioritize the non-standalone architecture with the option of reusing EPC or deploying NGC for Phase 1. The architecture of the base station itself, whether it be the existing eNodeB, Evolved eNodeB or NR is being redefined for Cloud RAN architecture.

3GPP have recently completed the service description and requirements for 5G captured in [205]. There are over 74 service and technical requirements which have been grouped into 4 broad categories (namely eMBB, URLLC, mMTC and V2X which is an extension of URLLC), see Table I.

The 5G core network will provide simultaneous support for the 5G use case categories. This flexibility and adaptability is a key distinguishing feature of the 5G core network. However it is likely that full support for the use cases will be split between phase 1 and phase 2 of the 3GPP 5G standards.

The requirement to support different core network configurations has already emerged for the existing 4G packet core. 3GPP have defined Dedicated Core Networks (DÉCOR) capability for operators to deploy networks supporting services like high data rate mobile broadband and low data rate Narrowband (NB) IoT. However, a further evolution is required for true flexibility and this is achieved by the adoption of Software Defined Networking (SDN), Network Function Virtualisation (NFV), Network Slicing, and Cloud RAN.

A. Software Defined Networking (SDN)

The motivation underpinning SDN is programmability of networks. This is achieved through the decoupling of the control and user plane. A highly scalable, distributed, stateless forwarding plane, is programmed with flow tables defining how packets are to be treated. The forwarding tables are populated by a centralised control plane entity which supports functions like mobility management, policy, subscription control and is able to maintain end-to-end path information for each service that the network supports.

When SDN is applied to the 3GPP Evolved Packet Core (EPC), the existing Functional Entities (FEs) such as Mobility Management Entity (MME), Serving Gateway (SGW), PDN Gateway (PGW) must be redefined because control functions exist in all entities of the current 4G core. A clear separation between control plane and user plane functions leads to the following FEs defined for the 5G core: Mobility Management Control Function (MMCF), Session Management Control Function (SMCF), Policy Function (PF), Subscriber Database Function (SDBF), Authentication Function (AuF), Application Functions (AF) and User Plane Function (UPF) [206]. The resulting architecture is shown in Fig. 5. 3GPP have notionally defined a new interface (NGx) between the key functional entities. Protocol realisations for NGx are yet to be developed.

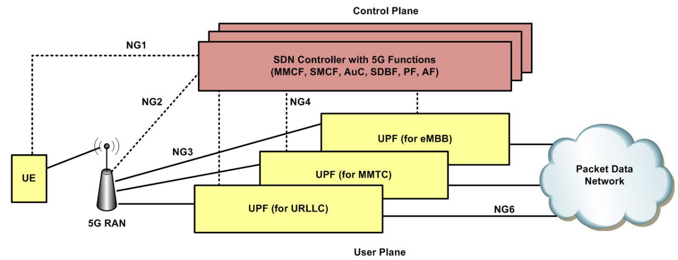

Fig. 5. SDN Enabled 5G Core Network.

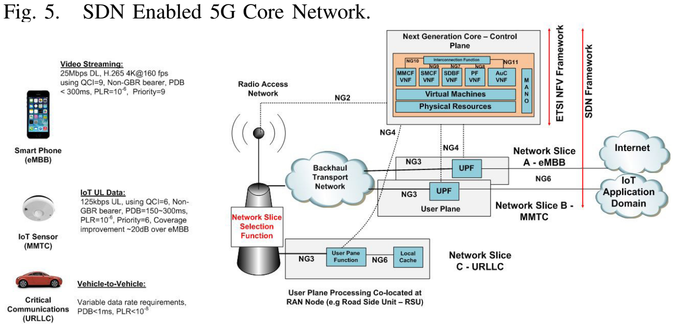

Fig. 6. SDN/NFV Supporting 5G Slicing.

B. Network Function Virtualisation (NFV)

The NFV architecture [207] when applied to NGC defines how virtualised software functions (such as the MMCF) can share common physical resources of compute, storage and networking through the creation of virtual machines (VMs). The VMs are instantiated either statically or dynamically through control functions defined in the Management and Orchestration (MANO) layer of the NFV framework.

While it is possible in theory to virtualise all FEs in the architecture and implement them on virtual machines, it may not always be the most optimal approach. Current research suggests that the next generation core network will consist of both Virtualised Network Functions (VNFs) and Physical Network Functions (PNFs).

