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# INSIGHTS ACROSS THE 5G NEW RADIO (NR) ECOSYSTEM AND AN OVERVIEW OF ITS PHYSICAL LAYER

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## Abstract

*The most imminent technology that Telecom sector is striving to deploy is the next generation mobile phone system IMT 2020, which is currently being disseminated as “5G”. There have been significant development in the research on fifth generation networks. Apart from being an evolution to broadband services (like increase in throughput, latency reduction, ultra-reliability, more bandwidth availability to users, etc.), it acts as a proverbial gateway to a plethora of services like Narrowband IOT, Machine-to-machine communication, Vehicle to anything(V2X), etc. All the stakeholders such as regulatory bodies, standardization authorities, industrial fora , mobile operators and workers must work in unison to bring 5G to fruition. The recently launched 3GPP 38 series expounds the specifications of 5G RAN, here known as 5G NR. In this paper, we aggregate the 5G related information coming from various stakeholders in order to have a comprehensive overview of 5G and to provide a succinct survey of the envisioned 5G technologies as per the 3GPP specifications.*

***Keywords:*** *5G NR, LTE, IOT, RAN, BBU, OFDMA, Beamforming, NFV, FDD, TDD, PAPR.*

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## 1. INTRODUCTION

A 5G system can be defined as a confluence of a motley of services, available on a unified platform. The motivation is to develop a malleable, integrated system wherein the system would be able to adapt itself according to the user’s needs. The proposed 5G system concept generalizes key characteristics of the services (use cases) and aligns the requirements, and combines technology components into three generic 5G communication services, which are as follows:

1. Enhanced Mobile Broadband (eMBB): It aims at curbing the extremely high competition for bandwidth acquisition among users in very crowded areas, by providing low latency, high data rate services, along with wide coverage. A unique device activation pattern is employed, wherein no
2. Two eMBB devices may share the same resources simultaneously, for an extended period of time, with a moderate packet error rate of the order of 10-3.
3. Machine-to-machine type communication (mMTC): With the advent of massive IoT, wherein the majority of devices would be network-enabled, mMTC serves to provide scalable connectivity for increasing number of devices, efficient transmission of small payloads, wide area coverage and deep penetration, which are prioritized over data rates. Unlike eMBB, the uplink transmission rate is typically low and the device is not active continuously. Moreover, mMTC devices share radio resources through random access since it is not feasible to allocate a priori resources to individual mMTC devices, due to the large number of mMTC devices connected to a Base Station. It has the highest packet error rate (of the order of 10-1) among all generic services, with a view to maximize the arrival rate.[11]
4. Ultra-reliable low latency applications (uRLLC): It is mainly concerned with enabling real-time control and automation of dynamic processes in various fields, such as industrial process automation and manufacturing, energy distribution, etc, thereby underscoring high reliability (low packet error rate) and low latency (for smaller volumes of data with high business value). As the name suggests, uRLLC provides high reliability with a PER lower than 10-5. It is an amalgamation of allocation of available resources via scheduling, as well as random access, to avoid too many resources to stay idle, because of the intermittent nature of traffic.

In order to encompass the above-mentioned use cases on a single platform, it became mandatory to define an advanced, eclectic air interface which was coined by 3GPP as 5G NR (New Radio).

A new architecture has been put forth by 3GPP, which would help meet the need for the myriad use cases of 5G. This new radio makes it viable by using two new spectrum bands i.e. Sub 6GHz band and millimetre wave band. The idea of beamforming, which is not a new concept would be used extensively in 5G NR (combination of analog and digital beamforming) to optimise the signal strength at mobile device, due to decrease in antenna size. As the frequency increases, beamforming becomes both necessary to counteract the decrease in received power due to decrease in antenna aperture and also practically feasible due to smaller antenna size. Although the candidate waveforms

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used in LTE i.e. OFDMA (downlink) and SC FDMA (uplink) overcame the problems of ISI, multipath fading (with cyclic prefix) but problems like high PAPR, out of band interference still persists. Hence, FOFDMA, FBMC, GFDMA, etc. candidate waveforms have been introduced. Significant changes in the numerology of radio frames have been made, which has been described in the paper. Also, at the Physical layer level, new coding techniques such as Polar coding and LDPC have supplanted Turbo Coding, in order to increase the overall hardware efficiency and throughput. This paper is a recapitulation of all the above key changes made in 5G NR with respect to LTE. Along with, the issues mentioned above, a few more changes have been addressed along with the motivation that led to such changes.

## 2. ARCHITECTURE

On a higher level, 5G network architecture is service based architecture (SBA), while 4G network architecture is reference point architecture. Although the currently deployed LTE network provides adequate speeds in the uplink as well as downlink direction, thus enabling real time and non-real time services, it fails to suffice the dynamism required for different types of services (also known as use cases). Hence, the need for such a network was realized which would be able to adapt itself to the altering user requirements.

In order to ensure highly energy, cost and resource efficient network, networks providing non-real time services will be softwarized at the core. Concretely, in 5G network architecture the Control and Data plane will be separated by NFV paradigm (Cloud RAN) and will be implemented on cloud based/generic core elements thus providing the network extreme flexibility of operation. Cloud RAN(CRAN) [10] involves execution of most of the gNodeB functions on the cloud network, thus dividing its functionality into control and data layers. The functionalities of these layers have been proposed as:

1. Data layer: It contains heterogenous physical resources (radio interface equipment) and performs signal processing tasks like channel decoding, demultiplexing, fast Fourier transform, etc.
2. Control layer: It performs baseband processing and resource management like application delivery, QoS, real time delivery, seamless mobility, security, network management, etc.

The building blocks of 5G architecture can be described as: User Equipment (UE) connected to the New Generation Radio Access Network (NG RAN) via the air interface, which in turn is connected to the Core Network (5GC) and Data Network.

The NG Ran is composed of gnodeB (analogous to enodeB in LTE) and is connected to core network(5G-C) through the NG-C interface. A gNB can support FDD mode, TDD mode or dual mode operation. gNBs can be interconnected through the Xn interface.

On shifting from 4G to 5G NR transport architecture, the main change is that the original BBU function in 4G/LTE is split here into three parts, namely Centralized Unit (CU), Distributed Unit (DU) and RRU (Remote Radio Unit). The motivation behind this was:

1**. Ease of RAN Virtualization**: The performance of a system in real time and non- real time depends on the number of baseband functions to be left in the physical unit and those which need to be virtualized in data centres, respectively. It is preferred to avoid virtualization of those functions that are necessary for implementing real time processes.

2.Due to **the splitting of BBU into CU and DU [9]**, the load on the fronthaul line is shared by the multiple fronthaul lines, thus meeting latency demands.

**gNB-CU:** Apart from controlling the operation of DUs over the fronthaul interface, it is responsible for transfer of user data, mobility control, radio access network sharing, positioning, session management etc. It also processes the non-real time protocols and services.

**gNB-DU:** It includes a subset of the gNB functions, whose operation is controlled by CU. It processes physical layer protocols and real time services.

If we start mapping the EPC functions of 4G LTE with 5G NR, one must pay heed to the following amendments [12]:

1. The Home Subscriber service (HSS) has been supplanted by Authentication User Function (AUSF) and User Data Management (UDM). It is in charge of storing and updating, when necessary, the database containing all the user subscription information and is in charge of generating security information from user identity keys. This security information is further communicated to other entities in the network.
2. The Policy and Charging Rules function (PCRF) which was responsible for supporting service data flow detection, policy enforcement and flow-based charging in EPC has been replaced by policy control function (PCF) in NR.
3. Along with initiating paging, authentication of mobile device and retaining local information at the tracking area level for each user, the new generation entity, namely, Access and Mobility Management supports termination of NAS signalling, NAS ciphering and integrity protection, connection management, mobility management, security context management. Etc.
4. A few functionalities of MME, SGW and PGW have been incorporated in Session Management Function (SMF). It also performs session management (session establishment, modification and release), UE IP address allocation and management, termination of NAS signalling related to session management, etc.
5. The User Plane Function (UPF) in 5G NR is analogous to SGW and PGW of LTE. It supports packet routing and forwarding, QoS handling and is an anchor point for intra and inter RAT mobility.

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## 3. RADIO FRAME STRUCTURE

As posited in the 36 series of 3GPP, a fixed subcarrier spacing (SCS) of 15kHz has been defined for LTE, which in turn curtailed the amount of flexibility provided by the network thus deployed, for the veritable use cases. However, 5G NR overcomes this foible by providing the provision of varying the sub carrier spacing **[1].** This ability of NR is directly related to data rate, latency, bandwidth, support of a wide range of services, and supported spectrum bands.

Increasing and decreasing the SCS has its own pros and cons.

