5G NR

A New Era for Enhanced Mobile Broadband

White paper

Introduction

Since an initial 5G RAN workshop in September 2015, the 5G standardization process over the past two years is now taking the industry to the home stretch of live deployments across the Globe. In the upcoming months we will see massive "early" 5G lab and live trials at a number of events, most notably XXIII Winter Olympics in Pyeongchang, South Korea in February, 2018, a traditional showcasing in Barcelona at the Mobile World Congress in the end of the same month and the FIFA World Cup in Russia in mid-summer 2018.

But more importantly, several carriers in the US, Japan, China and Europe are committed to 3GPP-based live pilot networks roll-out as soon as in 2019. This means that 5G is one step away from becoming a reality.

To help operators achieve this remarkable milestone the industry standardization body 3GPP has accelerated the delivery of 5G, producing an interim set of approved specifications at RAN#78 Plenary in Lisbon, Portugal in the end of December 2017 (ASN.1 due in March 2018). This first set defines 5G New Radio (NR) in Non-Standalone operation (NSA) enabling 5G NR deployments using existing 4G systems (LTE EUTRAN and EPC) as leverage. The specifications of 5G NR in Standalone operation are due for completion in June 2018 (ASN.1 due in September 2018), complemented by the complete set of specifications of the new 5G Core Network – hence the full 5G System.

MediaTek has been highly involved in the 5G standardization effort spanning radio and overall system architecture using extensive know-how acquired through numerous research activities on 5G technologies and in-depth knowledge of 4G and earlier mobile systems. MediaTek has been heavily investing in the development of 5G and is committed to accelerating its adoption, by bringing the technology to the mid-tier market from Day 1 in contrast to the usual premium-first approach. Our mission to quickly democratize 5G is already endorsed by many operators; it ensures a better network utilization from the start, faster ROI (return on investment) and faster deployments.

Carrier investments are indeed critical to the success of 5G. While on one hand the technology itself becomes cost-effective thanks to e.g. massive unification and cloud transformation (incl. into the RAN), on the other hand new spectrum is targeted that can address the future demand in capacity, requiring 5G operating frequencies reaching higher and into mmWave (millimeter Wave). This poses new challenges as the density of 5G networks and the transmission requirements are unprecedented and will draw more operator resources to deploy.

What use cases will become primary for 5G? **Figure 1** displays a simplified version of the ITU IMT2020 triangle with eMBB (enhanced Mobile BroadBand), URLLC (Ultra Reliable Low Latency Communications) and mMTC (massive Machine Type Communications) as key 5G use case directions and the initial 5G focus.

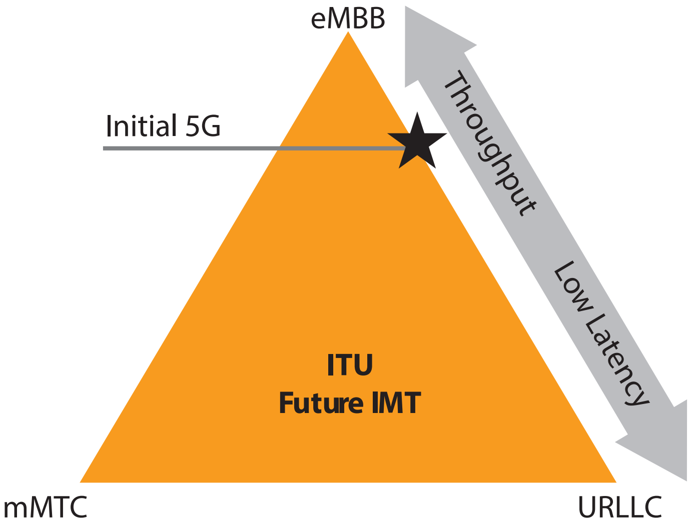


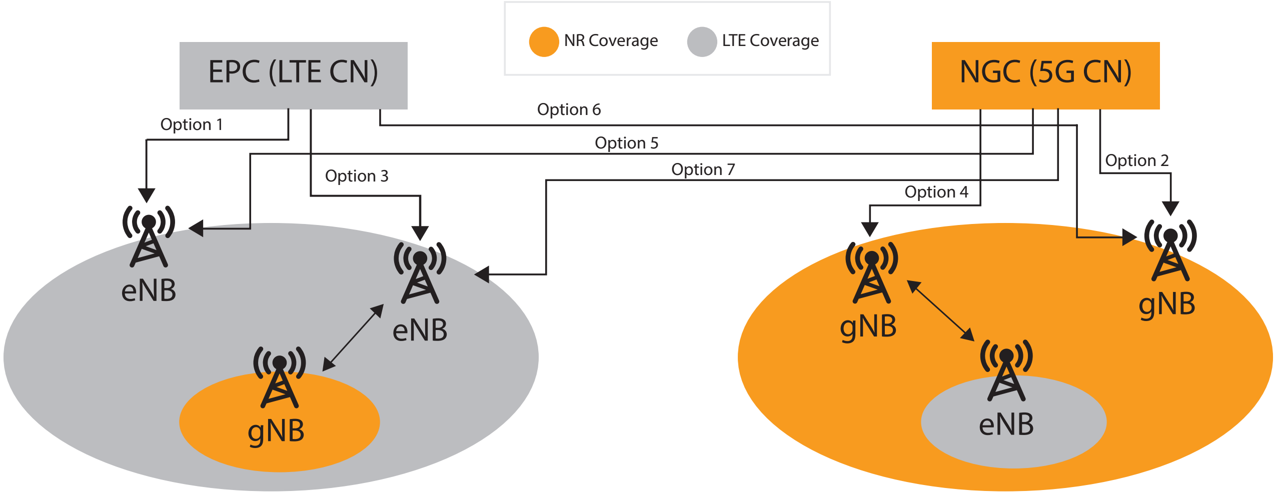
Figure 1: ITU IMT2020 Use Cases

These directions represent the essential requirements towards the wireless network: bandwidth, latency and density respectively. The initial phase of 5G deployments lays at the eMBB-URLLC side of the triangle closer to eMBB. MTC now witness the dawn of 3GPP Release 13 LPWA technologies NB-IoT and eMTC. These are expected to meet most 5G mMTC requirements albeit with limited throughput while full URLLC will require 5G Core deployment for full E2E latency reduction. Mission critical applications that are especially demanding for latency require full scale coverage as well which is hard to imagine for early deployments. So at the first stage we expect to witness further bandwidth growth complemented by latency improvements on 5G NR, but also LTE. This will help to develop today's mobile broadband use cases to leverage emerging AR/VR (augmented reality/virtual reality) applications, 360 UHD video and many more.

In this whitepaper we summarize all the compelling information regarding 5G NR concepts and the enhancements towards existing systems available today.

5G Deployment Options

We all can very well remember the birth of 4G. There was a new radio technology (commonly known as LTE or E-UTRA) for IMT-Advanced, a new access network (E-UTRAN) and a new core network (EPC or Evolved Packet Core) all delivered as one pack – the Evolved Packet System (EPS); 4G meant EPS and EPS meant 4G (at least from 3GPP standpoint), designed for mobile broadband. The situation is different with 5G; the IMT2020 directions (eMBB, URLLC and mMTC) and wide range of use cases call for 3GPP to submit each of 5G NR (Non-Standalone and Standalone), LTE and NB-IoT to ITU-R for IMT2020 technologies – MediaTek fully supports this approach. In addition, independent migration of the access and core networks is an essential enabler of 5G in the market allowing operators to choose the path that best fit their goals. These factors resulted in a number of deployment options for 5G NR, LTE and 5G Core, represented in **Figure 2**.



Option 3	EPC + LTE Assisted 5G NR	Interim Rel15 March 2018
Option 4	5 GC _ 5G NR Assisted LTE	Rel15 Sept. 2018 (TBC)
Option 5	5G + Standalone LTE	Rel15 Sept. 2018
Option 7	5GC + LTE Assisted 5G NR	Rel15 Sept. 2018 (TBC)

Figure 2: 5G NR Deployment options

It should be noted that the new 5G System specified by 3GPP includes a new access network (5G-AN) allowing both 3GPP access (NG-RAN) via 5G NR or LTE and Non-3GPP Access (N3IWF) via e.g. fixed access or WiFI and a new core network (i.e. 5G Core) with a single set of interfaces whether 3GPP or N3GPP access is used.

At the very initial stage of 5G NR deployment the LTE dual connectivity concept will use existing LTE networks – both EPC and E-UTRAN as leverage, adding to the picture a 5G NR RAN node, gNB i.e. 5G NR will be supported by today's LTE.

Dual Connectivity architecture for LTE was standardized in 3GPP Release 12 (though not used), in which the UE can consume radio resources from at least 2 different eNodeBs, namely Master eNB and Secondary eNB, connected with non-ideal backhaul while the UE is in RRC_CONNECTED mode. Different from Carrier Aggregation, Dual Connectivity can offer similar benefits but for non-co-sited deployments – this is a very important aspect for 5G NR deployments.

In Dual Connectivity, the split bearer concept is introduced, in which a data bearer is split between the two eNBs, at the PDCP layer. The PDCP layer at the anchoring User Plane node is responsible for the PDU numbering, distribution between master and secondary eNBs, aggregation, sorting and in-sequence delivery to upper layer.

Another option provided is bearer switching, in which no bearer split between Master and secondary eNBs is applied, but the user plane can be switched between both of them, which mean that there is no aggregation gain at PDCP layer unlike the bearer split scenario.

3GPP Release 15 NSA NR operation is based on 3GPP Network Option 3 family which is "LTE assisted EPC Connected". NSA options 3/3a/3x are shown at **Figure 3**.

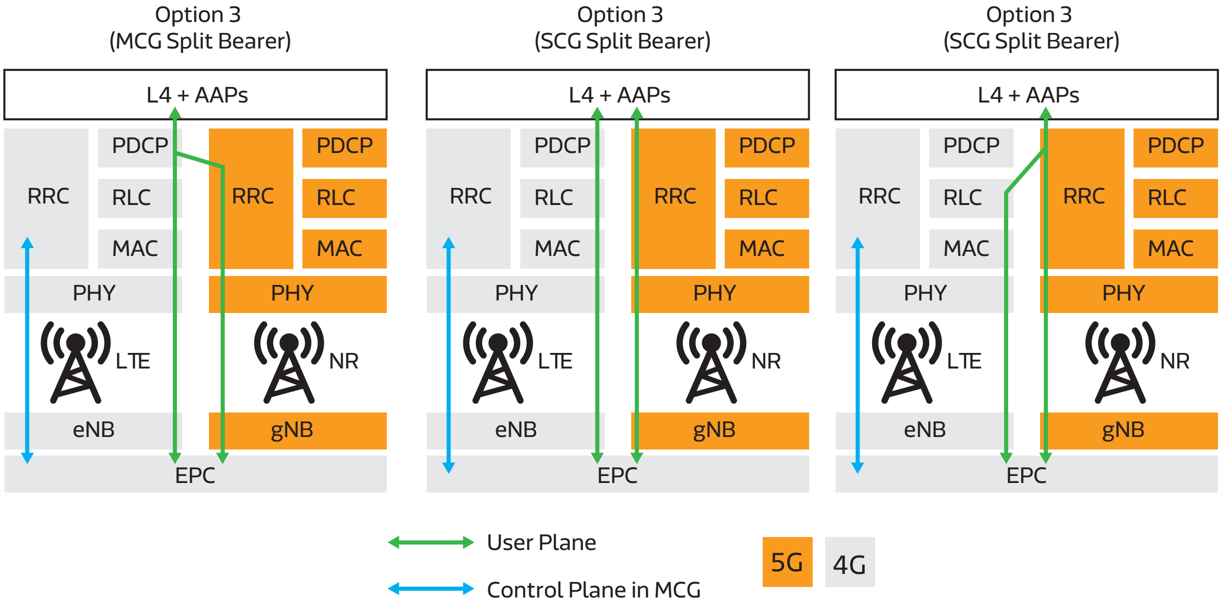


Figure 3: NSA Option 3 Family

What is the idea behind NSA Option 3 family? The UE connects to both 5G NR and E-UTRA. For Control Plane (CP), it fully relies on the existing EPS LTE S1-MME interface procedures and LTE RRC protocol. For User Plane (UP) there are variations. Originally, Option 3 assumed that LTE PDCP layer would be utilized but bringing an obvious bottleneck that can affect the whole design: LTE PDCP was not designed for the data rates achievable with 5G NR. Then there are 2 variants. The first is Option 3a which is based on separate LTE and NR PDCP layers. This option is the most simple for the UE as it requires no split bearer. It has its benefits for the network as well as it leaves existing LTE eNodeB (eNB) with the requirement to support 5G NR CP interworking only, no UP enhancements in sight. Another option in the Family is 3x which is the mirror of Option 3. The difference is that it utilizes NR PDCP layer thus avoiding the bottleneck of the Option 3 but of course it is more demanding to the eNB compared to 3a since it needs to support NR UP interworking.

The following table summarizes the major differences between the different flavors of NSA option 3.

