Enabling the Potential of 5G: Solutions to the Technical Challenges of the Diverse 5G Bands

Imadur Rahman, Thomas Chapman, Muhammad Ali Kazmi, and Farshid Ghasemzadeh

Introduction

During recent years, the 3GPP ecosystem has developed a fifth generation of wireless technology known as new radio (NR). The next generation specification aims to both improve the performance of mobile broadband and to expand the scope of mobile communications to encompass new so-called verticals (i.e., use cases related to specific industries). Examples of potential new areas include industry and automation, the evolving automobile industry, environmental technologies, the medical industry, and harnessing the potential of artificial intelligence systems (more details in [1] for interested readers).

In the mobile broadband sphere, the emergence of applications such as virtual reality and augmented reality drive continuing growth in both traffic and subscribers, and network quality demands such as latency performance. To enable 5G growth, it is thus essential to be able to exploit newly available spectrum resources in addition to currently used spectrum under 4G systems. In this column, we refer to 2.6–7.125 GHz as "mid band" and above 24 GHz as "high band." Providing mobile broadband services in this spectrum has presented new challenges that needed to be solved both in specifications and in implementation, as described herein.

Although the core waveform in 5G NR specification is cyclic prefix orthogonal frequency-division multiplexing (CP-OFDM)-based like LTE, the design of NR allows for a very high degree of flexibility in allocating different bandwidth and different numerologies, including decoupling of the total bandwidth supported by the BS and the bandwidths used for communication toward and from different user equipments (UEs). This, combined with advanced carrier aggregation and dual connectivity features, enables tailored support for complex and fragmented spectrum allocations.

At medium and high bands, path loss is greater than low bands, which is compensated by beamforming using advanced antenna array technologies. The NR specification includes a large number of features intended to support beamforming processing, ranging from support of a diverse set of MIMO schemes to the development of over-the-air (OTA)-based conformance requirements, which enables tight integration of radio and antennas in large advanced antenna arrays.

Even with array processing, uplink coverage with reasonable data rates may be restricted in medium and high bands. To enable flexible utilization of the available spectrum, the 3rd Generation Partnership Project (3GPP) has standardized solutions for sharing the same carriers in regular bands between LTE and NR, while operating CA between regular and mid/high bands for NR. With such solutions, the high bands can be used close to the base station (BS), while further from the BS the uplink (UL) is provided mainly by the low band part of the NR CA pair, and the downlink (DL) is provided in the high band. The sharing solutions also provide a very effective path for migration from LTE to NR.

Studies are ongoing into the usage scenarios and potential for further spectrum between 7 and 24 GHz and above 52 GHz in future 3GPP Releases. The existing LTE spectrum is also being refarmed for NR operation in low and mid bands (450 MHz–3.8 GHz). The status of the NR spectrum in the Release 15 specifications is shown in Fig. 1.

Once the standardization aspects were settled, harnessing the new spectrum with the 5G standard presented new challenges in network and UE implementation and testing. The success in both standardization and implementation means that deployment of both mid band and high band has commenced in some markets and can be expected to grow significantly.

In the remainder of the column, we summarize the challenges relating to implementing 5G in new spectrum and demonstrating compliance with radio and radio resource management (RRM) specifications in a satisfactory manner, which has been of crucial importance in getting to commercial grade hardware.

Base Station Aspects

The introduction of new spectrum for 5G requires innovative solutions to some challenging technical problems for BS design. In this column, a flavor of some key implementation and testing issues is presented.

The need for beamforming to combat the propagation conditions gave rise to a new design approach for BS technology based on active antenna systems (AASs). AAS BSs comprise a large number of transceivers, each operating at low power. Compared to traditional BS designs that have a low number of transmitters and do not integrate antenna and radio, the large number of transceivers imply challenges in relation to, among other things, processing power, interfaces, selection of beamforming and multi-antenna transmission schemes, radio algorithms, and additional new functionality within the radio subsystem such as advanced antenna calibration.

The dimensioning of the number of transceivers in an AAS BS differs depending on frequency. For mid band AAS, the number of transceivers could vary between 16 to 64, while for high bands, the array size could be very large (e.g., 8 × 16, 16 × 16, or even larger). For mid band, support for many simultaneous users with smaller numbers of transmit antennas is typical. For high bands, due to coverage, relatively fewer users per cell with larger data rates supporting applications, such as fixed wireless access and integrated access and backhaul (IAB), are expected in initial rollouts, although it may be expected that user numbers will increase with time.