**1.Decrease in SCS** results in an increment in the OFDM symbol duration, thus causing the CP duration to increase as well, in order to keep the CP overhead ratio constant (**CP overhead ratio = CP length/ OFDM symbol length**. This quantity is kept constant in NR). Now, to avoid ISI, **CP duration >> Delay Spread.**

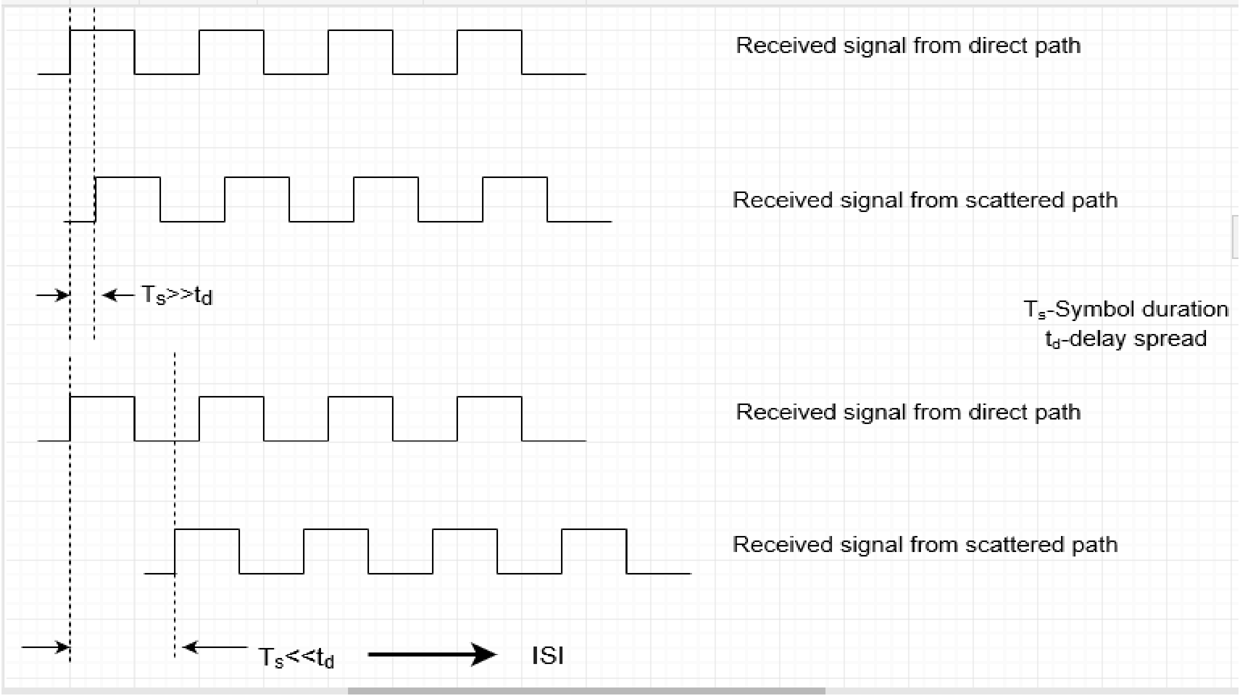

**Fig 1:** Intersymbol interference

Thus, decrease in SCS is quite propitious for both decrease in delay spread as well as ISI.

Since the minimum SCS offered in NR is 15 kHz (any value lower than this would result in ICI), ICI is eventually not encountered.

**2. Increase in SCS** accounts for lower turnaround transmission time (due to its shorter symbol duration) and low sensitivity to phase noise. The phase noise, which is a random process, increases with carrier frequency and gives rise to jitter in time domain. Larger SCS (i.e., smaller symbol duration) leads to lesser variation in phase, thus the phase noise can be modelled as a constant and can be compensated via estimation. This is one of the major advantages of larger SCS.

At higher carrier frequencies (mm wave band), in order to compensate for lower penetration, sharp beamforming is employed, which in turn decreases the multi-path delay spread. Thus, there is no need to further increase cyclic prefix duration.

### 3.1 Why Variable SCS?

It is well known that narrow SCS is more suitable for wide area coverage, low carrier frequency band and severe multipath channel environment. On the other hand, wide SCS is more effective for high speed movement, high carrier frequency band and latency reduction.

### 3.2 Radio Frames

In order to realise the above features, the NR radio frame is specified as:
1.Radio Frame in units of 10 ms.
2.Subframe in units of 1 ms.
3. Slots are defined as 14 OFDM symbols and their time interval description depends on SCS.

### 3.3 NR Numerology

Compared to LTE numerology (subcarrier spacing and symbol length), the most outstanding difference one can notice is that NR supports multiple types of subcarrier spacing (in LTE there is only one type of subcarrier spacing, 15 Khz). Each numerology is labelled as a parameter (u, mu in Greek). The numerology (u = 0) represents 15 kHz which is same as LTE. And as we see in the second column the subcarrier spacing of other u is derived from (u=0) by scaling up in the power of 2.

**Table 1:** 3GPP 38.211 Table: Supported transmission numerologies.

| $\mu$ | $\Delta f = 2^{\mu} \cdot 15[\text{kHz}]$ | Cyclic prefix |
|---|---|---|
| 0 | 15 | Normal |
| 1 | 30 | Normal |
| 2 | 60 | Normal, Extended |
| 3 | 120 | Normal |
| 4 | 240 | Normal |

### 3.4 Numerology and Slot Length

In NR, it is agreed that the overhead ratio of CP among OFDM symbols with different SCS is fixed. In other words, in case that OFDM symbols have double SCS, both OFDM symbol and CP length are halved.

There are many different slot formats available as against subframe formats (configuration 0 to 6) in LTE. In NR, DL and UL assignment changes at a symbol level (in LTE TDD, the UL- DL assignment is done on a subframe level).

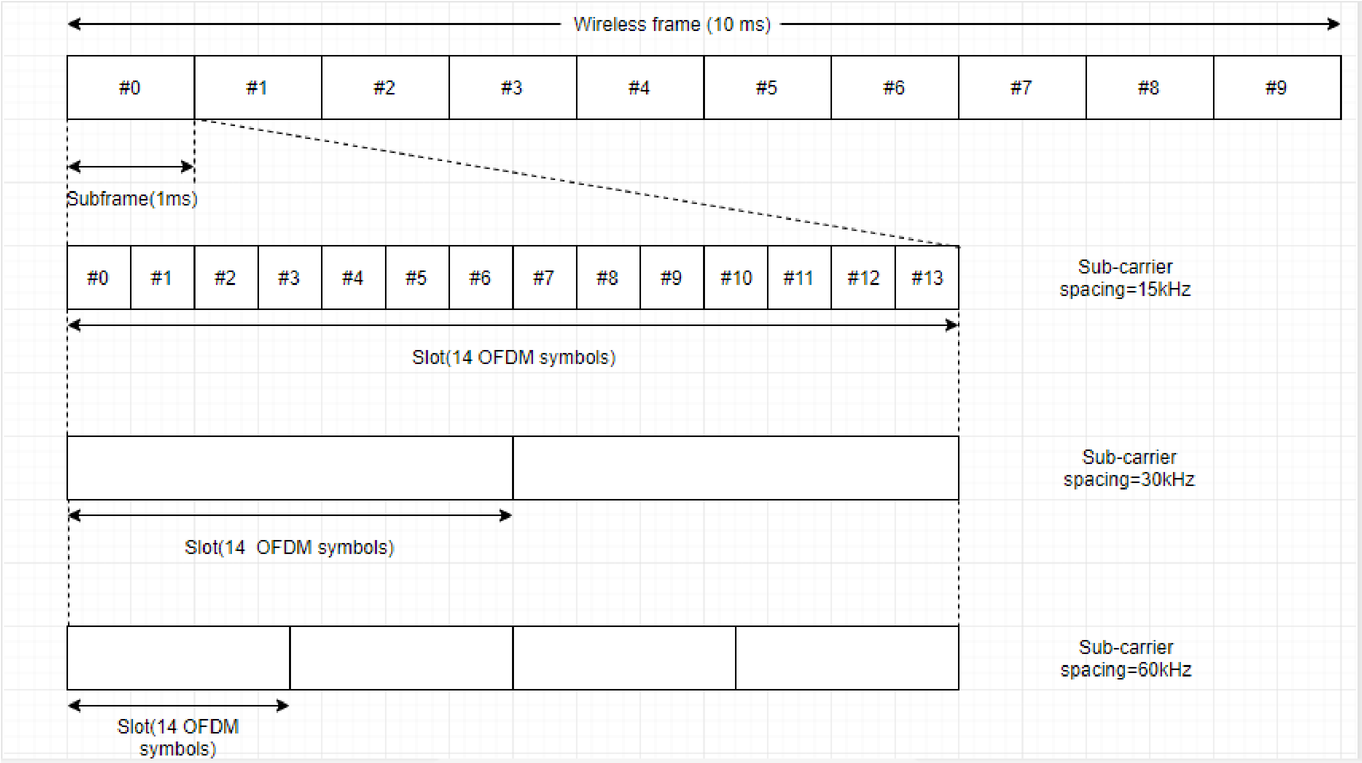

**Fig 2:** Frame Configuration [7]

As mentioned above, the duration of radio frames and subframes are fixed i.e. they are independent of type of SCS used. However, unlike LTE, where a subframe was composed of 2 slots, in NR the type of SCS governs the number of slots the subframe should support.