Table 1: Comparison of Non-Stand Alone Option 3

	Option 3	**Option 3a**	**Option 3x**
Utilisation of radio resources across LTE and NR	Possible for the same bearer	Not possible for the same bearer, requires at least two DRBs for having user plane traffics in LTE and NR	Possible for the same bearer
Dynamic offload	Controlled by LTE eNB, can be dynamic as long SCG is setup	Need to involve MME, very static	Controlled by NR gNB, can be dynamic as long MCG is setup
Additional processing capacity requirement	Additional PDCP processing capacity requirement in LTE modem to process SCG leg	No additional processing capacity requirement	Additional PDCP processing capacity requirement in NR mode to process MCG leg
Buffering requirements	Bearer splitting implies increased reordering-buffering requirement	No additional buffer required	Bearer splitting implies increased reordering-buffering requirement
LTE eNB-NR gNB backhaul requirements	The Xx/Xn interface has to offer the latency of 5-30 ms and sufficient capacity.	No additional throughput requirement on backhaul	The Xx/Xn interface has to offer the latency of 5-30 ms and sufficient capacity.
U-plane latency	Additional U-plane latency for SCG path in case LTE eNB and NR gNB are non-co-located	No additional U-plane latency	Additional U-plane latency for MCG path in case LTE eNB and NR gNB are non-co-located
LTE modem impact	High	Low	Medium

Many carriers worldwide announced their support to one of the flavors of Option 3 for initial 5G NR deployment. The gain is pretty clear. While the exact use cases and benefits of the 5G Core are being studied and gradually understood, the driver for 5G NR which enables so many operators to push the rapid commercialization of the technology is very straightforward – this is further bandwidth growth and further development of the existing LTE MBB use cases with clear benefits for end users.

Which flavor is going to be mainstream? Option 3x appears to gain more momentum with time as it provides throughput aggregation gains with minimum investment in LTE, followed by option 3a for its simplicity, while option 3 is getting less interest as it will require a considerable investment in LTE network on top of the 5G NR required investment.

Following NSA Option 3 Family 3GPP Release 15 will contain SA Option 2. The idea behind Option 2 is Greenfield 5G based on 5G NR in Standalone operation and 5G Core. Option 2 layout is depicted on **Figure 4**.

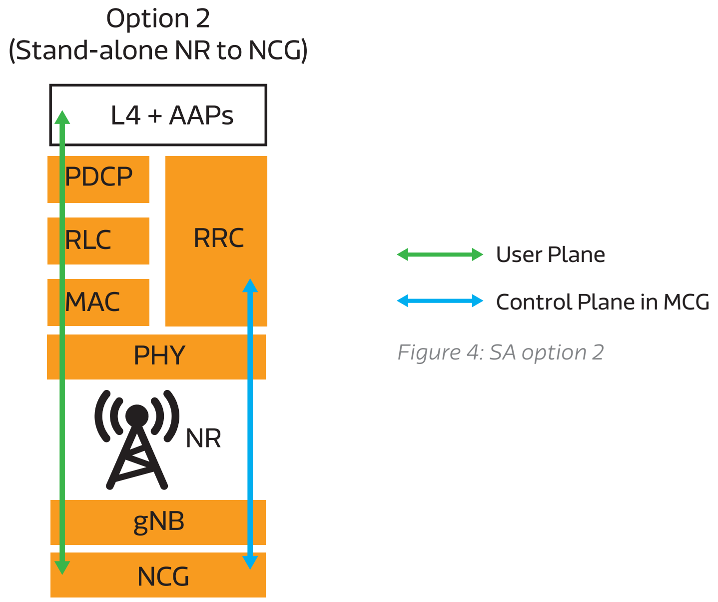


Figure 4: SA option 2

Compared to NSA Options 3, less carriers, led by China are adopting this option for their 5G NR initial launch.

Pros and cons of such approach are obvious. On one side of the scale it is direct evolution to the next generation mobile network and lower complexity due to less interfaces being involved. On the other this is bound to more massive investments from Day 1 as well as introduction of new products at both network subsystems at a time. We expect that LTE co-existence will prevail at least in the short/mid term.

The following table summarizes the major differences between Non-Stand Alone deployment option and Stand Alone one.

Table 2: Deployment Comparison between NR Standalone and Non-Standalone

	Non-stand alone option	**Stand alone**
RF and FE architecture	Complexity from Dual Connectivity definition	-
BB processing	-	Additional complexity on idle mode operation including cell (re)selection and paging reception.
Software design	Partial NR functions from SA · User Plane functions for different options. · Limited Control Plane functions · Additional func. for LTE-NR DC · LTE/NR RRC enhance and coordination · User Plane architecture ad Split bearer	Full NR functions · Control and User Plane functions · Additional functions to NSA: Paging, Cell (re) selection, System information acquisition, DR, etc.
Power	With active transmission, under the same data rate, NSA UE power consumption is higher than SA, due to two chip/modern architecture	
Buffer requirements	Additional buffer requirement for packet reordering due to latency between eNB and gNB	-
Processing unit requirements	Dual connectivity requires 2 modems being activated simutaneously, For option 3 or option 7 (MCG split bearer), more processing captability is required for LTE PDCP reordering in order to deal with NR throughout	-

But as highlighted previously, these are not all the deployment options available, for example Release 15 final version also will contain Option 7 family shown at **Figure 5**.

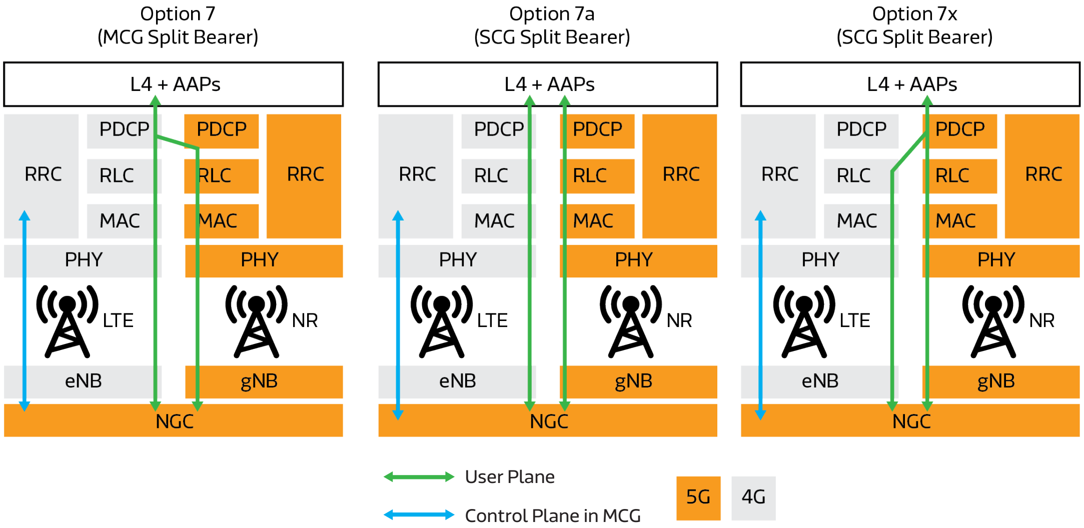


Figure 5: NSA Option 7 Family

This option is seen by many operators as an evolution from initial Option 3 deployment. The plot is to first get 5G network live on EPC, take them to some level of maturity and then introduce 5GC to the network to migrate both access technologies – NR and LTE to the new core and get most benefits from the investments done for all these years. Besides use cases for all 5G applications should be available by that time.

Option 7 also contains 3 flavors like Option 3 with similar layout. It is too early to say which flavor will prevail in this deployment as it is not an initial stage plan for carriers planning to launch their 5G within 2020 timeframe.

Option 4 is also under consideration, driven by 5G NR deployments and minimum LTE investments – though requiring an NR coverage layer, hence likely sub-GHz. This is in line with some deployment scenarios for 5G NR promoted by US carriers in 600 MHz band.

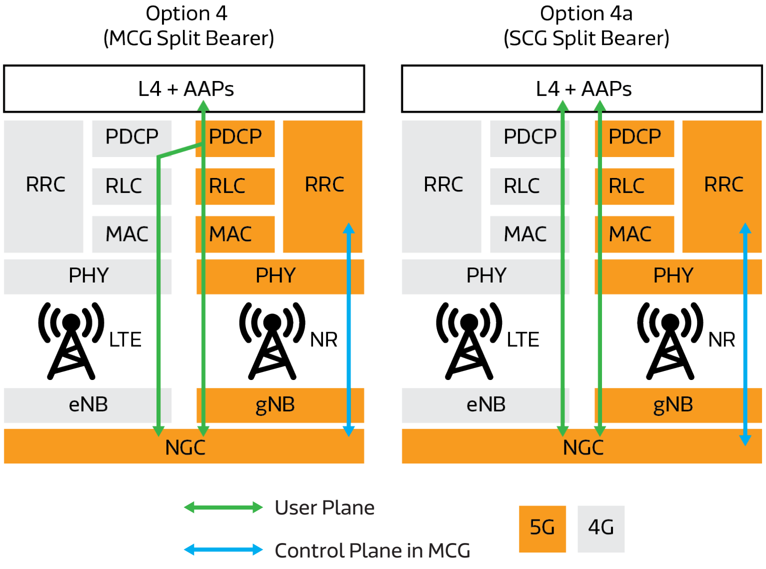


Figure 6:
NSA Option 4 Family

For option 4, only 2 flavors are available since the 5G NR cell will be considered as the primary cell due to its extended coverage, so no need to consider a scenario where bearer split is managed by eNodeB PDCP layer.

It is worth mentioning the last two options: 5 and 6.

Option 5 is an LTE eNodeB connected to the 5G Core Network Core (similarly to Option 7) but without dual connectivity with NR (unlike Option 7).

This option provides a core network migration path for operators that want to exploit the benefits of the 5G Core Network (e.g. Network Slicing) without relying on 5G NR – however the added value to end users remains unclear, whilst it requires also additional complexity and costs in the UE. This option may be most relevant for some specific vertical deployment but is not expected to be seen in the initial deployment phase of 5G NR that will focus on 5G NR NSA deployments in EPC (Option 3 family). Carriers are expected to start their 5G investment on the radio access part before the core part, and at best if the core is migrated the radio would also be migrated i.e. Option 2 will be the main interest.

Nonetheless, integrating eNodeBs with 5G Core (either in option 7 or option 5) is foreseen as the upgrade path for LTE.

In Option 6, a 5G NR standalone gNodeB will be connected to EPC. This option was discarded early on by 3GPP and will not be specified at this stage. A key deterrent against Option 6 is its irrelevance in view of Option 2, and 3GPP commitment to deliver it in a timely fashion in Release 15.

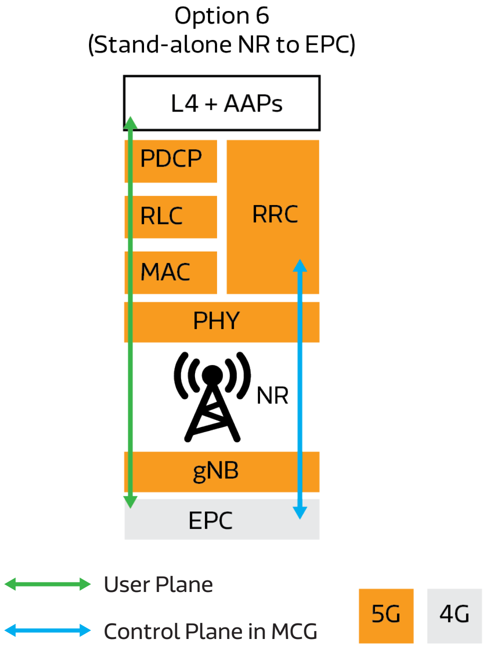


Figure 7: SA Option 6

Spectrum

If we need to consider an equivalent to raw material resource for the telecom industry, it will be the Radio frequency spectrum, allowing for all telecommunications – whatever the Radio Technology used – to take place.

Looking at 3GPP RAN4 activities for NR spectrum definition and allocation, 5G NR is defined with band agnostic operations, meaning that it can be deployed on low, mid or high bands with no restrictions. For Release 15, Bands are specified in two Frequency Ranges (FR):

FR1:

- from 450 MHz to 6000 MHz
- Bands numbered from 1 to 255
- Commonly referred to as Sub-6Ghz

FR2:

- from 24250 MHz to 52600 MHz
- Bands numbered from 257 to 511
- Commonly referred to as mmWave (although technically speaking mmWave starts from 30 GHz)

For NR, the letter “n” is preceding the band number to distinguish it from possible LTE deployed in the same band.