The approach to implementation of beamforming, at least initially, differs between mid and high band. For mid band deployments and associated array sizes, full-blown digital beam forming (i.e., one transceiver per antenna element) is feasible. For the first generation of millimeter-wave (mmWave) BSs, considering the extremely large number of transceivers, implementing full digital beamforming risks excessive cost and complexity, in particular due to a need for huge interface bandwidths. Currently, so-called analog beamforming is adopted by the industry as mainstream for high band. Analog beamforming is an implementation with fewer transceivers than antenna elements, such that part of the beam steering is performed in the analog domain after the radio. Analog beamforming reduces the number of transceivers (and associated thermal management issues etc.) and the interface bandwidths within the BS. An overview of BS architecture for a system implementing digital beamforming is depicted in Fig. 2. For BS architectures adapted for analog beamforming, much of the processing such as inverse fast Fourier transform (IFFT), CP addition, channel filtering, CFR, DPD, and digital-to-analog

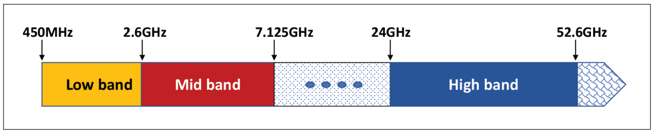

FIGURE 1. NR spectrum availability in low, medium, and high bands in Release 15.

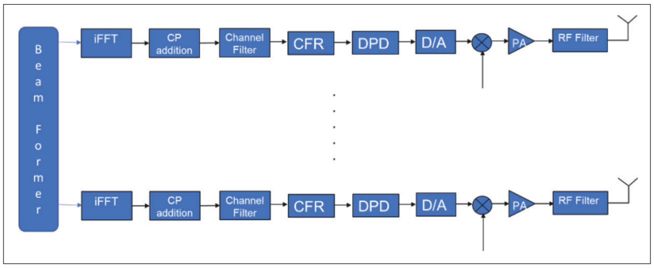

FIGURE 2. Overview of BS architecture for a system implementing digital beamforming.

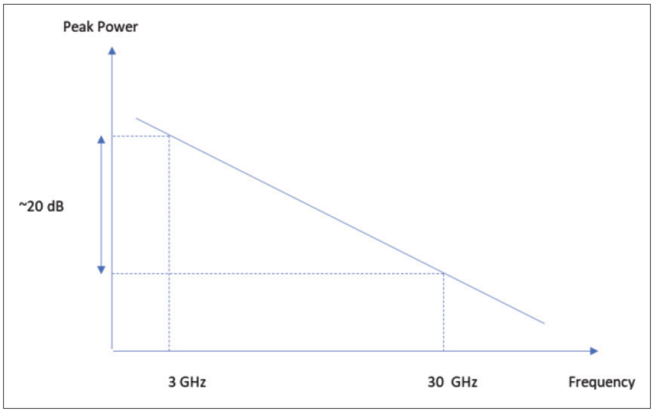

FIGURE 3. Visualization of achievable peak power over frequency.

(D/A) conversion can be performed per multiple-input multiple-output (MIMO) transmission layer instead of per transmitter. The number of layers is significantly lower than the number of transceiver chains, and hence the total amount of processing and interface bandwidth is correspondingly reduced.

The high-performance RF parts of a BS, including the radiating elements, have in many cases dimensions and tolerances on the order of wavelengths. This implies that for higher frequencies, at which the size of radio components decreases, the tolerances scale down to extremes. Furthermore, the performance of the RF components and subsystems decreases over frequency for both transmitter and receiver. In the following paragraphs, we outline four examples of RF challenges that were solved during 5G development: power amplifier performance and efficiency, receiver performance, phase noise, and filtering.

For power amplifiers, as a rule of thumb the output power degrades by around 20 dB per decade over frequency. This implies that the achievable saturated output power at 30 GHz is 20 dB lower compared to the power amplifies operating at 3 GHz, as depicted in Fig. 3. Thus, at higher frequencies a large number of transceivers are required to achieve sufficient output power, which is challenging for layout and thermal management [2].

In addition, the power added efficiency (PAE) also gradually becomes lower when the operating frequency increases. This exacerbates the thermal challenge and increases the effort needed to achieve good energy efficiency.