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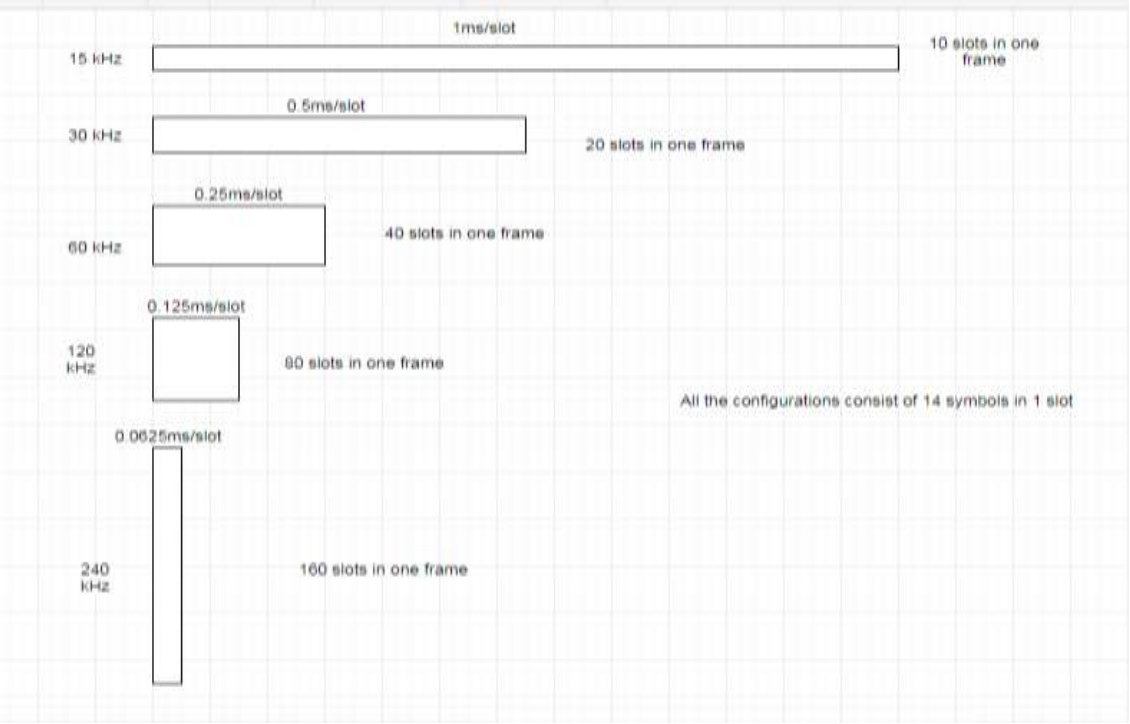

**Fig 3:** Variable SCS and the no. of slots in it

### 3.5 Resource Grid

Resource allocation in 5G NR looks similar to LTE, but the physical dimension (i.e. subcarrier spacing, number of OFDM symbols within a radio frame) varies in NR depending on numerology.

The relation between number of symbols in one subframe(α) and the parameter μ can be expressed as:

$$\alpha = 14.2^{\mu}\text{-}1$$

Let us consider the case where a subframe consists of only one slot (As seen in fig.3), i.e., μ=0. The value of α in this case is 13. This indicates that there are 14 symbols (i.e., α=0 to α=13).

Similarly, when the value of μ is changed to 1, α ranges from 0 to 27, thus accounting for 28 symbols in the subframe. To calculate the number of slots in the subframe:

$$No.of\ slot = \frac{No.of\ symbols\ in\ the\ subframe}{14}$$

As the number of slots in a subframe increases, the duration of a symbol and hence, of a slot decreases, which is illustrated in Fig.2

### 3.6 Why Shorter Slot Duration?

Along with curbing the drawback of larger latency (around 10 ms- 100 ms) through shorter slot duration, there is another advantage associated with the physical properties of 5G operating frequency. We know that, Doppler shift is directly related to the operating frequency. While operating in high frequency band (mm Wave), the doppler shift correspondingly increases. Hence, it’s the exigency to increase the SCS at higher frequency bands in order to maintain orthogonality and prevent ICI. Therefore, it is highly likely that 5G will use OFDM with much wider sub carrier spacing (meaning Wide Subcarrier) comparing to current LTE. If the subcarrier width gets wider, the symbol length gets shorter.

### 3.7 CORESET (Control Resource Set)

It is made up of multiple resource blocks (i.e., multiple of 12 REs) in frequency domain and ‘1 or 2 or 3’ OFDM symbols in time domain. It is equivalent to control region in LTE subframe. In LTE, the frequency domain of control region is same as total system bandwidth, so no parameter is needed to define frequency domain region for LTE control region. Time domain can be {1,2,3}, which is determined by PCFICH. However, in NR, both frequency and time domain regions can be defined by RRC signalling message.

### 3.8 SS Block

SS Block is referred to as Synchronisation Signal Block in NR and is composed of:

1. Synchronization signals: PSS (Primary Synchronization Signal) and SSS (Secondary Synchronization Signal).
2. PBCH: PBCH DMRS and PBCH data.

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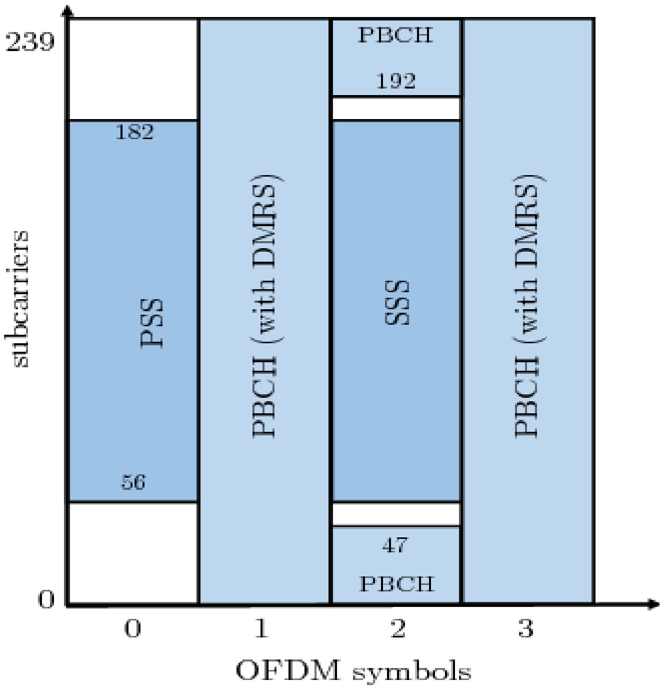


**Fig 4:** SS Block [3]

As shown above, 127 subcarriers are allocated for PSS and SSS, with guard bands of 10/11 subcarriers provided for SSS. PBCH data occupies the topmost and bottommost 4 subcarriers in the symbol containing SSS, as well as symbols 1 and 3, along with PBCH DMRS.

## 3.9 Sequence Generation of PSS and SSS

The NR PSS [16] provides radio frame boundary (position of first symbol in radio frame). It is mapped onto 127 active subcarriers around the lower end of the system BW. Unlike LTE PSS [16], which is constructed from Zadoff Chu sequences NR PSS is made up of 127 m sequence values. Its critical functions include:

1. DL frame synchronisation
2. Determination of cell ID

Following is the generation sequence of NR PSS and LTE PSS:

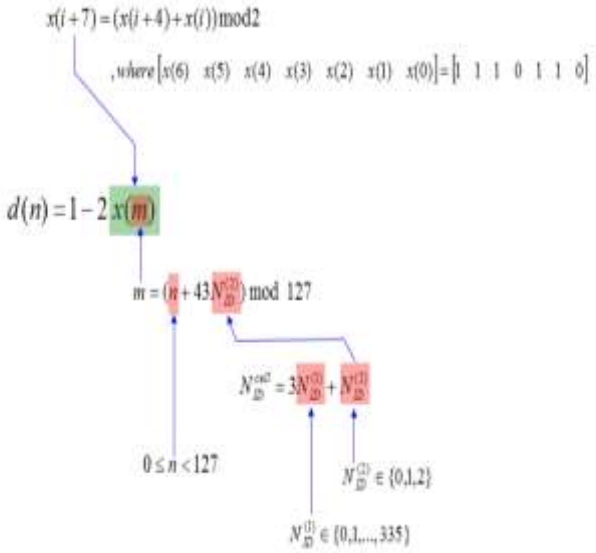
<38.211-7.4.2.1.1>

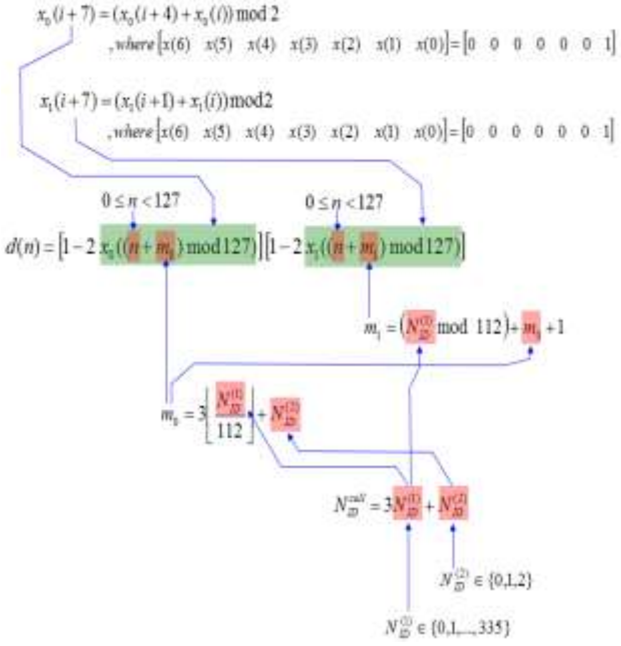
$$d(n) = 1 - 2x(m)$$

<36.211-6.11.1.1>

$$d_u(n) = \begin{cases} e^{-j\frac{un\pi\,(n+1)}{63}} & n = 0,1 \ldots 30 \\ e^{-j\frac{un\pi\,(n+1)(n+2)}{63}} & n=31,32\ldots 61 \end{cases}$$

NR SSS is constructed by combining 2 m-sequences to form a Gold sequence. Its mapping is similar to that of NR PSS. LTE SSS is generated in a more complicated manner as compared to NR SSS. LTE SSS sequence alters depending on which subframe it is transmitted in, whereas NR SSS [16] doesn’t vary with the subframe in which it is transmitted. NR SSS also provides Subframe boundary (position of first symbol in subframe).





Determination of Sequences [16]

Since Nid (1) has 336 possible values and Nid (2) has 3 possible values. Hence, 336*3=1008 PCIs are possible.

## 3.10 Mini Slots [15]

Since a slot is defined as a fixed number of OFDM symbols, a higher subcarrier spacing leads to a shorter slot duration. In principle, this could be used to support lower-latency transmission, but as the cyclic prefix also shrinks when increasing the subcarrier spacing, it is not a feasible approach in all deployments. Therefore, NR supports a more

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efficient approach to low latency by allowing for transmission over a fraction of a slot, sometimes referred to as “mini-slot” transmission. Such transmissions can also pre-empt an already ongoing slot-based transmission to another device, allowing for immediate transmission of data requiring very low latency.

Having the flexibility of starting a data transmission not only at the slot boundaries is also useful when operating in unlicensed spectrum. In unlicensed spectrum the transmitter is typically required to ensure that the radio channel is not occupied by other transmissions prior to starting a transmission, a procedure commonly known as listen-before-talk. Clearly, once the channel is found to be available, it is beneficial to start the transmission immediately, rather than wait until the start of the slot in order to avoid some other transmitter initiating a transmission on the channel.

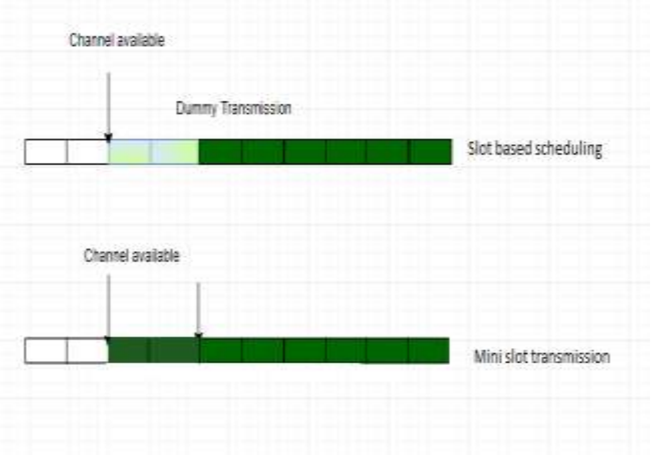

**Fig 5:** Mini Slot

### 3.11 Slot Aggregation

In 4G, TTI has 2 main parts: PDSCH and PDCCH. PDCCH occupies 3 of the 14 symbols in LTE, accounting for 20 percent of the overhead.

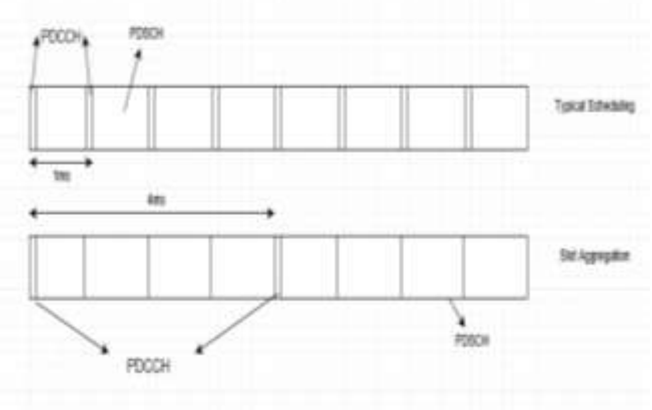

**Fig 6:** Slot aggregation

However, 5G introduces the concept of slot aggregation where it is not mandatory to have PDCCH in all TTIs. The main idea is that the gNB has the downlink data in its buffer so it knows the number of bits that are present, or atleast it can estimate the incoming bit rate for a specific UE. So, if the UE has a significant amount of data, then the gNB can assign a PDCCH that allocates multiple slots to that UE.

### 3.12 Beam Sweeping Transmission of SS and PBCH

At **frequency bands above 6GHz**, by applying beamforming, it is possible to extend transmission distance by concentrating transmit signal power in a specific direction. On the other hand, the range of direction in which signal is received with sufficient signal strength is narrowed due to beamforming. Since SS and PBCH need to reach all UE’s within a cell, “beam sweeping” transmission (where a BS transmits signals while switching beam direction sequentially to cover a whole cell area) is supported for multibeam operation and is applied to transmission of an SS/PBCH block, which is defined as a unit of beam sweeping.

It is also possible to adopt a configuration in which only 1 SS/PBCH block is periodically transmitted via single beam without applying beam sweeping in **low frequency bands.** Due to multiple candidate positions of SS/PBCH block within a radio frame unless a mobile terminal could identify which SS/ PBCH block is actually detected it is impossible to recognise radio frame timing and slot timing. Thus, a mechanism to identify index of SS/ PBCH block by using a PBCH and reference signal called “PBCH DMRS” (explained later).

### 3.13 Channel Bandwidth

Although LTE offers a wide channel BW of 20 MHz, it can be further augmented with the help of Carrier Aggregation (CA), which facilitates wideband communication by dynamic allocation of component carriers. This process is initiated by the activation/deactivation on the MAC control element (CE), which is not efficient due to repetitive HARQ feedback, thus accounting for high latency (about 8ms). Moreover, CA requires control signalling for each aggregated carrier, which exacerbates control overhead.

In order to do away with these drawbacks, NR introduces dynamic allocation of frequency resources via scheduling, which is more flexible and efficient than CA operation of LTE. Due to the provision of single wideband carrier in NR, its control overhead is low, thus overcoming the limitation of high latency of LTE. Only 1 BWP (analogous to LTE M) can be active at a time. Thus, the provision of activation/deactivation of carriers has been shifted from MAC to DCI in the physical layer, with a view to reduce latency. Although NR also supports CA, it allocates only up to 16 component carriers (CC), which is less than LTE’s maximum aggregation (32 CCs). This is because of larger channel BW offered by NR, thus making its need to allocate more CCs null and void.

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### 3.14 UE with Limited RF Capability

It is a known fact that channel bandwidth and IFFT block size have a positive correlation. Different UE's have different RF capabilities. Here, as in [1], we have considered two types of UE's – One employing only a single RF chain for a single wideband carrier while the other using multiple RF chains. The RF chains of case B UE may be distinguished from one another on the basis of their IFFT die size. For e.g. If a UE has 2000 subcarriers, then it would require an IFFT die of size 2048. A UE may either use an IFFT block of size 2048, or might opt for two IFFT blocks, each of size 1024 (these figures may vary). This is a classic example of UEs with different capabilities.