C. Network Slicing

The new core network will allow network operators to define Network Slices tuned to particular service level agreements and KPIs (see Fig. 6). This is referred to as a Logically Isolated Network Partition (LINP) in [208]. The network slicing concept is key to the high level reference architecture adopted by the ITU-T Focus Group on IMT-2020 [209]. Although network slicing can in theory extend to the ability to dynamically instantiate and chain Functional Entities, it is envisaged that standardised profiles will be produced for the key use case categories defined in Table I for phase 1.

Fig. 6 also illustrates the current assumption that a Network Slice Selection Function (NSSF) exists in the RAN node to determine which slice the UE intends to utilise. Note that the network slices can be configured in multiple ways. A single control plane node can instantiate multiple user plane slices (as depicted in Fig. 6). Likewise, it is possible to have network slices with dedicated control and user plane nodes.

D. Cloud RAN Architecture

In a Cloud RAN (or C-RAN) architecture, the base station functions are split into the Remote Radio Unit (RRU) and Baseband Unit (BBU). The RRU is located at the base station site and the BBU is centralised in a data centre facility. Current C-RAN solutions utilise an optical transmission link between the two components (the fronthaul link using CPRI [210] transmission). The main benefits of C-RAN are that it:

- improves the effectiveness of inter-site scheduling and cooperative techniques (because inter-site signaling is internalised to the BBU pool);
- enables efficiencies through statistical multiplexing gains of pooled resources;
- enables the benefits of NFV to be applied to some parts of the radio protocol stack.

The current approach for C-RAN adopts the transport of digitised I/Q samples between RRU and BBU. The encapsulation of the I/Q samples onto an optical transmission link is defined in the CPRI specification. The bandwidth required for CPRI scales linearly with system bandwidth, antenna ports and sampling frequency. With 5G NR system parameters we will require CPRI line rates approaching the 12Tbps rate [204]. The current maximum line rate for CPRI is 24Gbps.

3GPP is investigating new approaches for how the signal processing functions can be split between the RRU and BBU. Various protocol splits between the RRC-PDCP-RLC-MAC-PHY layers are being considered in 3GPP. Each option results in different fronthaul bandwidth and delay requirements that vary significantly from 10s of Mbps to 10s of Gbps, and from 10ms to 150μs round trip time. The IEEE P1914 working group is developing specifications for transport of the RRU/BBU payload resulting from the various split options over packet transport networks. The CPRI specification group is also developing an enhanced transport solution called eCPRI which can use Ethernet transport as well as optical transport.

The various signal processing and protocol functions of a base station cannot be virtualised with a single hardware platform like in the Core Network. The processing performance (in millions of operations per second - MOPS) required for real time computation in physical layer functions (e.g. FFT/FEC) will still require ASIC or FPGAs. Higher layer functions like Radio Link Control (RLC) may be implemented with general purpose compute resources. Because of this, the Network Function Virtualisation Infrastructure (NFVI) layer of a BBU datacentre is more complex than that proposed for the Core Network.

IX. Deployment

While it is early days to give precise details on deployment challenges for 5G networks, we can begin to see areas that need planning work to begin now. The 3GPP study item in [204] captures the various deployment possibilities between the 4G/5G RAN and the Core Network (either EPC or NGC). Most operators will look first to deploy 5G adopting the Non-Standalone approach described in section VIII as this allows them to reuse their EPC.

There are many deployment challenges in the RAN and we touch on the key issues below. We also make the assumption that 5G RAN deployment will be based on option 3 and 3A (see fig. 7) of [204] from which the key transport and Core Network deployment issues are also identified below:

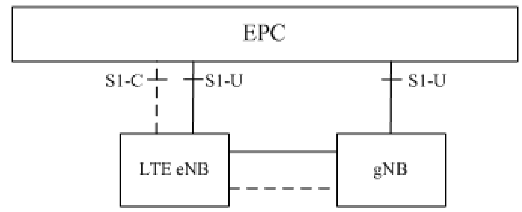

Fig. 7. Deployment option for 5G NR.