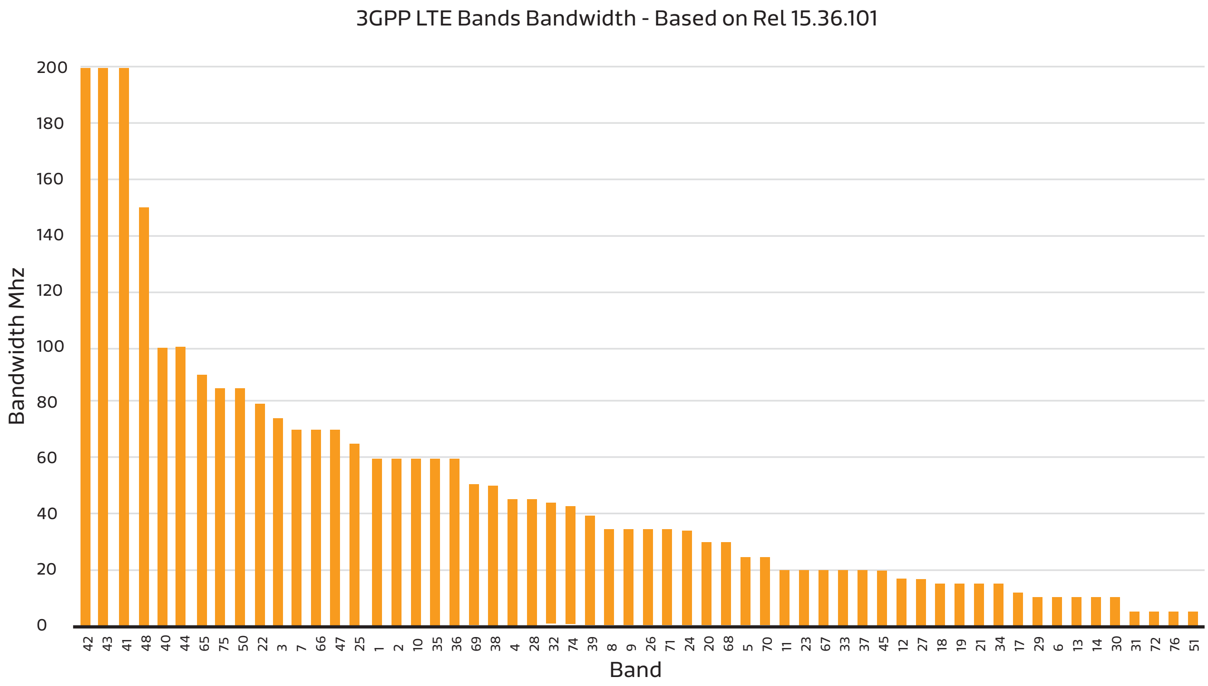


Figure 8: Bandwidth of different IT bands

Many of LTE bands clearly had to be planned for 5G NR operation, also some new bands proposals combining existing LTE bands into larger blocks, for example B42 (3.4 to 3.6 GHz) and B43 (3.6-3.8 GHz) have the largest bandwidth with 200 MHz each, and the fact that they are consecutive bands added to their suitability for 5G deployment as part of the largest available continuous bandwidth below 6GHz spanning from 3.3GHz to 4.2GHz in different regions.

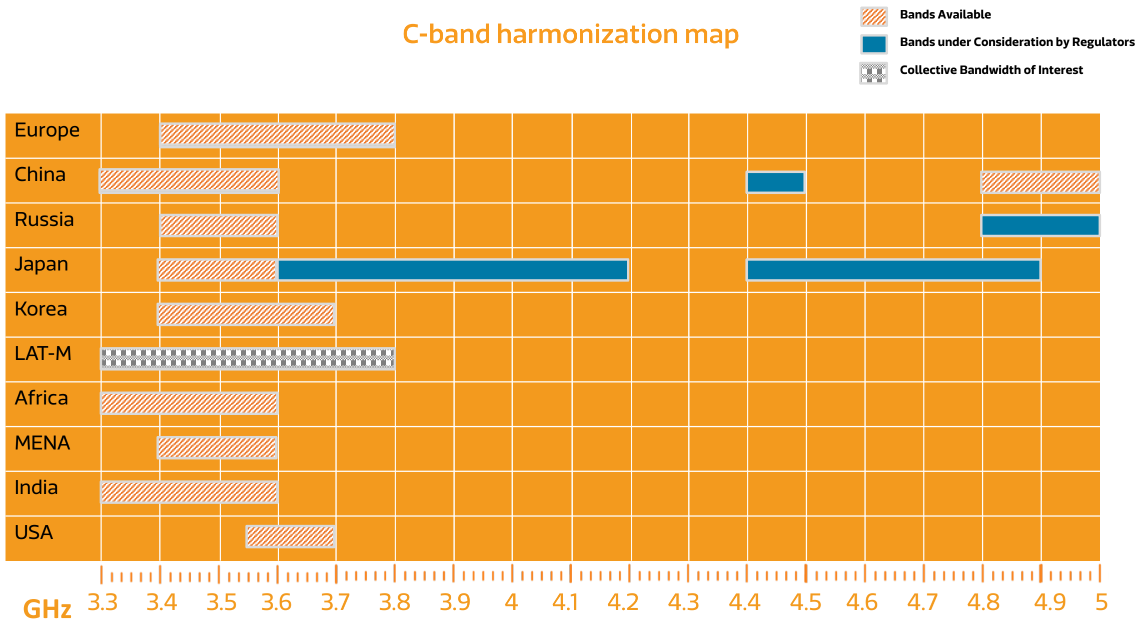


Figure 9: C -Band Harmonization across different regions

The table below provide the 27 bands defined for FR1 as per RAN4 #83 (12 FDD, 7 TDD, 2 SDL and 6 SUL).

Table 3: New Radio Frequency Bands (ref: RAN4 #83)

Band number	UL	DL	Duplex mode
n1	1920-1980 MHz	2210-2710 MHz	FDD FDD
n2	1850-1910 MHz	1930-1990 MHz	FDD
n3	1710-1785 MHz	1805-1880 MHz	FDD
n5	824-849 MHz	869-894 MHz	FDD
n7	2500-2570 MHz	2620-2690 MHz	FDD
n8	880-915 MHz	925-960 MHz	FDD
n20	832-862 MHz	791-821 MHz	FDD
n28	703-748 MHz	758-803 MHz	FDD
n38	2570-2620 MHz	2570-2620 MHz	TDD TDD
n41	2496-2690 MHz	2496-1690 MHz	TDD
n50	1432-1517 MHz	1432-1517 MHz	TDD
n51	1427-1432 MHz	1427-1432 MHz	TDD
n66	1710-1780 MHz	2210-2200 MHz	FDD
n70	1695-1710 MHz	1995-2020 MHz	FDD
n71	663-698 MHz	617-652 MHz	FDD
n74	1427-1470 MHz	1475-1518 MHz	FDD
n75	N/A	1432-1517 MHz	SDL
n76	N/A	1427-1432 MHz	SDL
n77	3.3-4.2 GHz	3.3-4.2 GHz	TDD
n78	3.3-3.8 GHz	3.3-3.8 GHz	TDD
n79	4.4-5.0 GHz	4.4-5.0 GHz	TDD
n80	1710-1785 MHz	N/A	SUL
n81	880-915 MHz	N/A	SUL
n82	832-862 MHz	N/A	SUL
n83	703-748 MHz	N/A	SUL
n84	1920-1980 MHz	N/A	SUL
n85	2496-2690 MHz	N/A	SUL

A new band operation mode is introduced in FR1, which is Supplementary Uplink (SUL), which is to be used through Carrier Aggregation or Dual Connectivity to provide Low-band UL for 3.5 GHz DL.

5 out of these defined bands are considered as pioneering bands for early deployment in 2020 by many carriers.

- **n77**: as shown above from the C-band harmonization plan, Japan possible allocation for 5G spans from 3.4 GHz
  to 4.2 GHz.
- **n78**: this band has a wider harmonization across different regions, especially Europe.
- **n79**: This band is starting to be considered for 5G allocation by regulators in China, Russia and Japan, as a possible extension for the Sub-6GHz spectrum.
- **n28**: to ensure the deep coverage with these bands for reliable communication, plus the UL limited link budget at these frequencies will require a huge number of cells deployment, that's why a lower frequency band needed to be identified, preferably below 1GHz, to ensure wide coverage. B28 (700 MHz), was identified as a pioneer candidate for the task as it was already announced in WRC-15, as a global harmonized band for mobile telecommunications, for countries where B28 is not available, B20 (800 MHz) is thought after as the second best choice available.

- Some deployment scenarios are considering B3 for UL pairing with n78 (3.5GHz) as B3 UL Coverage could be closely compared to 3.5GHz DL Coverage (assuming no massive MIMO beam forming gain), but it has to be highlighted that for this combination Maximum Sensitivity Degradation (MSD) could be foreseen due to the inter-modulation harmonics of these 2 bands as 3.5 is almost double frequency (and hence impacted by second harmonic) of B3.

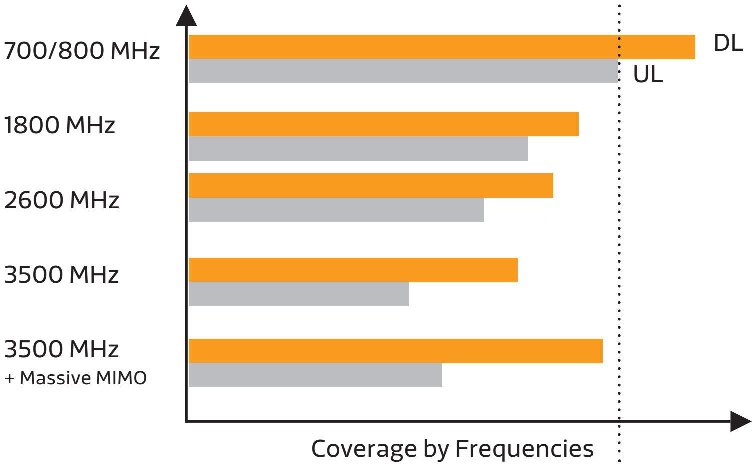


Figure 10: The UL coverage of 700MHz and DL Coverage of 3.5GHz with massive MIMO are almost similar.

- **n71**: considered by some carriers, especially in the US, with the target to provide wide 5G coverage for initial deployment.

Frequency Range 2 – mmWaves:

Even with the above bands identified, the throughput targets for 5G NR in later phases, reaching 50 Gbps, could not be achieved with the planned spectrum efficiency of 30 bps/Hz, that's why new frequency bands not previously used in cellular systems had to be considered. With these bands eMBB targets for 5G NR could be achieved leveraging the availability of ten times the amount of spectrum currently in use, with multiple GHz of contiguous spectrum.

The ITU organizes the World Radio communication Conference (WRC) every four years. The next one will take place in 2019, and (WRC-19) will be looking at spectrum for mobile broadband in the following frequencies bands:

Table 4: Possible ITU WRC-19 Frequency Bands

Bands already have allocations to mobile service on primary basis	Bands may requre additional allocations to the mobile service on a primary basis
24.25-27.6 GHz37-40.5 GHz	31.8-33.4 GHz
42.5-43.5 GHz	40.5-42.5 GHz
47.2-50.2 GHz	47-47.2 GHz

Nevertheless, and due to the complexity of global band harmonization, some countries might plan trials and deployments in specific non-globally harmonized bands, which is the case for the 28GHz band, targeted for 5G deployment by U.S., Korea and Japan while it is not in the ITU planned bands.

In other regions, possible example of such ranges could include 5.925-8.5 GHz and 10-10.6 GHz in Europe or 7.075 - 10.5 GHz and 15.35 - 17.3GHz in Africa.

As for 3GPP and RAN4 agreements, for Release 15 the interest is in frequencies up to 52.6 GHz only, higher frequencies will be looked into in next releases.

The identified bands in FR2 are in 3GPP are shown below:

Table 5: Frequency Range 2 Frequency Bands

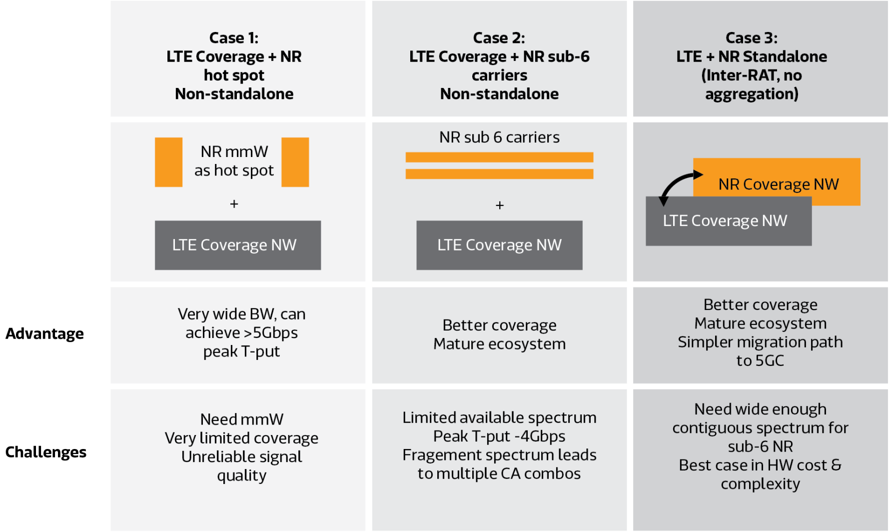
Band number	UL	DL	Duplex mode
n257	26.5 GHz-29.5 GHz	26.5-29.5 GHz	TDD
n258	24.75-27.5 GHz	24.75-27.5 GHz	TDD
n259	31.8-33.4 GHz	31.8-33.4 GHz	TDD
n260	37.40 GHz	37-40 GHz	TDD

bands agreed on by 3GPP will be pending ITU agreements for final approval, as for example, for Band n258, some concerns were raised by EESS (Earth Exploration Satellite System), on a possible impact utilizing this band, which might lead to change it starting allocation to allow for a sufficient guard band.