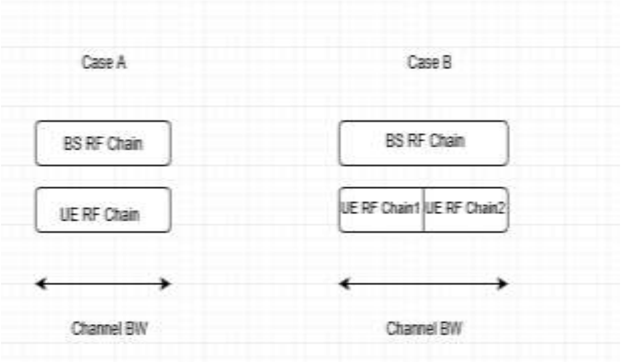

**Fig 7:** The two types of UEs used in this example [1]

In order to enable the NR to handle the coexistence of UEs, the following two scenarios were considered:

1. The network configures both Case A and Case B UEs with one wideband CC, while Case B UEs utilize multiple RF chains to cover one wideband CC.
2. The network configures Case A UEs with one wideband CC, while at the same time the network configures Case B UEs with a set of intra-band contiguous CCs with CA.

In the first alternative, the case B RF chains have been allotted a common bandwidth, thus forcing both of them to be activated at the same time. This increases the tendency of amplitude and phase differences to creep in, which would eventually lead to erroneous decoding. Moreover, since both IFFT dies are being activated simultaneously, power consumption also increases. Therefore, alternative 1 is not a very favourable choice, in terms of accurate synchronisation and optimum power consumption.

The second alternative makes use of CA for case B UEs. Each UE RF chain is allotted a separate subcarrier bandwidth, thus avoiding simultaneous activation of all RF chains. This curb the high-power consumption encountered in the first case and also accounts for more accurate data transmission, due to decrease in phase differences.

The 5G NR network would be designed in such a way so as to accommodate both types of UEs simultaneously- one using single wideband and the other using intra-band contiguous carriers with CA. It can thus be inferred that 5G NR gives more preference to UE for bandwidth allocation, in terms of RF capability, hence its behaviour can be defined as more UE specific rather than cell specific type.

This scheme also encourages minimization of guard bands between CCs of case B UEs employing intra band contiguous CCs. Since there would be only RF chain activated at a time, there won't be any scope for interference from adjacent CCs.

### 3.15 Bandwidth Parts

Due to the various use cases envisioned for the 5G, it is not necessary for different UE's to require high data rates, hence allotting them wider BW might lead to idling power consumption from baseband RF signal perspective. Thus, 5G NR comes up with a new perspective of Bandwidth part, which enables frugal use of BW by UEs (requiring smaller BW), despite supporting Wideband operation.

Thus, [2] ***Carrier Bandwidth Part is 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.***

Maximum 4 BWP can be specified in DL and UL. The minimum size requirement of a BWP is that it should be atleast as big as one SS Block, however it may or may not contain an SS Block. Also, it should be noted that the size of a BWP should not exceed the Component Carrier Bandwidth, as shown in figures 8 and 9.

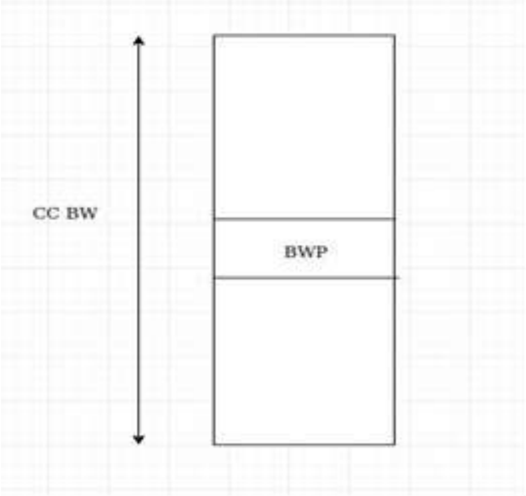

**Fig 8:** Assignment of one BWP to a UE

There may be more than one BWPs assigned to a single UE, with overlapping in the frequency domain a possibility

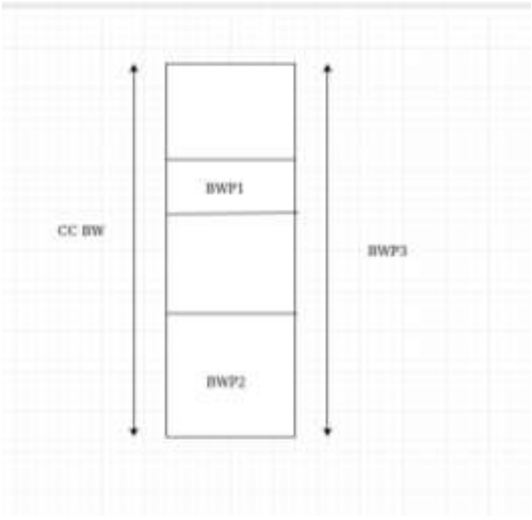

**Fig 9:** Assignment of multiple BWPs to a UE

### 3.16 Reference Signals in NR

Although, the reference signals used here are almost similar to those used in LTE, there are a few differences.

1. **CRS (Cell Specific Reference Signal) free transmission.**
   In LTE, CRS is used for channel estimation. However, since CRS is being transmitted continuously in 4G, it results in significant downlink interference, thus reducing the channel quality. 5G eliminates this by trying to minimize the number of 'always-on' active signals. In NR, a user specific DMRS will be used i.e. unless each user is connected to a base station, there won't be any reference signal sent to it. This reduces the overall interference, thereby improving the channel conditions (indicated by CQI, MCS and Spectral efficiency).

   However, this raises a fundamental question for cell selection and reselection, as UEs use CRS for RSRP estimation in LTE. In 5G NR, since SS block is transmitted periodically, this block will have its own reference signal which might be used by UE for cell selection and reselection. After getting allocations it will get its own UE specific RS.
2. In NR, there are new reference signals namely Phase Tracking Reference Signal, PBCH Reference Signal, Time/Frequency Tracking Reference Signal.

#### Reference Signals

1. **Phase tracking reference signal (PTRS)** can be used to compensate for phase error at high frequencies. Thus, this curbs downlink interference, improves channel quality and also enhances overall spectral efficiency.
2. **Sounding Reference Signal (SRS)** [3]**:** It is used to measure the uplink channel quality. It is due to channel reciprocity that the UL SRS can be used for downlink channel estimate in TDD. The timely knowledge of DL channel characteristics is key to enabling NR antenna techniques, such as massive MIMO.

   The gNB governs the transmission of the SRS by the UE attached to it, by signaling to the UE, the resource and direction to be used by UE for this purpose. The SRSs can span 1 to 4 OFDM symbols, and a portion of the entire bandwidth available at the UE.
3. **Channel State Information Reference Signal (CSI-RS):** NR also introduces a new CSI framework for multi-antenna use cases. CSI measurement, reporting, and DL transmission can be triggered on different beams to suit the antenna configuration, making use of the removal of strict timing in the self-contained subframe. NR CSI also supports Co-ordinated Multi-Point (CoMP) transmission and reception, allowing cell hand-over or a UE to be tracked by a cell beam as the UE roams.

   CSI-RSs can be used for Radio Resource Management (RRM) measurements for mobility management purposes in connected mode. As in LTE [3], it shall be possible to configure multiple CSI-RS to the same SS burst, in such a way that the UE can first obtain synchronization with a given cell using the SS bursts, and then use that as a reference to search for CSI-RS resources. Therefore, the CSI-RS measurement window configuration should contain at least the periodicity and time/frequency offsets relative to the associated SS burst.

   When considering directional communications, the best directions for the beams of the transceiver need to be periodically identified (e.g., through beam search operations), in order to maintain the alignment between the communicating nodes. For this purpose, SS- and CSI-based measurement results can be jointly used to reflect the different coverage which can be achieved through different beamforming architectures. CSI signals play a pivotal role in determining the channel signal quality. CSI defines a parameter, $N_{CSI,Rx}$ , which indicates the number of best beams chosen from all the available ones. It has been specified that a threshold should be defined, in order to determine the beams whose values need to be averaged. If there are no beams above threshold, then the best beam among the available ones are selected for cell quality derivation.

## 4. BEAMFORMING AND BEAM MANAGEMENT

Due to the overcrowding of the currently deployed spectrum, the usage of sub-6 GHz and mm-wave spectrum bands comes with a cost. However, these high frequency bands fail to provide the robustness characteristic to the lower frequency bands, due to harsher propagation conditions, owing to the decreased penetration power.