Considering the receiver performance, the noise figure (NF) of the whole receiver chain, including the losses in switches, filter and routing losses, and so on, degrades for higher operating frequencies. As an example, in 3GPP standards, the BS assumed noise figure for frequency bands below 5 GHz is 5 dB when setting requirements, while the corresponding BS noise figure assumption for bands around 28 GHz is ~10 dB. With reduced sensitivity performance, the array aperture needs to be increased. This need for an increased aperture exists regardless of whether the architecture consists of a small number of transceivers mapped to sub-arrays or transceivers are each mapped to an individual element. This is due to the fact that it is the total array aperture that determines the OTA sensitivity, not the number of individual transceivers.

Another important radio performance metric is phase noise, which relates to signal quality at both transmitter and receiver and also degrades substantially over frequency. Phase noise consists of a predictable component, known as common phase error (CPE), and random components. The 5G physical layer (PHY) standard specifies special reference symbols to enable compensation of the CPE by baseband receiver processing at the UE receiver, reducing the impact of increased phase noise for mmWave bands.

For non-AAS BSs operating in lower frequency bands with few transceivers, separate antennas, and enough mechanical space, high-performance low loss filters based on high-Q filter technologies are feasible. Such filters enable the BS to meet strict out-of-band emissions requirements while transmitting at high power in band. AAS BSs comprise many transceivers, each of which needs to be equipped with an RF filter. Mechanical size is very restricted due to the need for integration of RF and antennas. More compact filters with lower Q-value are the only feasible option for AAS implementations. Sufficient attenuation can only be achieved at the cost of increased in-band losses and/or increased guard bands. These factors make the design of filters for suppressing out-of-band emissions especially challenging for mmWave. The challenges are compounded by the fact that the performance of the filters degrades over frequency. The requirements for attenuation outside of the wanted band must be met, while attenuation in the wanted band risks a significant performance loss (due to high insertion loss) for mmWave band AAS BSs if not properly managed.

Apart from the technical challenges involved in designing BSs, the application of 5G in new spectrum also leads to significant work in developing RF conformance testing. This was needed because AAS, in particular for high band, requires extremely close integration of the radio transceiver and antenna to the point at which it is not cost effective or in some cases even feasible to provide connectors to the transceivers in order to perform conducted RF conformance testing. To enable close integration, an over-the-air (OTA) requirements specification was developed in 3GPP comprising relevant new metrics taking into account array behavior, beamforming, and OTA testing. In most cases OTA testing is far more complex than conducted measurements and involves more sources of uncertainty. 3GPP has carefully developed test methods, procedures, and measurement uncertainties for all OTA requirements such that OTA facilities can be realistically used with reasonable uncertainties.

User Equipment Aspects

Figure 4 presents a market survey on the availability of terminals in the near future (this is obtained from [1]). In 3GPP Rel-15 NR, the network carrier bandwidth may be very large (e.g., max. 100 MHz in case of midband and a maximum of 400

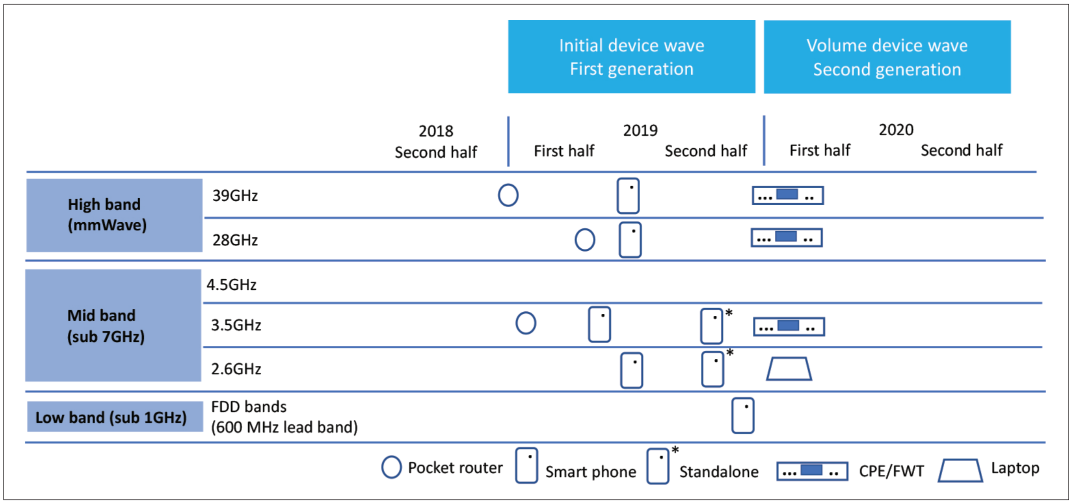

FIGURE 4. 5G device availability for different spectrum bands (obtained from [1]).