As a conclusion, the combination of lower and higher frequencies is therefore crucial for 5G operation. Lower bands can be devoted to coverage and control, while higher bands can provide better capacity and higher data rates. The lower and higher spectrum bands can operate in a carrier aggregation or dual connectivity model, and the Initial 5G specifications include such dual-connectivity capability as will be discussed in next chapters.

LTE + NR interworking

As discussed earlier, major initial 5G NR deployment could be summarized as follows



	Case 1: **LTE Coverage + NR hot spot Non-standalone**	**Case 2:** **LTE Coverage + NR sub-6 carriers Non-standalone**	**Case 3:** **LTE + NR Standalone (Inter-RAT, no aggregation)**
	NR mmW as hot spot + LTE Coverage NW	NR sub 6 carriers + LTE Coverage NW	NR Coverage NW LTE Coverage NW
Advantage	Very wide BW, can achieve >5Gbps peak T-put	Better coverage Mature ecosystem	Better coverage Mature ecosystem Simpler migration path to 5GC
Challenges	Need mmW Very limited coverage Unreliable signal quality	Limited available spectrum Peak T-put -4Gbps Fragement spectrum leads to multiple CA combos	Need wide enough contiguous spectrum for sub-6 NR Best case in HW cost & complexity

Figure 11: 5G NR Deployment

With non-standalone (NSA) option favored by many operators for initial deployment, LTE+NR interworking will have different implications on both network architecture, services and user equipment capabilities.

With option 3 initial deployment, for example Low latency application might have limitations on the achievable end to end latency, as while Low latency features introduced in Rel.14 and Rel.15 on LTE side, like short TTI and self-contained frame structures might improve Radio latency, the performance will be limited by the deployed EPC architecture and backhauling capabilities. A virtualized EPC design with Mobile edge Computing integration and backhauling upgrade might be required to achieve the expected targets for this application on NSA configuration.

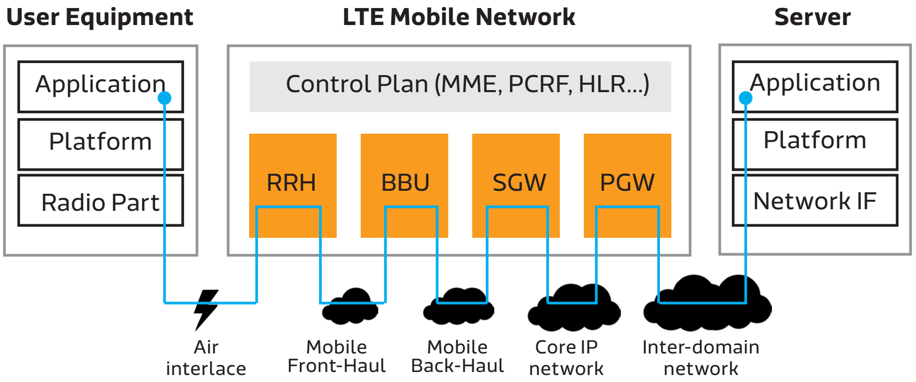


Figure 12: Latency Break down for LTE systems

With the New Generation Core (NGC) deployment, and integration of network slicing, Network Function virtualization (NFV) and Software defined network (SDN), more services and verticals could be addressed, after getting rid of the limitation imposed by legacy EPC core network.

And that's why NGC integration is not limited to 5G gNodeBs only, as LTE could also benefit from the new core capabilities and with 3GPP Rel15, LTE integration with NGC and its completely new NAS layer is referred to as eLTE or enhanced LTE.

From UE side, supporting the new bands for 5G NR, especially the mmWave bands, with the Dual Connectivity support required for NSA option and the carrier aggregation support expected for both LTE and NR will add to the complexity of the design of the RF front end, which includes the antennas, LNAs, filters, switches, and Power Amplifiers.

With multiple bands to cover, and parallel and simultaneous operations on different bands, complex designs are required to ensure minimum cross-talks and intermodulation distortion, efficient circuitry and minimum losses.

The amount of different band combinations for LTE+NR is huge, and it is an ongoing effort in 3GPP RAN4 to define the combinations to be supported within Rel15, the latest update as per RAN4 #83:

Table 6: 3GPP Rel-15 LTE+ NR Band Combination (ref: RAN4 #83)

CA Combination Type	Total CA combinations proposed	Total CA combinations proposed exluding mmWave CA
LTE_1CC_NR_1CC	99	71
LTE_2CC_NR_1CC	101	78
LTE_3CC_NR_1CC	69	56
LTE_4CC_NR_1CC	24	20
LTE_5CC_NR_1CC	1	1
CA intra-band xDL/1UL	2	0
CA intra-band 2DL/1UL	13	7
LTE_1uL_NR_ULDL	4	4
LTE_1CC_NR_2CC	5	5
LTE_2CC_NR_2CC	6	6
LTE_3CC_NR_2CC	4	4
LTE_4CC_NR_2CC	1	1
Total	**329**	**253**

But looking at all these different bands combinations, and considering the possible device implementation, DL combinations with 3 or 4CC LTE + 1 or 2 CC NR will have some negative impacts on device battery life due to the current requirements for activating the different needed RF components plus the processing capability requirements.

Nevertheless, such combinations are required for the cases where a carrier has a limited initial 5G spectrum allocation, for which leveraging the maximum throughput that LTE can provide is required to reach a “marketing grade” throughput for 5G promotions.

While for operators with large 5G Spectrum allocation (for example 100MHz Sub 6GHz carrier), having 1 or 2 LTE Carrier components to anchor the control plane is a more realistic approach.

Another aspect for the LTE+ NR interworking is the UL configuration expectations since within a Non-standalone configuration the UE is required to maintain 2 UL connections; one for LTE and the other for 5G NR. The 5G NR is expected to have UL 2x2 MIMO by default, but considering NSA deployment, following this requirement will mean that the UE will have to process 3 layers for UL, which introduce a new challenge.

- Using a single power amplifier, will mean that the power has to be split between the 3 layers leading to poor UL coverage.

- Using different power amplifiers to maintain the maximum power, and with 3 layers transmitting at the same time, battery consumption, heat dissipation will be negatively impacted, also SAR Concerns might be raised in some cases.

Studies and simulations are ongoing to draw a final conclusion, but maybe for such considerations, 2x2 MIMO in 5G NR could be promoted for Standalone deployment options while for NSA, a single layer 5G NR UL might make more sense.

5G NR Physical Layer

Introduction

For this section, we will go through the main aspects of the new physical layer, and while NR doesn't have to be backward compatible with LTE, we might be taking the LTE performance as a reference or a baseline to what we will have in NR.

From 3GPP point of view and for reference, the physical layer specification consists of a general document (TS 38.201), and six documents (TS 38.202 and 38.211 through 38.215). The relation between the physical layer specifications in the context of the higher layers is shown in Figure 13 below:

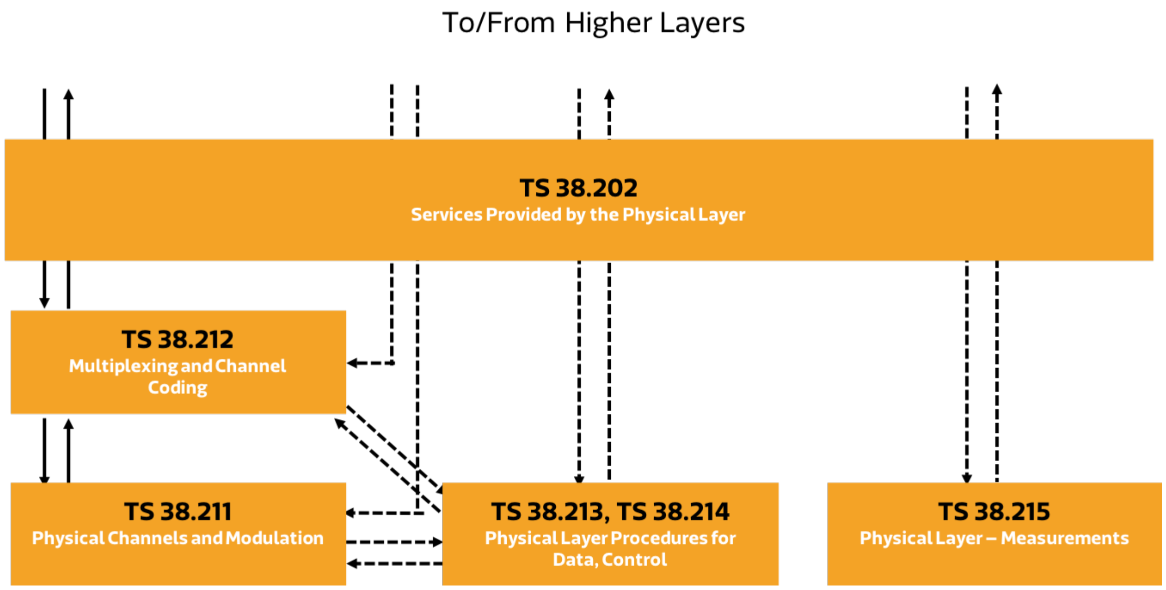


Figure 13: 3GPP Physical Layer Specs

Wave Form and Multiple Access Scheme:

Many options for waveforms were proposed at 3GPP, which required to set some performance targets to evaluate and compare each of them. The main targets proposed were the compatibility with MIMO, Spectral efficiency, Low Peak to Average Power ratio (PAPR), high time localization to support TDD systems and URLLC use cases, Acceptable complexity and low out of band emissions.

It was later agreed for 3GPP Release 15, that OFDM-based waveform with Cyclic Prefix (CP) will be supported for both DL and UL for 5G NR. DFT-S-OFDM based waveform will be also supported, complementary to CP-OFDM waveform at least for eMBB uplink for up to 40GHz. CP-OFDM waveform can be used for a single-stream and multi-stream (i.e. MIMO) transmissions, while DFT-S-OFDM based waveform is limited to a single stream transmissions targeting link budget limited scenarios.

But as a long term plan for the 5G-NR, and going beyond release 15, Orthogonal Multiple Access (OMA) is expected to fall short on delivering the required number of connections density required for mMTC (10^6 per Km^2), which is why the interest in Non-Orthogonal Multiple Access (NOMA) schemes is rising, an overview of these technologies is presented in the last section of this paper.

Numerologies:

With the vast use cases planned for NR, a scalable and flexible physical layer design is required for each one and different and scalable Numerologies are to be supported.

The main idea of OFDM is to divide a wide channel into orthogonal narrow subcarriers. A set of parameters define how this division is done and hence the OFDM system design, which are Sub-Carrier Spacing, Symbol length, cyclic prefix and transmission time interval (TTI). A Numerology is defined as a fixed configuration for this set of parameters.

Sub Carrier Spacing: a tradeoff between Symbol duration (the lower the SCS, the larger the symbol duration) and CP overhead (the higher the SCS the larger the CP overhead). It is proposed to be scaled as Δf * 2^N. This is to achieve high multiplexing efficiency between different numerologies. The subcarrier spacing varies with the frequency of the operating band and/or maximum UE speed to minimize the impact of the Doppler shift and phase noise.

CP Length: a tradeoff between CP overhead and ISI protection. It should be determined by deployment types (e.g, outdoor vs. indoor), and frequency bands, service type (e.g., unicast or broadcast) or determined by whether beam forming technology is used or not.

Number of Symbols per TTI: a tradeoff between latency (the lower the number of symbol, the better the latency) and spectral efficiency (the lower the number of symbols the higher the overhead of control Channels). It is proposed to be scaled as 2^M symbols per TTI. This is to ensure flexible TTI downscaling for URLLC (Ultra Reliable Low Latency Communication) from 2^M symbols to 1 symbol.

For 5G NR, 5 different Numerologies are defined, with one Numerology corresponds to one subcarrier spacing in frequency domain, allowing for scalable sub-carrier spacing from 15 KHz to 240 KHz. A slot consists of 14 OFDM symbols for all different SCS. For Sub-6GHz, SS blocks (beacon) can use 15 or 30 KHz, while for data transmission 15, 30 and 60 KHz could be used, as for mmWave; SS blocks (beacon) can use 120 or 240 KHz, while for data transmission 60 and 120 KHz could be used.

Table 7: Supported OFDM Numerologies

μ	Δf=15x2^μ	Cyclic prefix	Slot configuration		
			N^{slot}_{symb}	N^{frame}_{slot}	$N^{subframe}_{slot}$
0	15	Normal	14	10	1
1	30	Normal	14	20	2
2	60	Normal	14	40	4
		Extended	12	40	4
3	120	Normal	14	80	8
4	240	Normal	14	160	16

Multiplexing different numerologies within a same NR carrier bandwidth (from the network perspective) is supported in TDM and/or FDM manner for both downlink and uplink.

While from UE perspective, multiplexing different numerologies is performed in TDM and/or FDM manner within/across a subframe duration.