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Thus, there is a need for developing highly directional transmission links in order to avoid these impairments. Directional links, however, require fine alignment of the transmitter and receiver beams, achieved through a set of operations known as beam management.

In traditional LTE systems, control procedures (initial access, handover, radio link failure recovery) were carried out using omni directional signals, before the establishment of physical link. Omni directional signals, if used in high frequency spectrum control procedures would generate a mismatch between the UE and gnodeB. This entails the usage of beam management in all kinds of exchanges between gnodeB and UE. However, highly directional links increase the initial access delay and also make the performance more sensitive to beam alignment.

NR specifications incorporate a set of beam management procedures through which it could control multiple beams at frequencies above 6 GHz. The different operations are categorized under the term beam management, which is composed of four different operations (For Standalone DL) [3]

1. **Beam-sweeping**: This is a measurement process carried out exhaustively by gnodeB. Both UE and gnodeB have a set of predefined direction vectors(codebook), that analyses the spatial area covered by the phased array antennas. They are used to sequentially transmit/receive synchronisation and reference signals.

**2. Beam measurement:** The received beams are evaluated on the basis of their channel condition (particularly SNR). This is done by collective measurements of data from both CSI RS and SS blocks.

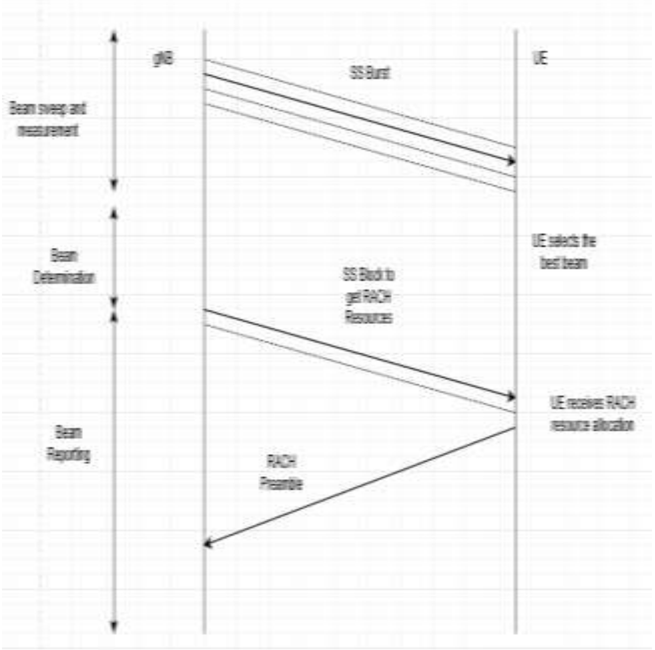


**Fig 10:** Beam management processes

**3. Beam determination**. The mobile terminal selects the beam through which it experienced the maximum SNR, if above a predefined threshold. The corresponding sector will be chosen for the subsequent transmissions and receptions and benefit from the resulting antenna gain.

**4. Beam Reporting:** After the best beam is determined by the UE, it sends a RACH preamble to the gnodeB through the selected direction for performing the random-access process, thus informing the gnodeB of the direction in which it should steer its beam for the required alignment. It has been agreed that for each SS block the gNB will specify one or more RACH opportunities with a certain time and frequency offset and direction, so that the UE knows when to transmit the RACH preamble. This may require an additional complete directional scan of the gNB, thus further increasing the time it takes to access the network.

### 4.1 Beamforming Techniques

In analog beamforming, amplitude/phase variations take place at the transmit end. The separation of beams on the basis of number of antennae is performed after the DAC processing. The signals from different antennas are summed up before the ADC conversion at the receiver end. Since only one RF chain is being utilised here, the beam will be transmitted /received only in 1 direction at a given instant. This scheme is cost and power efficient (by using single ADC) but also provides little coverage.

On the other hand, digital beamforming requires separate RF chains for each antenna element and the processing is done in digital domain. Hence, the amplitude/phase variation is applied before DAC at transmit end. The received signals from different antennas are first passed from ADC convertors and digital down convertors before summing operation. The availability of samples of each antenna allows assignment of weights to each beam, which provides more flexibility than in the analog domain.

## 5. PHYSICAL LAYER PROCESSING

The only observable difference in the physical layer processing of 5G NR (PBCH) is the absence of precoding. The only reason this precoding stage has been eliminated here is because beamforming has been implemented in the initial access procedure, while rest of the steps are same as of LTE.

Scrambling: Helps improve synchronisation, has relatively high autocorrelation property which can be used to tune synchronisation timing. It is used to distinguish between transmitters. When a cell is divided into different sectors, scrambling code distinguishes sectors from each other.

### 5.1 Code Block Groups

Previously in LTE, we had huge transport blocks and UE used to send HARQ feedback even if some bits were damaged. Now in 5G, we divide the transport block into numerous small sized blocks (groups). These groups will be decoded by UE, which in turn will end HARQ feedback for each group. For example, out of three subsets, if only one is damaged, only that damaged subset is retransmitted. This reduces overhead transmission and increases spectral efficiency.

On the other hand, if all groups in a block are damaged, then HARQ feedback is sent for all groups and this leads to increase in HARQ feedback overhead. Thus, this overhead is reduced by adaptive code block groups, such that it is enabled or disabled by gNB, whenever required.

## 5.2 Modulation

Modulation techniques define which of the properties are being manipulated. Higher order modulation schemes allow more information to fit into a single radio wave. In other words, higher order modulation equals more bits per wave. This is a powerful way of improving spectral efficiency. Sixty-four QAM is a higher order modulation technique, which allows one single radio wave to represent six bits of data by manipulating the amplitude and phase of the radio wave into one of 64 different discrete and measurable states.

The advantage of higher order modulation is the possibility to transmit more bits per radio wave. The disadvantage is that the data becomes more susceptible to noise and interferers since the receiver must accurately detect more discrete phases and amplitudes of a signal. Advancements in electronics have made it possible to use higher and higher order modulation techniques. And the small cell LTE deployment revolution is helping to create more and more environments with SNR appropriate for 64 QAM on the LTE uplink.

When the conditions are right, such as in a small cell serving a building with slow-moving or fixed wireless devices, modulation schemes of higher order make it possible to send much more data (up to 50% more) with the same amount of frequency resource (spectrum). The modulation mapper takes binary digits, 0 or 1, as input and produces complex-valued modulation symbols as output.

### 5.2.1 π/2-BPSK

In case of π/2-BPSK modulation, bit b(i) is mapped to complex-valued modulation symbol d(i) according to

$$d(i) = \frac{e^{j\frac{\pi}{2}(i\mathrm{mod}2)}}{\sqrt{2}}\left[(1-2b(i))+j(1-2b(i))\right]$$

The reason why π/2-BPSK is incorporated in 5G is, that when the bits transit from 0 to 1 (or vice versa), the phase transition which occurs is just 90 degrees, unlike the conventional BPSK, where phase transition of 180 degrees occurs. This is especially advantageous with a view that it helps mitigate PAPR.

### 5.2.2 BPSK

In case of BPSK modulation, bit b(i) is mapped to complex-valued modulation symbol d(i) according to

$$d(i) = \frac{1}{\sqrt{2}}\left[(1-2b(i))+j(1-2b(i))\right]$$

### 5.2.3 QPSK

In case of QPSK modulation, pairs of bits(2i), b(2i+1), are mapped to complex-valued modulation symbols d(i) according to

$$d(i) = \frac{1}{\sqrt{2}}\left[\left(1-2b(2i)\right)+j\left(1-2b(2i+1)\right)\right]$$

### 5.2.4 16QAM

In case of 16QAM modulation, quadruplets of bits, b(4i), b(4i+1), b(4i+2), b(4i+3) are mapped to complex-valued modulation symbols d(i) according to

$$d(i) = \frac{1}{\sqrt{10}}\{\left(1-2b(4i)\right)\left[2-\left(1-2b(4i+2)\right)\right]+j(1-2b(4i+1))\left[2-\left(1-2b(4i+3)\right)\right]$$

### 5.2.5 256QAM

In case of 256QAM modulation, octuplets of bits, b(8i), b(8i+1), b(8i+2), b(8i+3), b(8i+4), b(8i+5), b(8i+6), b(8i+7) are mapped to complex-valued modulation symbols d(i) according to

$$\begin{aligned} d(i) = \frac{1}{\sqrt{170}}\{&\left(1-2b(8i)\right)\left[8-\left(1-2b(8i+2)\right)\left[4-\left(1-2b(8i+4)\right)\left[2-\left(1-2b(8i+6)\right)\right]\right]\right] \\ &+j\left(1-2b(8i+1)\right)\left[8-\left(1-2b(8i+3)\right)\left[4-\left(1-2b(8i+5)\right)\left[2-\left(1-2b(8i+7)\right)\right]\right]\right]\} \end{aligned}$$

### 5.3 Channel Coding

Owing to the low computational complexity and flexibility to operate at all supported block lengths and coding rates, LDPC (for data channel) and Polar codes (for control channel) have been propounded for use in 5G NR.