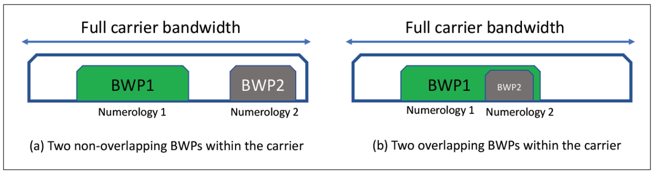

FIGURE 5. Non-overlapping and overlapping BWPs within a carrier.

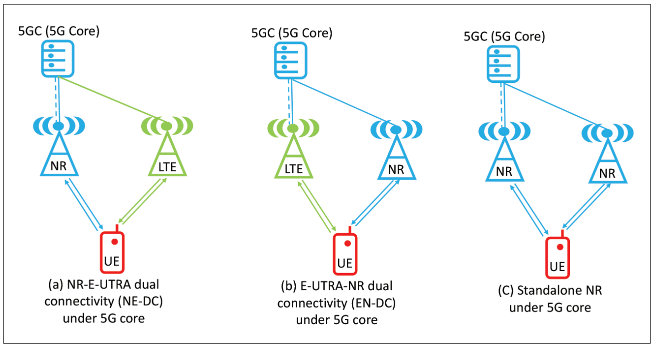

FIGURE 6. NR deployment options: a) NE-DC; b) EN-DC; c) standalone NR.

MHz in case of high-band), thus providing much higher carrier bandwidth compared to legacy 4G systems. For a UE, such a large bandwidth may be difficult to handle efficiently (considering power efficiency in particular). To be able to utilize the full network bandwidth flexibly, a new concept of "bandwidth part (BWP)" has been defined for NR, described in Fig. 5. The BWP concept provides essential flexibility to UE design to manage power usage dependent on throughput needs, such that the benefits of 5G can be obtained without a power cost. The network can configure a UE with a maximum of four BWPs in both UL and DL; however, only one BWP may be activated at any time. By managing the bandwidth of the active BWPs appropriately, the network can provide opportunities for UE power saving when possible while still exploiting larger bandwidths when needed.

The very first deployments of 5G systems have been based on the non-standalone mode, meaning that although a UE will be served using 5G core (5GC), the PCell will be based on LTE, such that the control, mobility, and so on are based on existing LTE protocols. Typically, in such a deployment, coverage will be obtained using an LTE system on a lower band, and additional capacity will be provided using the NR system on a higher band. This is also known as EUTRA-NR dual connectivity (EN-DC). Standardization of so-called standalone is now complete, and deployments are emerging. For standalone deployments, LTE is not the PCell or maybe LTE is not even configured at all to the NR UEs. Thus, there are three different variations of NR and LTE carrier configurations for deployments, as shown in Fig. 6.

The introduction of EN-DC (and NE-DC and NR-NR DC) will result in typical UE implementations in the first wave of devices having two different radios in the same device, which enables re-farming scenarios in which the LTE carrier can continue to serve existing pre-5G users, using one of the approaches in Fig. 6. Further innovation in so-called dynamic spectrum sharing (DSS) provides an opportunity for both LTE and NR to be operated in the same spectrum, where a new NR operation operating exclusively NR carriers for NR UEs can be established on top of an existing LTE network without shutting off the legacy LTE network such that legacy LTE UEs can be served on the same carrier as the standalone NR. With DSS, from the NR UE perspective, scenario c of Fig. 6 is operated.

Many of the RF implementation challenges w.r.t. high band front-end design remain the same for BS and UE, including front-end nonlinearity behavior, power amplifier design, phase noise issues, filter design, receiver noise figure, and so on. The UE transmitters need to avoid interfering with one another and provide acceptable performance; however, the technology constraints for UEs differ. As an example, the power amplifier of a high-band-capable UE may be designed based on complementary metal oxide semiconductor (CMOS) or other advanced solutions such as GaN [2]. A GaN architecture may provide higher performance but cause increased device power consumption and cost as well.