The different numerologies are applied to different deployments and will allow for different performance. For example the lower the Sub carrier spacing the larger the cell size will be, which will be suitable for the lower frequency deployment. At the same time larger sub carrier spacing will allow for better latency performance since the symbol duration will be shorter.

These different aspects could be summarized in the below diagram, showing for each frequency range, what are the possible numerologies applied and what is the expected cell size and latency performance for such configuration.

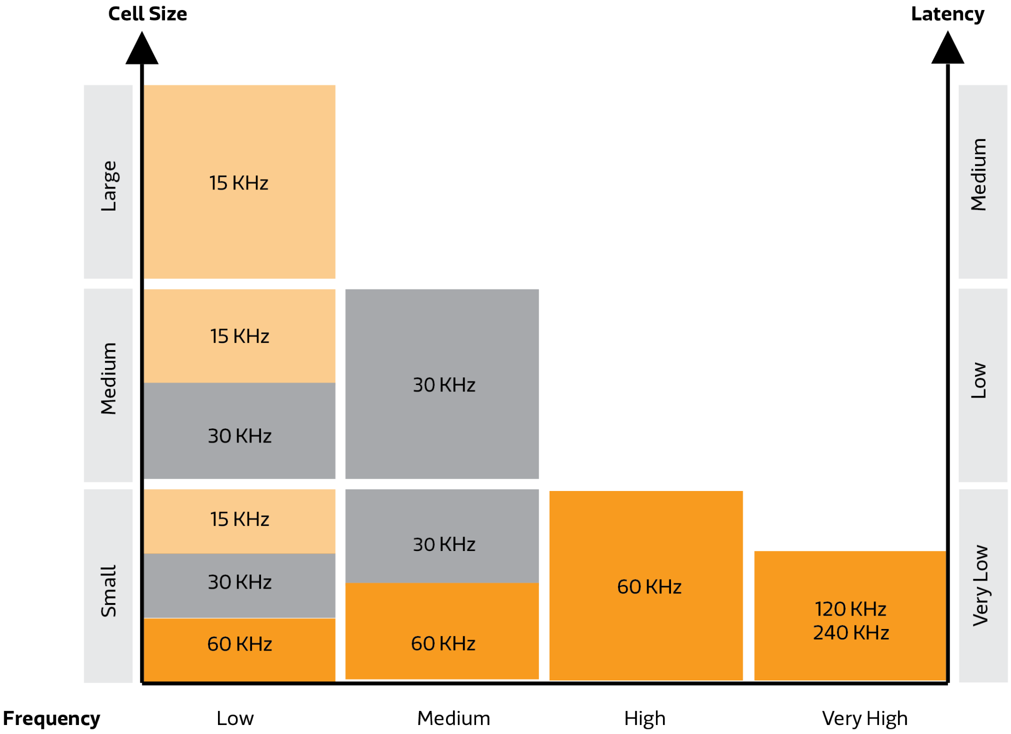


Figure 14: Numerologies versus frequency versus cell size

Frame Structure

Regardless of the numerology used, the length of one radio frame is fixed to 10ms and the length of 1 Sub-Frame is fixed to 1ms, which is used as a timing tick for the physical layer configuration.

Different Numerologies will be then translated in the number of slots per sub-frame. The higher the Sub-carrier spacing, the higher the number of slots per sub-Frame.

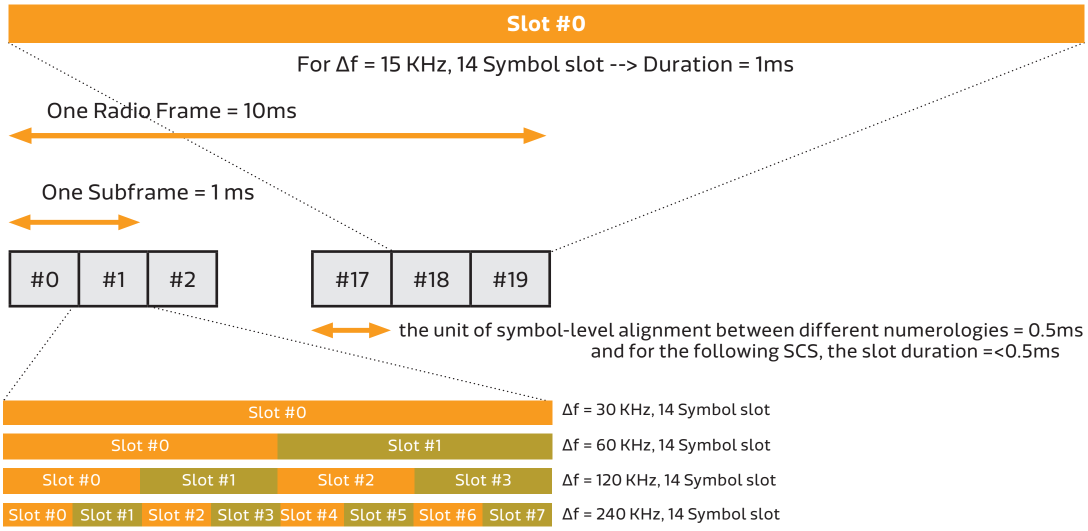


Figure 15: Frame, Sub frame and Slot Structure

2 slot configurations are defined, slot configuration 0, containing 14 OFDM symbols and could be applied to all Numerologies and Slot configuration 1, containing 7 OFDM symbols applied only for SCS less or equal to 60 KHz.

As for the structure, any slot, except for the ones carrying beacon transmissions, can be all downlink, all uplink, or at least one downlink part and at least one uplink part, which gives the option to have a Self-contained integrated subframe that combine scheduling, data, and acknowledgement.

Slot aggregation is supported, i.e., data transmission can be scheduled to span one or multiple slots and the slot type switching done by physical signaling through a narrow band anchor.

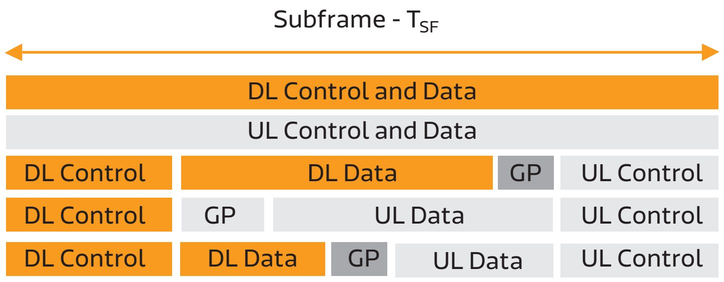


Figure 16: Different Subframe structures

Some new concepts were added to the frame structure definitions to deal with the different numerologies and the wide carrier bandwidth in 5G NR, notably the Carrier Bandwidth Part concept, which was proposed by MediaTek to allow for the multiplexing of narrowband and wideband UEs and to allow for UE bandwidth adaptation for power savings. A Bandwidth part is defined as a contiguous set of physical resource blocks selected from a contiguous subset of the common resource blocks for a given numerology (u) on a given carrier.

A UE can be configured with up to four carrier bandwidth parts with only one carrier bandwidth part active at a given time

The UE is not expected to receive PDSCH, PDCCH, CSI-RS outside and active bandwidth part.

Carrier resource blocks (CRB) are numbered from 0 to Max-1 RB of a carrier while Physical Resource Blocks PRB are defined within a carrier BW part as illustrated in Figure 17.

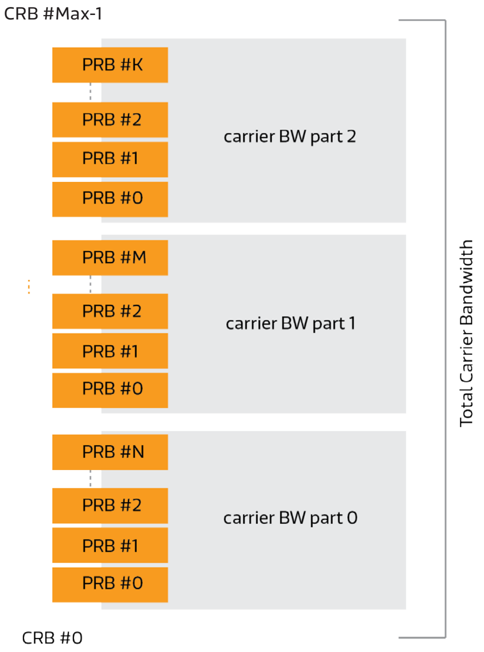


Figure 17: Carrier BW part concept

Physical Channel Bandwidth:

It was agreed that max channel bandwidth is 100MHz for sub6 and 400MHz for mmWave.

Compared to LTE, 5GNR is designed to have higher Bandwidth efficiency, reaching 99% (compared to 90% in LTE, where 100 RB covered only 18 MHz in a 20 MHz Bandwidth carrier)

Another difference with LTE is that there is no explicit DC subcarrier reserved both for downlink and uplink.

Table 8: Minimum and Maximum Bandwidth Relation with Supported Numerologies

U	min RB	Max RB	sub carrier spacing (kHz)	Freq BW min (MHz)	Freq BW max (MHz)
0	24	275	15	4.32	49.5
1	24	275	30	8.64	99
2	24	275	60	17.28	198
3	24	275	120	34.56	396
4	24	138	240	69.12	397.44

Whatever the numerology used, a resource block consists of 12 Sub-carriers, but for each numerology a minimum and maximum number of resource blocks is defined, and with the knowledge of the corresponding Sub-carrier spacing the minimum and Maximum Bandwidth for the channel could be calculated, as shown above.

Synchronization and Reference Signals:

In 5G NR, Primary Synchronization Signal (PSS) and Secondary Synchronization signal (SSS) are used by UE for initial cell search to obtain frame timing, Cell ID and find reference signals for demodulation.

PSS, SSS, and NR-PBCH are transmitted in a synchronization signal block (SS block) by time-domain multiplexing (TDM) with the same numerology. One or more SS Block(s) compose an SS burst, one or more SS Burst compose an SS Burst Set. SS Burst Sets are transmitted periodically.

An SS block consists of 4 consecutive OFDM symbols

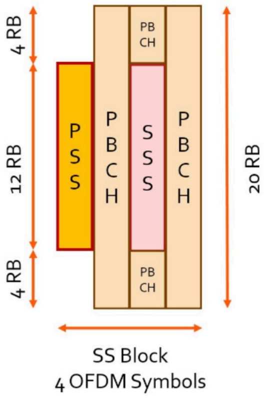


Figure 18: SS Block

- First symbol: PSS with 12 RB’s
- Second symbol: PBCH with 20 RB’s
- Third symbol: SSS with 12 RB’s + upper PBCH with 4 RBs + lower PBCH with 4 RBs
- Last symbol: PBCH with 20 RB’s

For 5G NR, there are 1008 unique physical-layer cell identities that are grouped into 336 unique physical-layer cell-identity groups, each group containing three unique identities.

A physical-layer cell identity is uniquely defined by a number $N_{ID}^{(1)}$ in the range of 0 to 335, representing the physical-layer cell-identity group, and a number $N_{ID}^{(2)}$ in the range of 0 to 2, representing the physical-layer identity within the physical-layer cell-identity group as in the following simple formula.

$$N_{ID}^{cell} = 3N_{ID}^{(1)} + N_{ID}^{(2)}$$

As for the reference signals, In LTE Cell Reference Signals (CRS) were designed to be continuously broadcasted, and to be distributed in both Time and Frequency domain across the whole carrier Bandwidth to help the UE to lock the time/frequency raster and ease the decoding of DL data.

Such design has different draw backs, the large number of resource elements (RE) carrying CRS are always transmitting even when there is no users in the cell, wasting DL power and causing interference to all neighboring cells.

Later in LTE, DM-RS were used instead of CRS for decoding of data, and features like lean carrier/Pilot breathing were proposed to limit CRS broadcast.

5G NR is designed to have ultra-lean physical layer, replacing continuous reference signals with on-demand ones:

CSI-RS: Reference signal with main functionalities of CSI acquisition, beam management. CSI-RS resources for a UE is configured by RRC information elements, and can be dynamically activated/deactivated via MAC CE or DCI.

DM-RS: Reference signals which are UE specific and could be beam formed, will be used for data and control demodulation. They are transmitted only on the PRBs upon which the corresponding PDSCH is mapped.

A new type of reference signals is introduced, called Tracking Reference Signals, and it is used for:

- Time and Frequency tracking at UE side
- Estimation of delay spread and Doppler spread at UE side

It is transmitted in a confined bandwidth for a configurable period of time, controlled by upper layers parameters.

UE Measurements:

As in NR the idea of getting lean reference signal design, and get rid of the Cell Reference Signals (CRS) overhead, previously used in LTE, a new definition for UE measurements had to be put in place, and below some of the new definition for measurement metrics are provided.

SS-RSRP: is defined as the linear average over the power contributions (in [W]) of the resource elements that carry SSS. For RSRP determination, demodulation reference signals for PBCH and, if indicated by higher layers, CSI RS in addition to SSS may be used. This measurement is applicable for Idle, Inactive and Connected modes for both intra and inter frequency measurements.