1) NR will be deployed in both microwave bands (3.3 to 4.2GHz is a popular choice) and higher frequency bands (24.25 to 27.5GHz, see section 1B). The use of other bands is likely to be part of phase 2. However if 5G is deployed on existing 4G sites, there is likely to be many coverage holes as the inter-site distances on these frequencies (i.e 20 to 200m) is much smaller than the present inter-site distances. Providing contiguous coverage would mean significant increase in site density.
2) The use of antenna arrays with numbers of antenna elements in the 100s is required but the placement of these antennas on existing structures has deployment issues especially posed by wind loading. Furthermore there are many options on the architecture of the antenna arrays as discussed in section V.
3) Beamforming strategies have been discussed in section IV but the number of RF chains is also restricted by EIRP levels.
4) Single or multi-stream transmission has an impact on precoding algorithms used at the transmitter. The support of peak rates requires multi-streams per user but at the cell edge only a single stream may be preferable. Therefore the choice of single and multi-stream transmission is not simple and may vary over the cell.
5) Channel measurements play an important part in performance prediction, signal processing algorithms, co-existence, and many hardware/software requirements of the radio. The body of mm-wave measurements in the published literature needs to be significantly enhanced so that real world performance can be predicted with confidence using the existing channel models (section III).
6) When the 5G NR is deployed in overlapping coverage, the techniques that will be defined to mitigate inter-cell interference will place requirements on how channel state information is shared in a timely manner. This in turn will place constraints on which transport and RAN architectures can be deployed.
7) A key decision that affects the deployment topology is whether the 5G NR will be deployed in the C-RAN architecture. When option 3 (or 3A) of figure 7 is used, there is a tight coupling to the existing eNodeB. In most cases today, the eNodeB is not deployed in a C-RAN configuration. To adopt C-RAN in 5G may require that the eNodeB location may become a mini-datacentre itself. This in turn has implications on resiliency, backhaul, and fronthaul.
8) If the 5G NR is deployed in locations without existing transmission facilities, there is an option to use self-backhauling. This would mean sharing capacity between backhaul and access.

X. Summary and Challenges

This paper has reviewed the road ahead for the commercial deployment of 5G and identified many of the corresponding technical challenges. Timelines are extremely challenging and deployment is something of a race against time, with many activities happening in parallel, standardisation in its early stages and proprietary hardware being trialled. Spectrum is not formally identified but it is assumed that some of it will be in mm-wave bands. There are many trials, but these are essentially for eMBB only, and even these are very limited; almost all of them are single cell and there are no results with other cell interference and how to mitigate its impact. Even in the single cell case, there is little data to show the performance of the UL and that 20 Gbps/10 Gbps peak rates can be achieved in DL/UL. There are no published trials yet on mMTC and URLLC; the connection density required to validate the requirements for mMTC is simply too large for a trial. Many of the fundamental parameters in the hardware are open for discussion and require finalising. For example, at the time of writing this article there remains a variety of views on waveforms and multiple access techniques for 5G, yet without this a fundamental building block of 5G is undecided.

Some of the key questions relating to 5G deployment are:

- There is widespread belief that mm-wave bands will provide large bandwidths but will this be one contiguous bandwidth or the aggregation of smaller bandwidth component carriers? Given the SNR decrease when bandwidth is increased, 100 MHz seems to be a practical size for a component carrier.
- Network densification is also a key part of the techniques needed to meet 5G capacity, but are there fundamental limits to densification set by intercell interference? Will these limits be less restrictive when antenna arrays that have narrow beamwidths are used?
- 5G will use active antenna arrays, but how many antennas and how to arrange them are key issues that need further study. The arrangement of antennas in a 2D array and the vertical/horizontal dimensions will depend on the angle spreads in azimuth and elevation. There cannot be a single optimal answer for every environment.
- Beamforming architectures that perform both analog and digital signal processing also need to have some of their parameters aligned with the environment and system. For example, the numbers of RF chains, the numbers of streams to be carried and the numbers of clusters in the environment are all interlinked.
- Having a good channel model is fundamental to any study of the physical layer. The data on channel models, especially for mm-wave bands, is very limited. More measurements are needed on the values of both large scale and small scale parameters for these channels.

Due to reasons of space, we have not reviewed many important 5G aspects. These include issues such as the protocol stack, handset designs, transport network requirements and compatibility. For example, the protocol stack architecture will impact the fronthaul needs, which will require some functional split between RF and base-band to avoid massive fronthaul rates. Nevertheless, all aspects of the protocol stack need further study. Very little is known about 5G handsets, such as how many antennas and RF chains will be accommodated in the handset? Current mobile technology uses Planar Inverted F Antennas (PIFA), but will this also be the case for mm-wave? Lastly, interaction with existing 4G, system flexibility over a wide range of bands and applications are identified as key requirements but no studies show any results in practice.

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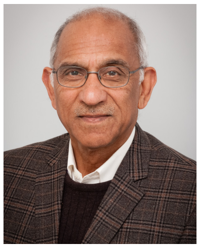

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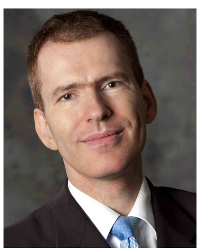

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