One of the prime benefits of 5G NR is achieved from beamforming. This essentially means that, compared to previous 2G/3G/4G systems, the UEs in the 5G era will have to support higher numbers of antennas for both spatial diversity and spatial multiplexing benefits. Note that low bands will be used mainly for coverage, while mid and high bands will be used for capacity; thus, multiple antennas at mid-band and high-band are an essential part of 5G UE design. For mid-band, a small number of antennas are needed to achieve RX diversity and

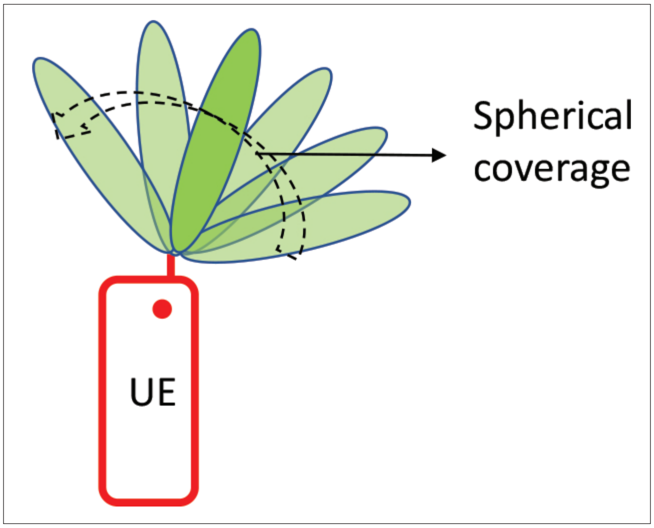

FIGURE 7. UE spherical coverage.

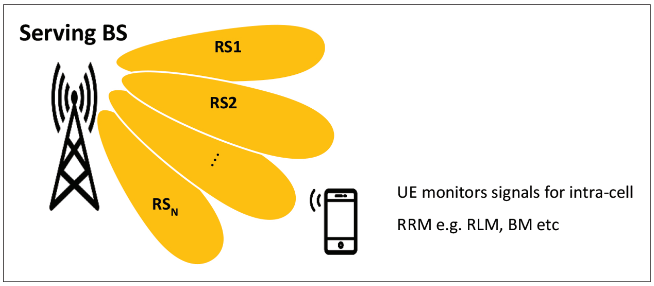

FIGURE 8. UE monitors beams in serving cell for intra-cell procedure.

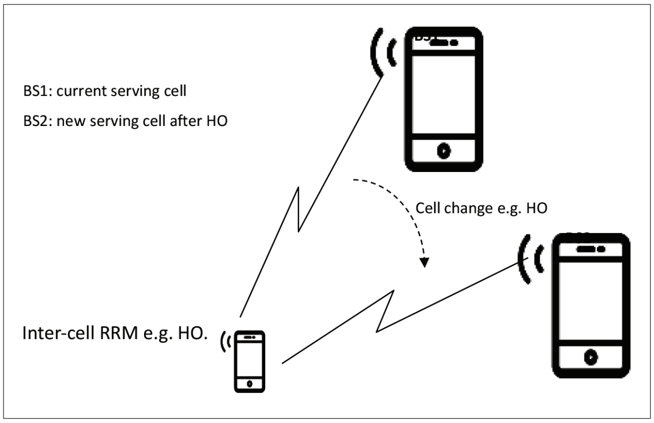

FIGURE 9. An example of an inter-cell RRM technique such as HO.

TX/RX MIMO capacity enhancements. In high-band, due to higher path loss, the coverage is limited compared to mid-band and low-band. Beamforming is one of the ways to enhance the link connectivity in high-band. Supporting a greater number of antennas at high-band UE will most probably use distributed PA architecture, meaning that the PA will be closer to the antenna to reduce the feeder loss compared to a single common PA architecture.

Since antenna dimension is proportional to effective wavelength, the current form factor allows more possibilities for higher numbers of antennas at high-band compared to mid-band UEs. As with the BS, there are two different possibilities for BF implementation in high-band, namely digital and analog beamforming. While increasing the cost, power consumption, and complexity, digital beamforming provides a high degree of flexibility in terms of beam shaping in high-band. A fully digital BF architecture is unlikely at high-band UE at this stage. Alternatively, an analog BF architecture is more cost effective and consumes lower power since it has fewer RF chains than antenna elements. One pragmatic approach could be hybrid BF architecture that consists of a limited number of RF chains but employs digital precoding to achieve digital BF like performance. Digital and hybrid beamforming can provide opportunities for spatial multiplexing in high-band, since potentially multiple beams can be created, whereas spatial multiplexing possibilities to the same UE are difficult with analog UE beamforming.