CSI-RSRP: is defined as the linear average over the power contributions (in [W]) of the resource elements that carry CSI-RS configured for RSRP measurements within the considered measurement frequency bandwidth in the configured CSI-RS occasions. CSI reference signals are transmitted on specific antenna ports. This measurement is applicable for connected mode only for both intra- and inter frequency measurements

For each of the above RSRP measurements, a corresponding RSRQ measurement could be derived.

SS_RSRQ: is defined as the ratio of N×SS-RSRP /NR carrier RSSI, where N is the number of resource blocks in the NR carrier RSSI measurement bandwidth. The measurements in the numerator and denominator shall be made over the same set of resource blocks

CSI-RSRQ: is defined as the ratio of N×CSI-RSRP to CSI-RSSI, where N is the number of resource blocks in the RSSI measurement bandwidth. The measurements in the numerator and denominator shall be made over the same set of resource blocks.

And also a SINR corresponding metric could be defined as follows:

SS-SINR: is defined as the linear average over the power contribution (in [W]) of the resource elements carrying SSS divided by the linear average of the noise and interference power contribution (in [W]) over the resource elements carrying SSS within the same frequency bandwidth.

CSI-SINR: is defined as the linear average over the power contribution (in [W]) of the resource elements carrying CSI reference signals divided by the linear average of the noise and interference power contribution (in [W]) over the resource elements carrying CSI reference signals within the same frequency bandwidth

Where both SS-SINR and CSI-SINR are applicable for connected mode measurement only.

For frequency range 1, the reference point for all the measurements above shall be the antenna connector of the UE.

Modulation:

For 5G NR, the modulation schemes supported are

- For OFDM with CP and for both DL/UL: QPSK, 16QAM, 64QAM, and 256QAM (with the same constellation mapping used in LTE)
- For the DFT-s-OFDM with CP for UL: π/2-BPSK, QPSK, 16QAM, 64QAM and 256QAM.

π/2-BPSK was added for UL, with mMTC in mind to achieve better efficiency for Power amplifiers for Lower PAPR in very low data rate cases.

But aside the π/2-BPSK, these are the same Modulation orders currently used in LTE-A, and hence studies and discussions are ongoing for adding the support of 1024QAM to the list of supported modulations.

From theoretical point of view, 1024QAM should provide 25% gain in throughput compared to 256QAM, as 1 symbol will carry 10 bits instead of 8 bits. But the problem is coming from the real deployment, as for proper decoding of the high order modulation transport blocks, a very high SINR levels are required to achieve acceptable BLER targets.

But again, as highlighted above the idea of lean reference signals is already in place for NR, which might be an enabler to go for further higher order modulation like 1024QAM.

Channel Coding:

Channel coding is one of the areas where 5G NR is taking a completely different path from LTE.

For 5G NR Low Density Parity Check (LDPC) coding is replacing the Turbo coding that was previously used for PDSCH coding and Polar Codes are replacing the Tail Biting Convolutional Codes (TBCC) used previously for PDCCH coding, except for very small block lengths where repetition/block coding may be preferred.

Turbo codes generally have a low encoding complexity and high decoding complexity whereas LDPC codes have it vice versa. Considering eMBB use case with code block sizes greater than 10,000 and the code rate reaching 8/9, Turbo codes falls short for the implementation complexity required at decoder.

LDPC codes on the other hand have relatively simple and practical decoding algorithms. Decoding is done by iterative belief propagation. The accuracy of decoding will be improved in each iteration and the number of iterations is decided based on the requirement of the application, providing a tradeoff between the bit error performance, latency and complexity.

In terms of latency, LDPC codes are parallel in nature while Turbo codes are serial in nature, which allow LDPC to support low latency application in a better way than Turbo codes.

Also Turbo codes BER have higher error floor BER compared to LDPC, and LDPC parity-check matrix can be extended to lower rates than the LTE turbo codes, achieving higher coding gains for low rate applications targeting high reliability.

As for Polar codes, they were introduced in 2009 and they are the first provably capacity-achieving codes with low encoding and decoding complexities. They provide full flexibility with very good performance in any code length and code rate without error floor i.e. they do not suffer a decrease in the slope of BLER versus SNR.

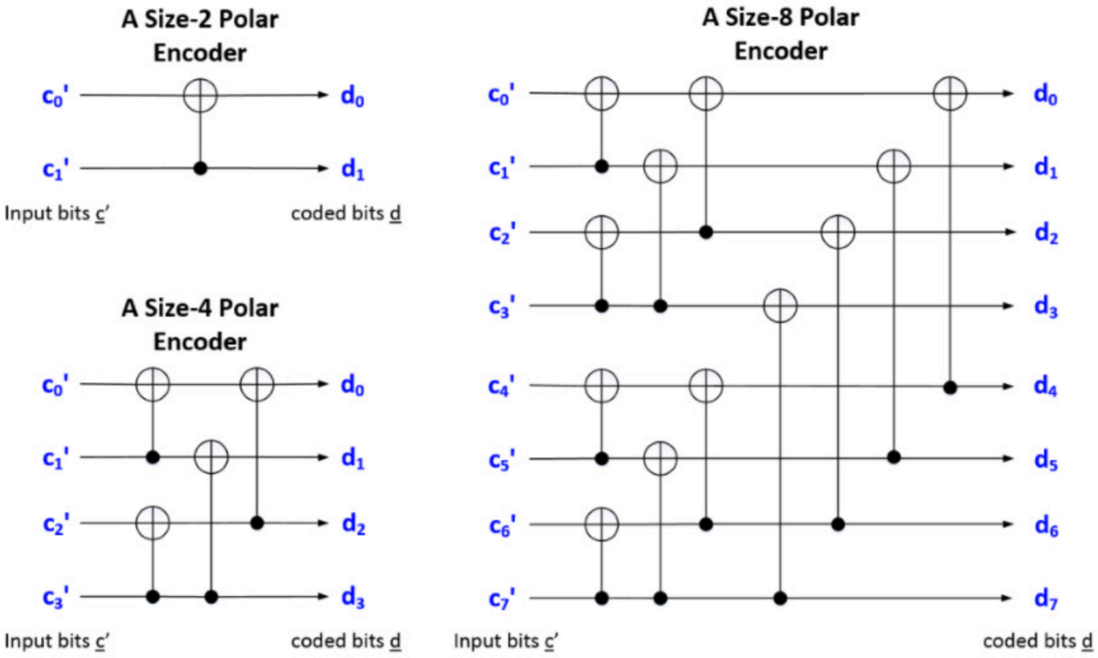


Figure 19: Polar Encoder of different sizes

Multiple Antenna Techniques and Beamforming:

Looking at the frequency ranges planned for NR operation, different characteristics lead to different design requirements for MIMO systems.

Lower frequency bands tend to be in FDD mode, and hence CSI-RS transmission in DL and reporting in UL is required for the proper performance. Also with smaller bandwidth, capacity enhancement solutions like MU-MIMO is required to be supported.

For these bands, the plan is to extend Release 13 and Rel14 FD-MIMO framework to support 64,128 or even 256 total physical elements, with flexible CSI acquisition and beamforming.

Higher frequency bands tend to be in TDD and hence reciprocity based operation could be assumed. Also for mmWave, higher number of antenna elements could be used, increasing the beam forming gain, specially required for the high losses propagation at these bands.

With the high number of Antenna elements planned, Hybrid beamforming architecture was proposed to achieve the balance between system performance from one side and complexity and cost from another side. Simply rather than supporting each antenna element with a dedicated RF Chain, Multiple array elements are combined into subarray modules. Each element within a subarray has a phase shift applied directly in the RF domain, while digital beamforming techniques are applied on the signals that feed each subarray.

In LTE, many transmission modes were introduced to individually optimize the MIMO performance for each deployment scenario. The switching between those transmission modes is semi-static and cannot dynamically adapt to the changing environment. In NR, dynamic adaptation of transmission schemes will be adopted.

The table next page provide a summary of the physical layer changes for 5G NR in comparison with LTE for reference.

Table 9: Detailed Comarison between TEl and NR (3GPP Rel-15)

	LTE	R15 NR
Frequency Range	<6GHz	Up to 52.6 GHz (really high frequency usage)
Services	Voice, MBB	Voice, eMBB, URLLC
Waveform	DL: CP -OFDM; UL: DFT -S-OFDM	DL: CP-OFDM; UL: CP-OFDM, DFT-S-OFDM
Max Carrier Bandwidth	20MHz	Sub6: 100MHz; Above6: 400MHz
Subcarrier Spacing (SCS)	15KHz	15/30/60/120/240KHz
Cylic Prefix	Normal CP; Extended CP	Normal CP for all SCSs; Extended CP for 60KHzs SCS only
Max Number of Subcarriers Per Carrier	1200	3300
Radio Frame Length	10ms	10ms
Slot Size	2/7/14 OFDM symbols	1-14 OFDM symbols (including both slot & mini-slot)
UL/DL Ratio Change	Semi-static change with 5/10ms periodicity; Dynamic change per -10ms	Semi-static change with 0.5/0.625/1.25/2.5/5/10ms periodicity Dynamic change per 1/2/5/10/20ms change
Synchronization Signals	PSS: 6_2 ZC sequence; SSS: 6_2 m-sequence; Periodicity: 5ms	PSS: 127 m-sequence SSS: 127 Gold-sequence Periodicity: 20 ms for intial access;{5, 10,20,40,80,160}ms for CONNECTED/IDLE mode
PBCH	4-symbolx 72 subcarriers; Content: 40bits, including CRC bits Periodicity: 10ms	2-symbol x 288 subcarriers; Content: 56 bits, including CRC bits Periodicity: 20 ms for intial access;{5, 10,20,40,80,160}ms for CONNECTED/IDLE non-standalone cases
SS-block Sweeping	1	4 for <3GHz; 8 for 3-6GHz; 64 for 6-52.6GHz
RACH	PRACH: 839 ZC sequence with 1.25KHz; 4-step RACH	Long PRACH: 839ZC sequence with {15,30,60,120} KHz 4-step RACH
MIMO Transmission	Digital beamforming; Diversity Tx:SFBC; Open-loop TX:CDD with precoder cycling (PC); 1-port PC Closed-loop TX:Spatial multiplexing	Hybrid (analog = digital) beamforming; Open-loop Tx: 1-port PC (UE transparent); Closed-loop Tx: Spatial multiplexing
Reference Signals	DL:CRS, DMRS, CSI-RS; UL: DMRS, SRS	DL: DMRS, PT-RS (phase tracking RS) CSI-RS, TRS; UL: DMRS, PT-RS, SRS
Channel Coding	PBCH/PDCCH; TBCC; PDSCH/PUSCH: Turbo code; PUCCH: RM block code	PBCH/PDCCH/PUCCH: Polar code; PDSCH/PUSCH: LDPC
PDCCH	Multiplexing with data: FDM; Tx: Distributed + SFBC; Demodulation: CRS	Multiplexing with data: TDM/FDM; Tx1 Distributed - precoding (UE transparent); Tx2 Localied = precoding (UE transparent);
PUCCH	Multiplexing with data: FDM; PUCCH size: 14 OFDM symbols	Multiplexing with data: TDM/FDM; Long PUCCH size: 4-14 OFDM smbols; Short PUCCH size: 1-2 OFDM symbols;
HARQ Round-trip Time	FDD: 9ms; TDD: ≥ 8ms	0.25-16 ms
Wideband Operations	Single Carrier: Up to 20MHz; Full carrier BW initial access & IDLE; No UE bandwidth adaptation; CA: Up to 32 carriers; DuCo: Up to 64 carriers	Single Carrier: Up to 100 MHz or 400 MHz; Narrowband anchor intial access & IDLE; UE bandwidth adaptation allowed; CA: Up to 16 carriers; DuCo: up to 32 carriers
Mobility	CRS-based RSRP	SSS-based RSRP for cell or beam; CSI-RS based RSRP for beam or transmission point

5G User Plane

5G NR User Plane (UP) will in many aspects build up on the LTE concepts. However there are differences of course. The protocol stack for NR UP will follow the Figure 20 and is generally applicable to the new 5G radio access network i.e. NG-RAN (containing both 5G NR and LTE).

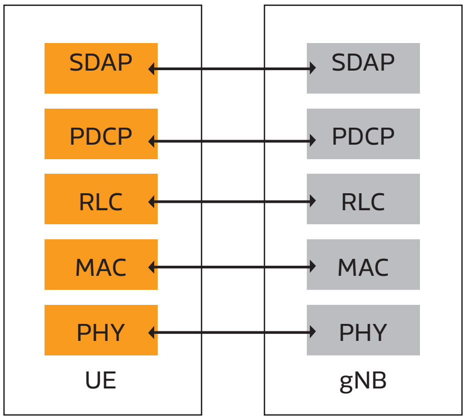


Figure 20: NR UP Protocol Stack

A new layer SDAP is introduced which stands for Service Data Adaptation Protocol. The functions of this new layer are bound to the new QoS framework of the 5G System (in the 5G Core). SDAP will also apply to LTE when connected to the 5G Core (i.e. Options 5, 7) It is responsible for the following tasks

Mapping between a QoS flow and a data radio bearer

Marking of QoS Flow ID (QFI) in DL and UL packets

The new QoS framework is shown in Figure 21. It enables uplink QoS mapping in two ways – either it is a reflective mapping meaning that for each DRB (Data Radio Bearer), the UE monitors the QFIs and headers the downlink packets and applies same QoS policy for the corresponding uplink packets or it can be an explicit configuration – in this case the network may directly order required QFI for the DRB uplink via RRC.