### 5.4 LDPC Coding

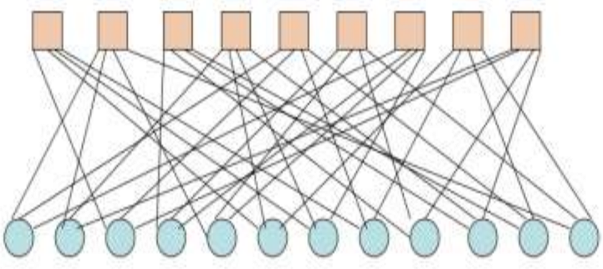
A low-density parity-check (LDPC) code is a linear error correcting code, a method of transmitting a message over a noisy transmission channel. An LDPC is constructed using a sparse bipartite graph. LDPC codes are capacity-approaching codes, which means that practical constructions exist that allow the noise threshold to be set very close to the Shannon limit for a symmetric memoryless channel. A binary parity check code is a block code, i.e., a collection of binary vectors of fixed length n. The symbols in the code satisfy r parity check equations of the form

$$Xa \oplus Xb \oplus Xc \oplus Xd$$

where, '$\oplus$' indicates modulo 2 addition.
A regular LDPC code has the property that:
1. Every code digit is contained in the same number of equations.
2. Every equation contains the same number of code symbols.
For n=12, the equations and parity check matrix are given as:

$$\begin{array}{cccccccccccc}
c_1 & c_2 & c_3 & c_4 & c_5 & c_6 & c_7 & c_8 & c_9 & c_{10} & c_{11} & c_{12} \\
0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\
0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\
1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 \\
0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0
\end{array}$$

In this example, each code symbol is contained in 3 equations and each equation involves 4 code symbols. Decoding of LDPC codes is best understood by a graphical representation. Graph has two types of nodes- bit nodes and parity nodes. Each bit node represents a code symbol and each parity node represents a parity equation.



Squares represent parity equations (parity nodes) while circles represent symbols (bit nodes). Each bit node has 3 lines connecting it to parity nodes and each parity node has 4 lines connecting it to bit nodes.
1. All bit nodes send a message (initial estimate) to their parity nodes containing the bit they believe to be correct. At this stage, the only information a bit node has, is the corresponding received bit.
2. Every parity node calculates a response (new estimates) to every connected variable node. The response message contains the bit that the parity node believes to be the correct one for the particular bit node, assuming that the other bit nodes connected to that parity node had sent correct initial estimates. For example, consider the parity node corresponding to the equation

$$c_3 \oplus c_6 \oplus c_7 \oplus c_8 = 0$$

This parity node has the estimates p3, p6, p7, and p8 corresponding to the bit nodes c3, c6, c7, and c8, where pi is an estimate for Pr[ci=1]. The new estimate for the bit node c3 is:

3. Bit nodes receive these messages and use this additional information to decide if their originally received bits were correct or not. This is usually done by a majority vote.

$$p_3' = p_6(1-p_7)(1-p_8) + p_7(1-p_6)(1-p_8) + p_8(1-p_6)(1-p_7) + p_6p_7p_8$$

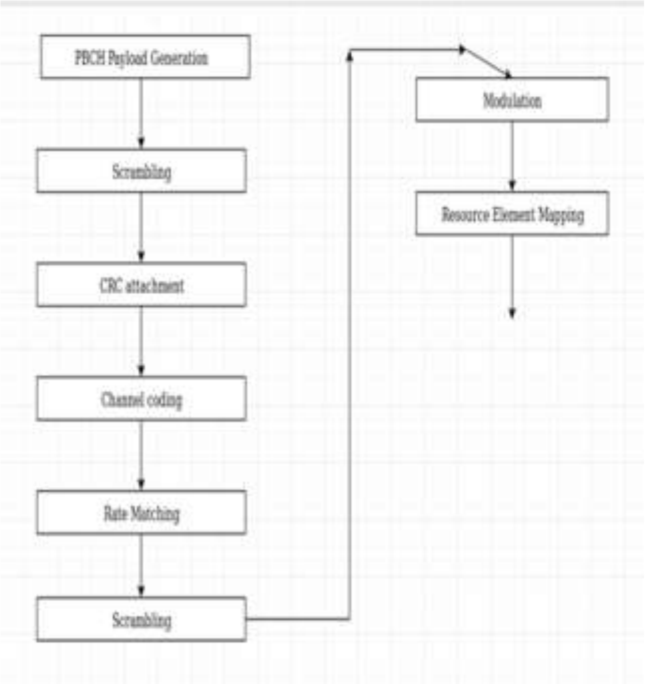


**Fig 11:** Physical layer processing of PBCH

### Advantages

1. Lower complexity than Turbo codes.
2. Better Block Error performance.
3. Improved performance without using CRC.

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### Disadvantages

In order to provide for variable bit rate, a buffer system must be designed.

### 5.5 Polar Coding

Polar codes operate on blocks of symbols/data and are therefore, members of the block code family. They will be used in eMBB 5G NR as control channels. It involves two key operations called channel combining and channel splitting. At the encoder, channel combining initially assigns carefully curated combinations of bits/symbols to specific channels. The channel splitting that follows translates these combinations inti decoder-ready, time-domain vectors. The decoding operation at the receiver tries to estimate these bit streams by using a successive cancellation decoding technique.

### Advantages

1. Have modest encoding/decoding complexity.
2. Help in achieving higher throughputs.
3. High hardware efficiency.

### Disadvantages

1. Polar coding uses Successive Cancellation Decoder whose performance is poor compared to
LDPC and turbo coding techniques.
2. It aggravates the problem of high latency.
3. Not very cost efficient.

## 6. CALL FLOW

PSS and SSS are transmitted in SS blocks together with PBCH. The blocks are transmitted per slot at fixed locations. During initial search, UE correlates received signal and synchronisation signal sequences by means of matched filters and performs the following steps[15]:

1. Find PSS and obtain symbol and 5ms frame timing.
2. Find SSS and detect CP length and FDD or TDD duplexing method and obtain exact frame timing from matched filter results, from PSS and SSS and obtain cell identity from reference signal sequence index.
3. Decode PBCH and obtain basic system information.
4. The UE reads PBCH providing the basic cell configuration and finds the downlink control channel (which schedules the shared channel).
5. UE reads minimum system information, providing scheduling information for all other system information blocks.
6. UE reads other required system information.
7. UE requests on-demand system information, eg. System information that is only relevant to a specific UE.

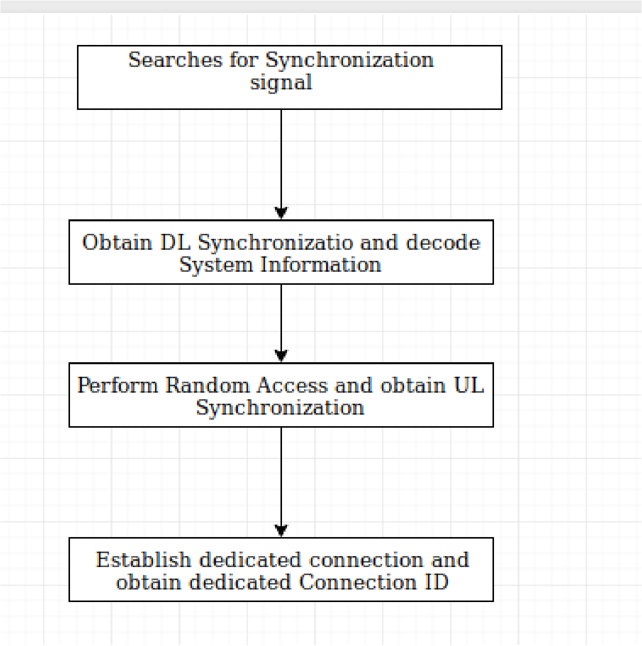

**Fig 12:** Call flow procedure

### 6.1 Initial Access Procedure

Initial access consists of downlink synchronisation and RACH procedure (uplink synchronisation).

1. Downlink synchronisation: UE detects the radio frame and OFDM symbol boundaries, by analysing the SS Block.

**SSB indexing**:

Each SS Block set (group of SS Blocks) is transmitted after every 20ms, with each SS Block set occupying an interval of 5ms.Each SS Block is given a unique number starting from 0 and incrementing by 1, which is informed to UE via two different parts within SSBlock. This is known as SSB indexing.

a. One part is carried by PBCH DMRS (Minimum System Information). It consists of a parameter c_init (initial value), which is composed of physical cell ID, half frame number and SSB index. By decoding the DMRS, UE is able to figure out SSB index and half frame number.

b. Other part is carried by PBCH Payload (Remaining Minimum System Information).