All UE RF requirements are defined as OTA requirements (similar to BS requirements). Unlike a BS, a UE may be oriented in any direction, and thus it is important that the performance of the beamforming is to some extent uniform in all directions. At high-band, spherical coverage requirements are defined to characterize UE beamforming performance. Spherical coverage ensures that beamforming can be achieved consistently regardless of instantaneous required direction [6].

In the latest 5G specification [5], the UL spherical coverage is evaluated by the cumulative distribution function (CDF) of effective isotropic radiated power (EIRP) over the sphere in high-band. For mobile handset type UE, the peak EIRP value and the spherical coverage performance are both essential. The peak EIRP is measured at CDF = 100 percent, which actually shows the beamforming capability of the UE, and the spherical coverage performance is measured at CDF = 50%.

To meet the spherical coverage requirements, the UE needs suitable antenna topologies (e.g. multiple antenna panels), efficient device integration (including materials used in the cover, placing of the components, etc), reasonably fast switching between antenna panels, beam correspondence between DL and UL so that the beam is transmitted in the right direction, and so on. The actual spherical coverage of a UE will depend on many factors (e.g., device integration, device form factor, antenna topologies, body loss caused by actual usage). Depending on the materials used for UE device integration, the diffractions of the surface current will cause sidelobes. These sidelobes can cause interference to other systems. Moreover, strong sidelobes may also decrease the power in the wanted direction [6].

The data rate for 5G will be much higher compared to previous systems, and battery consumption continues to be an important consideration. This will especially be an issue in high-band due to high carrier bandwidth and reduced PA efficiency. As mentioned earlier, BWP is one way of increasing energy efficiency of the UE. Above and beyond this tool, there is a need for further exploration on the energy efficiency of UE for ensuring longer battery life of 5G UEs.

Radio Resource Management Aspects

Robust RRM techniques are required for efficient utilization of radio resources and for ensuring reliable mobility procedures such as handovers. For example, several algorithms in the BS rely on the UE behavior and measurement reports, whose performance can only be guaranteed by means of standardized RRM measurement requirements [7]. The 5 GHz spectrum ranging from low band to high band puts additional constraints on the RRM techniques required in 5G as described later. The wide range of use cases for 5G (enhanced mobile broadband [eMBB], fixed wireless, etc.) also brings additional challenges for RRM algorithms. One of the key 5G features is the ability of

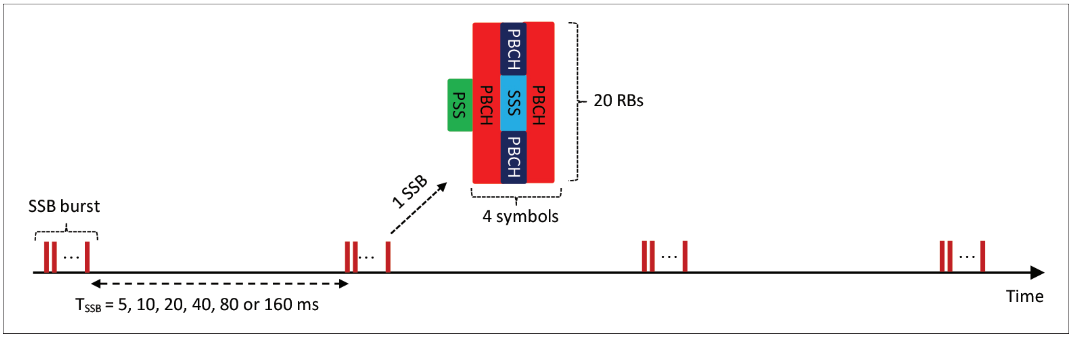

FIGURE 10. Illustrates an example of periodic SSB resources transmission in a cell.