Overall the introduction of new SDAP layer enables the first ever true end-to-end QoS framework working in both directions.

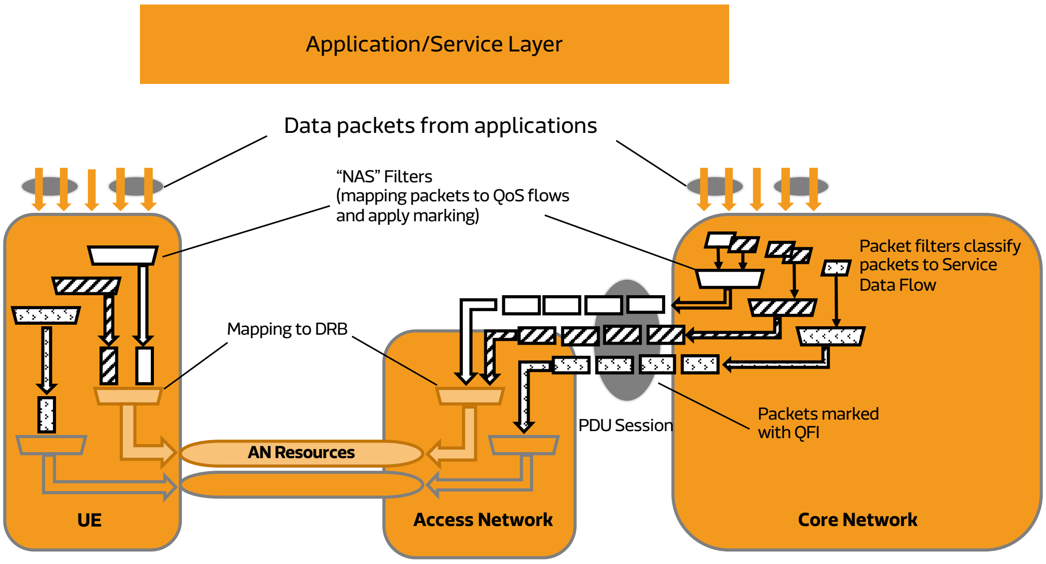


Figure 21: 5G System QoS

Other layers of the NR UP are designed to provide various enhancements to the existing LTE systems. We will go through these enhancements to see what is new on the table and what the motivation behind each solution is.

Let's start with PDCP layer which stands for Packet Data Convergence Protocol. The functions of PDCP are:

- ▪transfer of data (user plane or control plane);
- ▪maintenance of PDCP Sequence Numbers (SNs);
- ▪header compression and decompression using the ROHC protocol;
- ▪ciphering and deciphering;
- ▪integrity protection and integrity verification;
- ▪timer based SDU discard;
- ▪for split bearers, routing or duplication;
- ▪reordering and in-order delivery;
- ▪duplicate discarding;

One of the enhancements introduced for PDCP layer is designed for Receive operation and aimed at overcoming the LTE PDCP Out-of-Order deciphering drawback of LTE. In LTE the in-sequence delivery from RLC layer is causing the latency to be increased due to deciphering and re-ordering delays at lower level. In NR there is no re-ordering at RLC anymore and PDCP PDU can be delivered out-of-order. PDCP is enabled to track such deliveries and decipher/perform integrity checking only in case if the SN of the received PDU does not matches the flow. If integrity checking is successful the PDU shall be stored in buffer until the PDU with lower SN is received from RLC. After that the PDUs will be re-ordered and corresponding SDUs will be sent to the upper layer in correct sequence.

Another important enhancement targeting URLLC use cases is **data duplication** for Carrier Aggregation (CA) and Dual Connectivity (DC) based on PDCP split bearer. This concept has all chances to be accepted by 3GPP rather than competing options based on the same MAC PDU (which enables transmission synchronization between carriers) and MAC duplication of MAC SDU among carriers (which represent similar advantages but appears to be more complicated in implementation). DC-based PDCP duplication provides a flexible way to achieve diversity for different deployment and backhaul scenarios, by building on separate MAC/schedulers. For URLLC highly reliable transmissions with a very low BLER are targeted (e.g. 10^-5 residual error). The PDCP duplication solutions helps in maintaining this low residual error rate, in cases it cannot be reached on the respective carriers e.g. due to a temporary outage/fading dip, or due to unanticipated change or wrong channel state information

The MAC duplication with PDCP split bearer is represented at **Figure 22.**

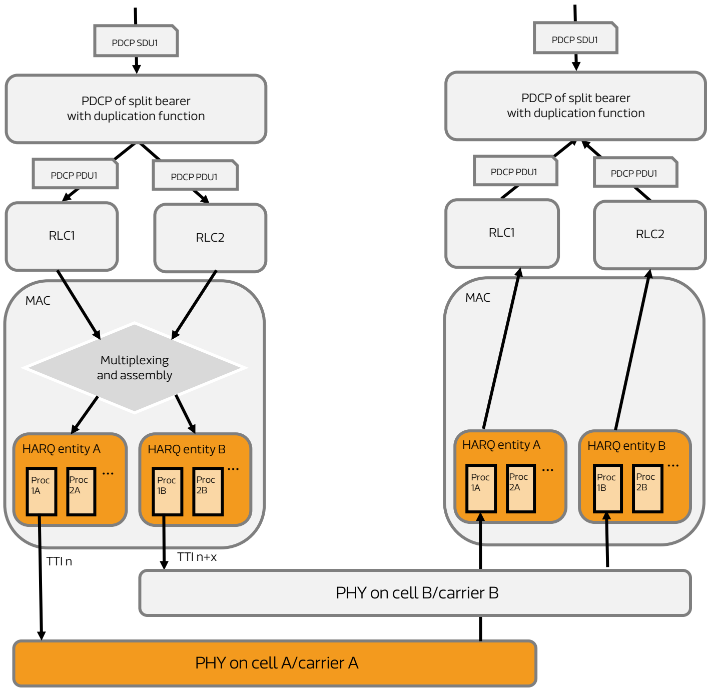


Figure 22: MAC Duplication in CA with PDCP bearer split

Now let’s see what is new at the RLC layer (of which MediaTek is rapporteur in 3GPP RAN WG2). RLC operates in one of three transmission modes – Unacknowledged (UM), Acknowledged (AM) and Transparent (TM). The RLC configuration is per logical channel with no dependency on numerologies and/or TTI durations, and ARQ can operate on any of the numerologies and/or TTI durations the logical channel is configured with. For SRB0, paging and broadcast system information, TM mode is used. For other SRBs AM mode used. For DRBs, either UM or AM mode are used.

RLC layer maintains the following functions:

- ▪transfer of upper layer PDUs;
- ▪error correction through ARQ (only for AM data transfer);
- ▪Segmentation and reassembly of RLC SDUs (only for UM and AM data transfer);
- ▪re-segmentation of RLC SDUs or RLC SDU segments (only for AM data transfer);
- ▪duplicate detection (only for AM data transfer);
- ▪RLC SDU discard (only for UM and AM data transfer);
- ▪RLC re-establishment
- ▪Protocol error detection (only for AM data transfer).

The other new concept besides already mentioned absence of re-ordering for NR RLC comparing to LTE is no concatenation of RLC SDUs aiming the latency improvement. The example of L2 Data flow is depicted on Figure 23, where a transport block is generated by MAC by concatenating two RLC PDUs from RBx and one RLC PDU from RBy. The two RLC PDUs from RBx each corresponds to one IP packet (n and n+1) while the RLC PDU from RBy is a segment of an IP packet (m).

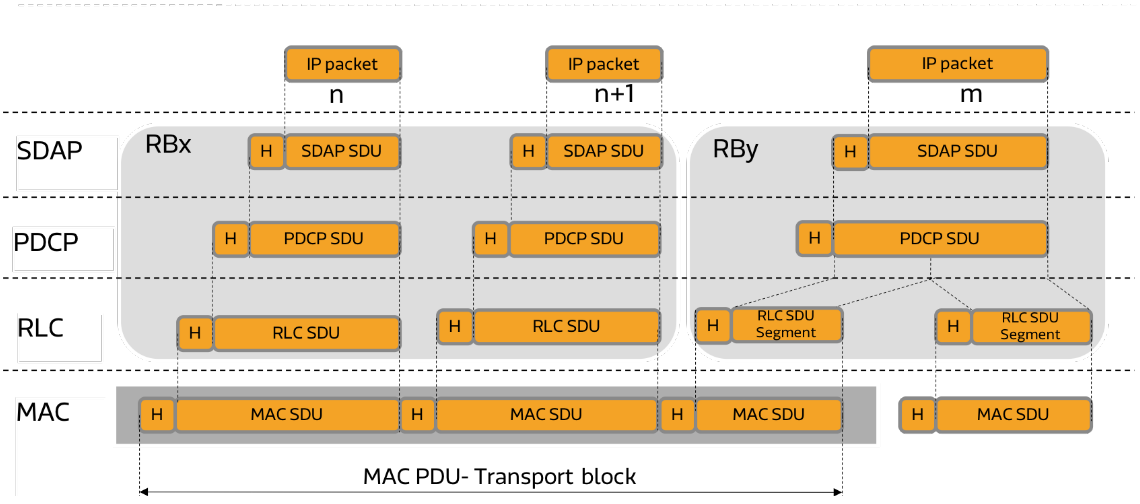


Figure 23: Data Flow Example

Let’s now take a look at the MAC sublayer. Its functions include

- ▪Mapping between logical and transport channels;
- ▪Multiplexing/demultiplexing of MAC SDUs belonging to one or different logical channels into/from transport blocks (TB) delivered to/from the physical layer on transport channels;
- ▪Scheduling information reporting;
- ▪Error correction through HARQ (one HARQ entity per carrier in case of CA);
- ▪Priority handling between UEs by means of dynamic scheduling;
- ▪Priority handling between logical channels of one UE by means of logical channel prioritisation;
- ▪Padding.

A single NR MAC entity can support one or multiple numerologies and/or TTI durations and mapping restrictions in logical channel prioritization (LCP) controls which numerology and/or TTI duration a logical channel can use. This is the one enhancement comparing to LTE. For the purpose of LCP, the MAC entity learns the TTI duration/numerology from the PHY layer. Logical channel priority is configured per UE as a baseline.

Different kinds of data transfer services as offered by MAC. Each logical channel type is defined by what type of information is transferred. Logical channels are classified into two groups: Control Channels and Traffic Channels. Both logical channels and their mapping to transport channels are exactly same as that used in LTE.

The enhancement was made to the MAC PDU format. Following agreements were reached in RAN2 WG:

- ▪MAC SDUs, MAC subheaders, and MAC PDU are byte aligned (i.e., multiple of 8 bits).
- ▪MAC subheaders are placed immediately in front of the corresponding MAC SDUs, MAC CEs (Control Elements), or padding. The possibility to parse the MAC PDU from the back is not precluded. This allows to arrange parallel processing of MAC and PHY layers.
- In LTE the MAC header containing all the subheaders was placed strictly ahead of the MAC payload
- ▪MAC CEs are grouped together
- ▪UL MAC CE(s) is placed after all the MAC SDUs. For DL the placement will be deterministic (i.e. it should not be up to the network to decide).

The proposed structure of MAC PDU is shown in **Figure 24**

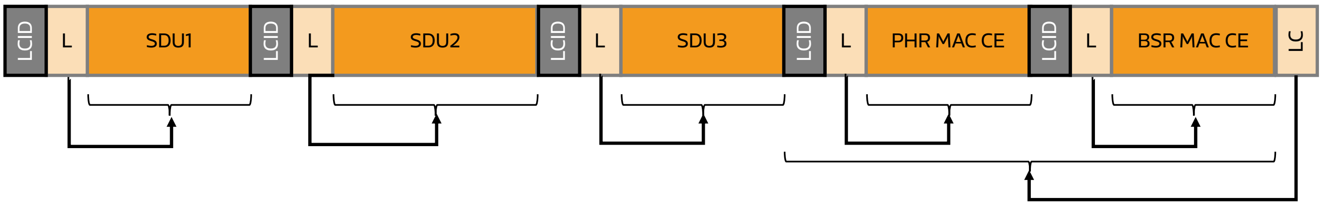


Figure 24: Proposed structure of MAC PDU

Code Block Group (CBG) based transmission with single or multi bit HARQ-ACK feedback is supported. For the case of CBG-based re-transmission, HARQ-ACK multiplexing should also be supported. The motivation for CBG-based re-transmission is improving spectrum

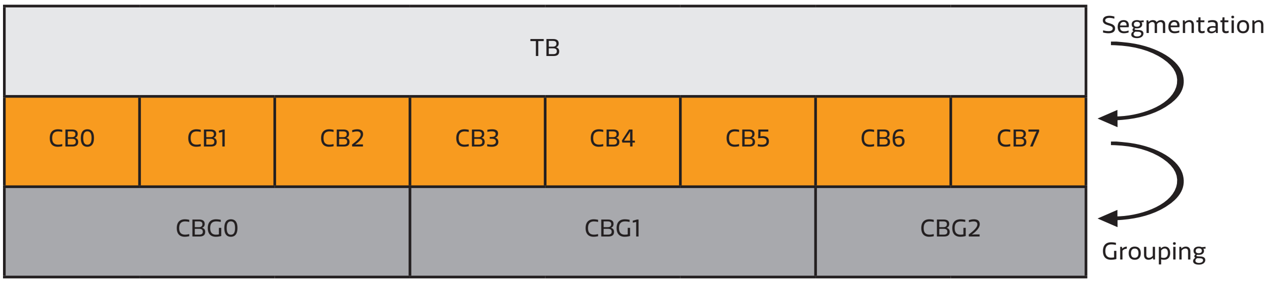


Figure 25: CBG Transmission

5G Control Plane

The NR CP protocol stack can be seen on Figure 26. It is applicable equally to 5G NR and LTE, in the 5G System (i.e. with the new 5G Core).