2. Uplink synchronization (initial access): It is through RACH that uplink synchronization can be achieved between UE and gNB. It also helps to obtain the resources for RRC connection request. In NR, synchronisation on the downlink side is achieved by periodic transmission of SSBlock after a certain interval. However, in uplink, it is not efficient as it may cause high interference to other UEs and energy wastage, if such periodic broadcasting mechanism is adopted.

The major difference encountered here is just before when RACH preamble is transmitted. Unlike LTE, beamforming mode is used by UE to detect and select the best beam for RACH process.

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Random access after acquisition of Broadcast System Information:

After broadcast system information is acquired, mobile terminals use the four-step process for random access, as used in LTE. However, the fundamental differences with respect to LTE are:
1. For PRACH transmitted as Msg.1, in addition to some formats using same sequence length and OFDM subcarrier spacing as LTE PRACH formats, PRACH formats using wide OFDM subcarrier spacing and shorter sequence length are used for high frequency band.
2. In case transmission beamforming is applied to SS Block for additional cell coverage, it is vital to apply equivalent reception beamforming at base station for receiving the PRACH preamble from mobile terminals. Rest of the steps are similar to as of LTE.

## 7. RRC STATES

### 7.1 5G NR RRC Procedures and States

Out of the many protocols operating in the air interface, RRC (radio Resource Control) is one of them. The major functions of RRC protocol include connection establishment and release, broadcast of system information, radio bearer establishment, reconfiguration and release, RRC connection mobility procedures, paging and outer loop power control. It is the signalling functions which enable the RRC to configure the user and control planes according to network status, thus allowing the implementation for radio resource management strategy.

### 7.2 RRC State

State machine is an essential constituent for the RRC operation, which defines certain specific states that a UE may be present in. Each RRC state in this state machine has variable amount of radio resources associated with them and UE uses these resources when present in a given specific state.

### 7.3 RRC States in 5G NR

The previous generation LTE had RRC Connected and RRC Idle states only. 5G NR has come up with a new RRC state, namely, RRC Inactive.

Following actions are performed by **RRC Idle mode:**

- Selection of PLMN
- Broadcast of SI messages.
- Cell re-selection mobility
- Paging for mobile terminated data is initiated by 5GC
- Paging for mobile terminated data area is managed by 5GC
- DRX for CN paging configured by NAS, Support for UE discontinuous reception (DRX) is carried out to enable power saving in 5G UE.RRC Inactive mode:
- Broadcast of system information
- Cell re-selection mobility
- Paging is initiated by NG-RAN (RAN paging)
- RAN-based notification area (RNA) is managed by NG-RAN
- DRX for RAN paging configured by NG-RAN
- 5GC to NG-RAN connection (both C/U-planes) is established for UE
- The UE AS context is stored in NG-RAN and the UE
- NG-RAN knows the RNA which the UE belongs to

### RRC Connected Mode

- 5GC to NG-RAN connection (both C/U-planes) is established for UE
- • The UE AS context is stored in NG-RAN and the UE
- • NG-RAN knows the cell which the UE belongs to
- • Transfer of unicast data to/from the UE
- • Network controlled mobility including measurements

The main aim of introducing RRC Inactive mode was to maintain RRC connection, along with reduction of signalling and power consumption. RRC states serve as a solution to the system access, power saving and mobility optimization. With the variety of use cases like eMBB, URLLC and Massive IoT services to be enabled at same cost and same energy dissipation per day per area, introducing such a mode becomes a necessity. Also, 5G system access and requested services provide control of connectivity, which need to be flexible and programmable. Hence, the new RRC state model serves the very purpose.

## 8. CONCLUSION

Thus, this paper tries to cover all the nuances of 5G NR according to the recently released 38 series of 3GPP. The flexibility in radio frame design (which was absent in previous generations) acts as a major cornerstone for the use of 5G in the myriad use cases. The study covered the main component technologies and techniques which include: frame structure, beamforming, etc. Significant progress has been made as reported in the results of the work that was examined.

Reduced subcarrier spacing (SCS) insures the data from ISI (Inter Symbol Interference), while an increased SCS, decreases the probability of ICI (Inter Carrier Interference). The symbol duration, having an inverse relation with subcarrier spacing, makes it imperative to reduce symbol duration with increase in SCS, thus increasing the number of slots in a subframe. An NR slot accommodates 14 OFDM symbols, as against LTE, which accommodates 7 symbols, providing many diverse patterns. respectively. Unlike in traditional LTE, in which PSS sequences were constructed from Zadoff-chu sequences, in NR both PSS and SSS sequences are generated by m-sequences. Also, the number of PCIs (Physical cell identities) have been increased from 504 to 1008, in order to provide enough deployment flexibility. A few new reference signals such as PTRS, PBCH Reference signals have been introduced. The role of SS Block and Channel State Information Reference Signal

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(CSI-RS) in proper alignment of gnodeB and UE to attain maximum SINR has been explained. Unlike LTE, which transmits cell-specific reference signals four times per millisecond, synchronizes every 5 MS, and broadcasts every 10 ms, 5G has no cell-specific reference signals and synchronizes and broadcasts every 20 ms. This enables greater base station power savings Due to shift of emphasis to higher frequencies and to curb penetration losses, beamforming is initiated in the initial access stage itself (unlike LTE, which used non-beamformed signals for initial access, handovers, etc.).

We conclude our discussion with a resonating notion that the design of 5G infrastructure is still under progress. Although the precise spectrum band to be used for 5G hasn't been specified yet, sub 6Ghz band and above 24Ghz has been proposed for now. 5G NR sub 6 Ghz band (1 GHz to 6 GHz) and high-band (above 24 GHz) operate in the same or in adjacent spectrum to other wireless communications systems. With devices covering multiple bands, there is increased risk for sideband interference or new shared spectrum issues. 5G NR devices will need to operate adjacent to or even in the same spectrum as existing wireless communications systems without causing interference. Designers of 5G chipsets and components need to know the different types of coexistence interference issues, where coexistence interference is likely to occur, and how to test for coexistence interference. [16] specifies the different waveforms which can be used in 5G, but the use of appropriate waveform still remains a mystery.

## REFERENCES

[1] NR Wide Bandwidth operations (Final manuscript to IEEE Communications Magazine on Key Technologies for 5G New Radio) by Jeongho Jeon, Intel Corporation (December 18, 2017).

[2] 3GPP TS 38.211 (Release 15) 4.4.5- Bandwidth part - March 2018

[3] A Tutorial on Beam Management for 3GPP NR at mm Wave Frequencies by Marco Giordani, Student Member, IEEE, Michele Polese, Student Member, IEEE, Arnab Roy, Member, IEEE, Douglas Castor, Member, IEEE, Michele Zorzi, Fellow, IEEE arXiv:1804.01908v1 [cs.NI] (5 April 2018)

[4] http://www.sharetechnote.com/html/5G/5G_CarrrierBandwidthPart.html

[5] 3GPP TS 38.211 (Release 15) 5.1- Modulation mapping- March 2018

[6] http://www.sharetechnote.com/html/5G/5G_FrameStructure.html#Resource_Grid

[7] NTT Docomo Technical journal Jan. 2018 – 2.1 Radio Frame,

[8] NTT Docomo Technical journal Jan. 2018 – 2.2- Initial Access

[9] ITU-T Technical Report GSTR - TN5G Transport network support for IMT 2020/5G (9 Feb. 2018)

[10] A Survey on 5G: The Next Generation of Mobile Communications- 4.4 Cloud Based Architecture By Nisha Panwar, Shantanu Sharma and Awadhesh Kumar Singh (November 4, 2015)

[11] 5G wireless network slicing for eMBB, uRLLC, : a Communication - Theoretic view- Petar Popovski , kasper F Trillingsgaard, Osvaldo Simeone and Giuseppe Durisi -arXiv:1804.05057v2 (1 Aug 2018)

[12] https://www.netmanias.com/en/post/techdocs/10997/lte-pcrf/policy-and-charging-rules-function-pcrf-in-lte-epc-core-network-technology December 08, 2016 | By Mojtaba HOUSHMAND @ MobinNet Telecom.

[13] An introduction to error correcting codes part 3 - Jack keil wolf - Spring 2010.

[14] http://www.rfwirelessworld.com/Terminology/Advantagand-Disadvantages-of-Polar-Coding.html

[15] Novel mobile radio research -5G Frame Structure August 2017- Frank Kowalewski, Eiko Seidel Nomor Research GmbH, Munich, Germany.

[16] https://www.google.co.in/search?q=ZTE+communication+5G&oq=ZTE+communication+5G&aqs=chrome..69i57.5805j0j7&sourceid=chrome&ie=UTF-8