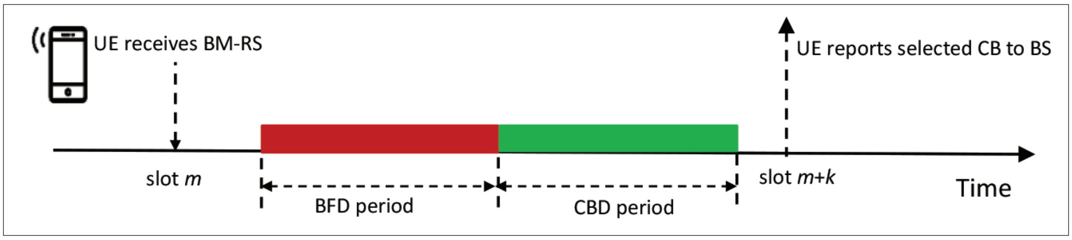

FIGURE 11. Illustrates an example of the beam management procedure in a serving cell.

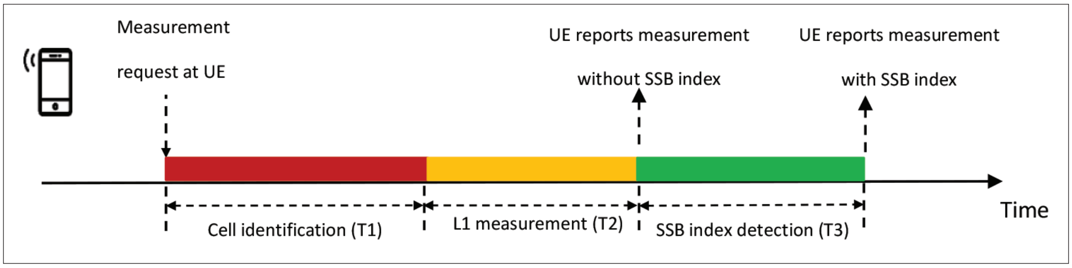

FIGURE 12. An example of measurement reporting for a neighbor cell

the UE to regularly track beams in serving and neighbor cells. Therefore, in 5G, both intra-cell and inter-cell procedures are of paramount importance.

For intra-cell RRM procedures the UE is configured to monitor a periodic pattern of downlink reference signals (synchronization signal block [SSB] or channel state information-reference signals [CSI-RS]) in the serving cell, as shown in Fig. 8. For inter-cell RRM procedures the UE is also configured to monitor a periodic pattern of SSB bursts per carrier frequency by means of SSB Measurement Timing Configuration (SMTC) in serving as well as neighbor cells as shown in Fig. 9. The SMTC configuration comprises SMTC duration containing SSB burst, SMTC periodicity, and time offset. An example of SSB resources comprising periodic SSB burst is shown in Fig. 10. The number of SSBs within one SSB burst and the SSB burst periodicity (T_{SSB}) are configurable. Each SSB is enumerated by an SSB index, which is an integer starting from 0.

To avoid coverage limitation in high band, each SSB is beamformed by the BS. To adequately cover the entire cell in high band, a larger number of finer SSB-based beams are transmitted compared to the beams typically transmitted in low band or mid band. For example, in each cell the BS can configure up to 4, 8, and 64 SSB based beams in low band, mid band, and high band, respectively. To track several beams in the serving and neighbor cells, the UE has to employ efficient beam management procedures, especially at high band. In order to reduce UE cost and complexity, the UE employs analog beamforming implying that the UE, while tracking beams, is not required to receive or transmit control or data channels. The analog beamforming in conjunction with the TDM-based SSB design enables the UE to sweep a large number of beams in the serving and neighbor cells in order to find the most appropriate beams for the relevant operation and ensures robust RRM performance.

The intra-cell beam management (BM) procedure is triggered by the UE based on the configured sets of BM radio resources (BM-RS) to monitor the beams and detect candidate new beams upon UE experiencing beam failures. To realize efficient beam management, the UE regularly monitors the quality of the configured beams by comparing each beam's signal quality with a threshold corresponding to pre-defined hypothetical physical downlink control channel (PDCCH) block error rate (BLER) of 10 percent [7]. Upon beam failure detection (BFD) for all the configured beams, which occurs when the signal quality of all the beams falls below the threshold, the UE initiates candidate beam detection (CBD) procedures, as shown in Fig. 11. During the CBD procedure, the UE determines one or more candidate beams whose signal strength is above certain configurable threshold and reports the candidate beam results to the serving BS. In high band, the BFD and CBD evaluation periods are extended for allowing the UE to track all potential beams in accordance with the configured radio resources. The extended evaluation periods lead to acceptable beam management performance at lower UE speed than typically expected in a high band deployment scenario.