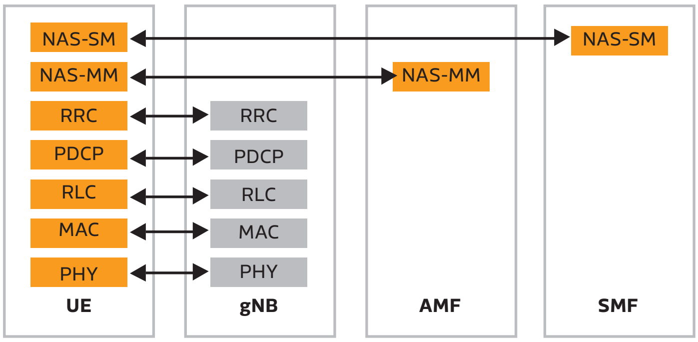


Figure 26: NR Control Plane Protocol Stack

*NAS – Non Access Stratum, AMF –Access and Mobility Management Function, SMF – Session Management Function

The connection management in the 5G System is enhanced with a new RRC state – RRC INACTIVE. This state is comparable to UMTS CELL_PCH. It is intended to reduce signaling for always-on UEs. Its main characteristics are:

- Cell reselection mobility
- Established CN-RAN connection for both CP and UP
- The UE AS context is stored at the UE and in gNB
- NR knows the RAN-based notification area which the UE belongs to NR RRC states and transitions between them are shown on **Figure 27**. State transitions between new RRC INACTIVE state and RRC CONNECTED/RRC IDLE study is still in progress.

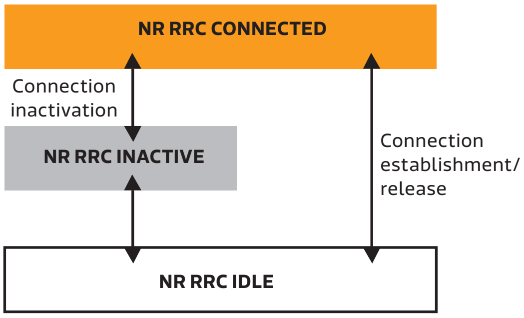


Figure 27: NR RRC Layer States

Other NR RRC features include on-demand broadcast meaning that the gNB does not need to broadcast all the system information at all times but rather makes use of the stored system information in the UE. The new system information broadcasting concept is depicted on **Figure 28.**

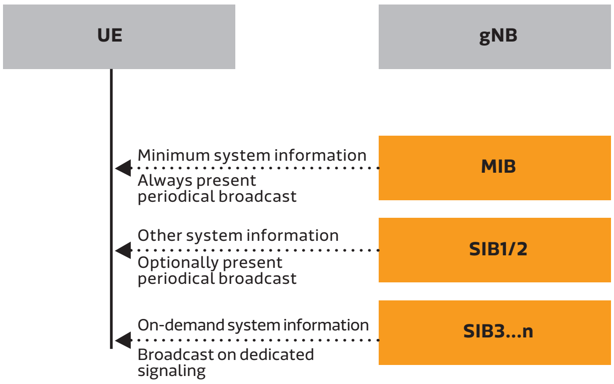


Figure 28: System Information Blocks in NR

Now a few words about 5G NAS signaling.

One of the key features of 5G System is that it is access agnostic meaning it supports both 3GPP access networks like 5G NR and LTE and non-3GPP access (for example WLAN). There is a single NAS protocol which applies on both types of access. A single NAS connection is used for each access to which the UE is connected. The same NAS connection is used for both Registration Management and Connection Management (RM/CM) and for Session Management (SM) messages and procedures though the MM and SM functions are now decoupled in the NGC (refer to Figure 26). Hence the NAS protocol comprises a NAS-MM and NAS-SM components.

The NAS-MM handles RM/CM procedures and provides security function for the NAS connection (integrity protection, ciphering). NAS-MM knows if the NAS messages should be transferred to any other network function (SMF for example) via AMF.

The RM state models are very similar to the concept now used in LTE/EPS with two RM states DEREGISTERED and REGISTERED and transition cases between them. However the new thing here is the Registration Area which can be a Tracking Area (TAI) for 3GPP access networks or Non-3GPP TAI (N3GPP-TAI) for non-3GPP access. A specific RM context is maintained for each access type if the UE is simultaneously registered in both though a single globally unique temporary identity is assigned to the UE.

CM states are also coming from LTE without changes representing CM-IDLE and CM-CONNECTED. A UE in CM-CONNECTED mode can be RRC-INACTIVE – a new RRC state discussed earlier in this paper. The UE must resume connection in this state in case of uplink data pending, mobile initiated NAS signaling procedure, as a response to NAS paging, notifying the network that it has left the RAN Notification Area or upon periodic RAN time expires.

The NAS-SM protocol supports UP PDU session establishment, modification and release. It is transferred via the AMF to SMF in a transparent way. The SMF is responsible for checking whether the UE requests are compliant with the subscription defined for it including PDU session type, QoS information and allowed SSC (Session and Service Continuity) modes.

The SSC is another new concept in 5G which enables to address various continuity requirements of different application and services for the UE. There are three modes of SSC, of which SSC1 is deemed the most relevant initially:

- With SSC mode 1, the network preserves the connectivity service provided to the UE. For the case of PDU session of IPv4 or IPv6 type, the IP address is preserved.

- With SSC mode 2, the network may release the connectivity service delivered to the UE and release the corresponding PDU session. For the case of IPv4 or IPv6 type, the network may release IP address(es) that had been allocated to the UE.

- With SSC mode 3, changes to the user plane can be visible to the UE, while the network ensures that the UE suffers no loss of connectivity. A connection through new PDU session anchor point is established before the previous connection is terminated in order to allow for better service continuity. For the case of IPv4 or IPv6 type, the IP address is not preserved in this mode during relocation of the anchor.

One of the most marketed concepts of 5G systems has been the network slicing aiming at providing a dedicated and most proper piece of network to the UE, A Network Slice is defined within a PLMN and shall include:

- the Core Network Control Plane and user plane Network Functions,

And, in the serving PLMN, at least one of the following:

- the NG Radio Access Network
- the N3IWF functions to the non-3GPP Access Network

Network slices may differ for supported features and network functions optimizations. The operator may deploy multiple Network Slice instances delivering exactly the same features but for different groups of UEs, e.g. as they deliver a different committed service and/or because they may be dedicated to a customer.

A single UE can simultaneously be served by one or more Network Slice instances via a 5G-AN. A single UE may be served by at most eight Network Slices at a time. The AMF instance serving the UE logically belongs to each of the Network Slice instances serving the UE, i.e. this AMF instance is common to the Network Slice instances serving a UE.

There are 3 standardized Slice/Service Types (SST) described for the global interoperability support including eMBB, URLCC and mIoT. The support of each kind of slice is network-specific meaning that one network can support any combination of SST. All other SST are PLMN-based.

The UE registering to the network can provide the information on required network slice if available to both RRC and NAS. For these purposes a specific identifier S-NSSAI (Single Network Slice Selection Assistance Information) is used which is initially provided to the UE by the network and is stored there until the update is received. The network then selects the appropriate slice for the UE according to this information.

The Way Forward

Release 15 is the first step on the 5G technology road, and more study items and work items are yet to come, and while the initial focus was to provide eMBB and partial URLLC support, more use cases and verticals are expected to arise and to be addressed in the next releases.

In this section we will shed light on some of the most promising work items planned for next releases for the 5G New Radio.

New Multiple Access

Non Orthogonal schemes allow different users to use the same radio resources, and relay on advanced Multi User Detection (MUD) algorithms to recover users superimposed signals.

In recent trials DoCoMo and MediaTek, demonstrated the possibility to have 2.4 times increase in mobile spectral efficiency, using NOMA (non-Orthogonal Multiple Access) proposed by DoCoMo and MUIC (Multi-user interference Cancellation) Developed by MediaTek.

Different proposals for Multiple Access schemes are available, and which could be categorized in 3 families:

- Codebook based MA
- Sequence based MA
- Interleave/Scrambler MA.

The table below lists some of the most common proposals done, for reference as the detailed characteristics for each of the proposed schemes is out of the scope of this paper.

Table 10: New Multiple Access Proposals for Future 3GPP Releases

Category	Scheme	Proposed by	Complexity
Codebook Based MA	Sparse Code Multiple Access (SCMA)	Huawei	High
	Pattern Division Multiple Access (PDMA)	CATT	
Sequence based MA	Ulti-User Shared Access (MUSA)	ZTE	Relatively Low
	Non-Orthogonal Coded Multiple Access (NCMA)	LG	
	Non-Orthogonal Coded Access (NOCA)	Nokia, ALU	
	Group Orthogonal Coded Access (GOCA)	MediaTek	
Interleaver/Scrambler-based MA	Interleave Division Multiple Access (IDMA)	Nokia, Interdigital	Moderate
	Interleave Grid Multiple Access (IGMA)	Samsung	Moderate/High
	Repetition Division Multiple Access (RDMA)	MediaTek	Relatively Low

Self-backhaul

With the larger bandwidth allocation for NR compared to LTE, especially with mmWave, an opportunity to a new deployment schemes could arise.

Self-backhauling is simply defined as the deployment scenario in which the access part – which is between the gNodeB and the UE - and the backhaul part – Between gNodeBs or gNodeB and Core Network – share the same wireless channel. Different sharing option could be applied by multiplexing the access and backhaul links in time, frequency or Space as in beam-based operations.

5G NR in Unlicensed Spectrum

Similar to LAA and Multefire for 4G, studies to adopt 5G NR in unlicensed spectrum will be further discussed in Release 16, taking into consideration both licensed assisted access and stand-alone deployments.

Satellite and Non-terrestrial Networks

There is increasing interest and participation in 3GPP from the satellite communication industry, with companies and organizations convinced of the market potential for an integrated satellite and terrestrial network infrastructure in the context of 5G. And while study items on satellite communication started from release 14, further studies and work are expected in the coming releases of 3GPP for using the satellite access in 5G.

Beyond satellites, Non-terrestrial networks (NTN) refer to networks, or segments of networks, using an airborne or spaceborne vehicle for transmission. Airborne vehicles refer to High Altitude Platforms (HAPs) encompassing Unmanned Aircraft Systems (UAS) - including tethered UAS, Lighter than Air UAS and Heavier than Air UAS - all operating at altitude; typically between 8 and 50 km, quasi-stationary. These Non-terrestrial networks feature in TSG RAN's TR38.811 "Study on NR to support non-terrestrial networks" and are also expected to have more focused studies in next releases.

V2X

Vehicle-to-everything (V2X) communication is essential in providing real-time and highly reliable information flows to enable safe, efficient and environmentally-conscious transportation services and paving the way to connected and automated driving (CAD). Cellular V2X (C-V2X) is the technology developed in 3GPP1 and is designed to operate in two modes [1]:

Device-to-device: This is Vehicle-to-Vehicle (V2V), Vehicle-to-(Roadway) Infrastructure (V2I) and Vehicle-to-Pedestrian (V2P) direct communication without necessarily relying on network involvement for scheduling.

Device-to-network: This is Vehicle-to-Network (V2N) communication which uses the traditional cellular links to enable cloud services to be part of the end-to-end solution by means of network slicing architecture for vertical industries.

In the next releases for 5G NR, more studies will focus on investigating and evaluating the possible reuse/ enhancement of existing functionalities and architectures in 5G NR Phase 1 in order to support advanced V2X services, including but not limited to: platooning, extended sensor sharing, ranging to enhance positioning accuracy and other network based positioning enhancements, advanced driving, and remote driving.

... And many more

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[R4] 3GPP TR 38.804 V1.0.0 (2017-03) Study on New Radio Access Technology; Radio Interface Protocol Aspects (Release 14)

[R5] 3GPP TS 38.300 V1.1.0 (2017-10) NR; NR and NG-RAN Overall Description; Stage 2 (Release 15)

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[R10] 3GPP TS 38.300 V1.1.0 (2017-10) NR; NR and NG-RAN Overall Description; Stage 2 (Release 15)

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