For inter-cell RRM, the UE is typically configured with one SMTC configuration per NR carrier frequency. In high band, the major challenge in the UE has been to track SSB-based beams on multiple cells on multiple carriers. To limit the UE complexity in RRC idle, inactive, or connected states, the UE is not required to measure on more than seven NR carriers in parallel [7]. The term "measurement" on a carrier broadly comprises UE identifying a physical layer identity (PCI) of a neighbor cell based on SSB within a specified cell identification period (T1) and performing one or more physical layer (L1) measurements also based on SSB on the already identified cell within a specified physical layer (L1) measurement period (T2). In RRC connected state, the UE may optionally be requested to identify SSB indices within a specified SSB index identification period (T3). In RRC idle state or inactive state, the UE further evaluates the identified neighbor cell over an evaluation period (T4) for cell reselection by measuring the cell once every discontinuous reception (DRX) cycle. An example of UE performing and reporting neighbor cell measurements with and without acquiring SSB index is illustrated in Fig.12.

In high band, the UE performs beam sweeping to detect appropriate beams on each cell whose signal quality is above the pre-defined level and continue doing the measurements only on the detected beams. The inter-cell measurement requirements for measurements on high band or TDD bands in low or mid band are specified assuming that the SSBs of the same SSB indices are used in all cells on a carrier. This assumption, being realistic from the deployment perspective, also reduces UE complexity as it has to identify SSB indices of beams only of a cell on non-serving carriers.

In high band, the measurement period, comprising multiple samples, for each type of measurement is adequately specified to enable the UE to detect the relevant beams in all cells with acceptable signal quality without compromising the UE mobility performance.

Conclusions

5G provides new opportunities to exploit both existing and new spectrum in a flexible manner. Challenges range from degraded component performance at higher frequencies to the need for advanced beamforming architectures in order to achieve link budgets to new procedures for managing radio resources taking into account the beamforming. Over the past years, these challenges have been addressed in the context of providing appropriate tools within standardization, defining radio performance requirements in a manner that facilitates new designs (e.g., OTA performance requirements for AAS systems) and in creating new and novel implementation solutions. With first networks being deployed and devices emerging onto the market, 5G is taking the first steps in demonstrating the tremendous potential that exists to solve these challenges and move forward to the next generation of cellular mobile experience in both the traditional mobile broadband and new vertical domains.

Looking ahead, new spectrum is being considered for future wireless systems. There are extensive efforts in the 7–24 GHz range, which was not covered by 3GPP Release 15 specification (i.e., first 5G specification) and in extending the boundaries of technology to beyond 52 GHz spectrum. The 7–24 GHz spectrum lies between the mid and high bands. It is not yet clear how the challenges in this spectrum relate to those of the spectrum below and above, so further research is needed to understand which technology solutions are reusable and what is required that is new. In particular, beamforming solutions may differ, and the performance of different types of PA, receiver, and filter technologies differs from either of the two existing ranges. For the higher spectrum, a concerted standardization effort will be needed at the right time to determine appropriate waveforms and radio performance requirements considering the likely spectrum environment, technology, and test solutions. As 5G grows in stature and success, research in these topics will be needed to further exploit the benefits and opportunities of newly available spectrum.

References

[1] Ericsson Mobility Report, June 2019.

[2] 3GPP TR 38.803 V14.2.0 (2017-09), "Study on New Radio Access Technology: Radio Frequency (RF) and Co-existence Aspects" (Release 14).

[3] 3GPP TS 38.104 V16.3.0 (2020-03), "NR: Base Station (BS) Radio Transmission and Reception" (Release 16)

[4] 3GPP TS 38.101-1 V16.3.0 (2020-03), "NR; User Equipment (UE) Radio Transmission and Reception; Part 1: Range 1 Standalone" (Release 16)

[5] 3GPP TS 38.101-2 V16.3.0 (2020-03), "NR; User Equipment (UE) Radio Transmission and Reception; Part 2: Range 2 Standalone" (Release 16)

[6] K. Zhao *et al.*, "Spherical Coverage Characterization of 5G Millimeter Wave User Equipment With 3GPP Specifications," *IEEE Access*, Dec. 2018.

[7] 3GPP TS 38.133 V16.3.0 (2020-03), "NR; Requirements for Support of Radio Resource Management" (Release 16).