

# Receiver Design for Physical Broadcast Channel in 5G NR

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In Partial Fulfillment of the Requirements for  
The Degree of Master of Technology



Department of Electrical Engineering

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## Declaration

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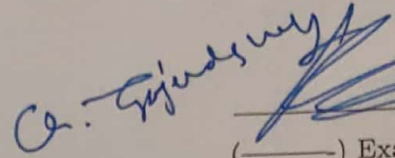
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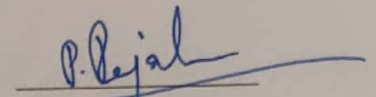
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## Approval Sheet

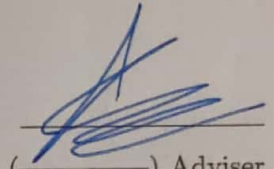
This Thesis entitled Receiver Design for PBCH in 5g-NR by Siddhesh Bahadkar is approved for the degree of Master of Technology from IIT Hyderabad

  
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## Abstract

The 5th Generation Wireless Technology known as New Radio or NR is being developed by 3GPP (3rd Generation Partnership Project) since past few years which aims to address scenarios from Mobile Broadband to highly reliable communication with very low latency. Key advances in 5G include advanced antenna systems like Massive MI-MO, operations in higher frequency bands and achievable uplink and downlink high data rates in GBps. The Radio air interface of 5G NR includes physical layer and other higher layers as well.

With the focus on physical layer, the technical specifications for NR released by 3GPP provide means to state-of-art realization and implementation of physical channels for both uplink and downlink. In NR, SS/PBCH block(SSB) consists of Synchronization signal(SS) and Physical Broadcast channel(PBCH). SSB is used to carry out cell search and identification to initialize a connection between UE and eNB. It also helps to manage handovers and beam sweeping for the radio coverage within the cell. The report aims at a detailed description on PBCH design, transmission and reception subject to a time varying wireless channel. PBCH transmitter is designed based on the technical specifications by 3GPP for 5G NR. PBCH data is generated and loaded with Demodulation reference signal(DMRS) for channel estimation at receiver. The combined data thus generated is mapped on sub-carriers and converted to time domain frames using Inverse Fourier transform (IFFT) as 5G NR is uses OFDM for both uplink and downlink transmissions. The time frames generated are convoluted with a time varying channel. The time varying channel is fast fading and follows Rayleigh distribution simulated using Jake's model and Vehicle-A type power delay profile. AWGN noise based on SNR value is added which represents the environment noise and attenuation.

The distorted and attenuated signal at the receiver is converted to frequency domain using FFT. Channel estimation is performed using DMRS. The channel equalization equalizes the time varying channel effect on the symbols and is further decoded to obtain PBCH payload. Finally the performance of the PBCH receiver is analyzed at low SNR values.

# Contents

Declaration . . . . .	ii
Approval Sheet . . . . .	iii
Acknowledgements . . . . .	iv
Abstract . . . . .	vi
<b>Nomenclature</b>	<b>viii</b>
<b>1 Intro</b>	<b>1</b>
1.1 Literature . . . . .	1
1.1.1 5G and its evolution from 4G . . . . .	1
1.1.2 Fundamentals of Physical Layer for 5G NR . . . . .	3
1.1.3 Physical channels and signals . . . . .	5
<b>2 Physical Broadcast Channel (PBCH)</b>	<b>7</b>
2.1 NR SSB Design . . . . .	7
2.1.1 SSB Design and Numerology . . . . .	7
2.1.2 PBCH and NR frame mapping . . . . .	9
2.1.3 PBCH and DMRS signal Generation and Mapping . . . . .	11
2.1.4 RESOURCE MAPPING . . . . .	16
2.2 PBCH transmitter . . . . .	18
2.2.1 Transmitter design . . . . .	18
2.2.2 System Model . . . . .	20
2.2.3 Wireless Channel Model . . . . .	20
<b>3 Receiver for Physical Broadcast Channel</b>	<b>22</b>
3.1 PBCH Receiver . . . . .	22
3.1.1 Receiver design . . . . .	22
3.1.2 Channel Estimation and Equalization . . . . .	24
3.1.3 Resource de-mapping . . . . .	26
3.1.4 Demodulation and De-scrambling . . . . .	26
3.1.5 De-rate Matching and Decoding . . . . .	26
<b>4 Simulation and Results</b>	<b>27</b>
4.1 Performance testing . . . . .	27
4.2 Simulation table: . . . . .	27

4.3 Results . . . . .	28
4.4 Conclusion . . . . .	29
<b>References</b>	<b>30</b>

# Chapter 1

## Intro

### 1.1 Literature

#### 1.1.1 5G and its evolution from 4G

5G or 5th Generation or New Radio is the evolved version of 4G LTE (Long Term Evolution). There is no single official definition for 5G but various organizations working on developing 5G have defined it according to its key aspects and goals. 5G cannot be defined in a single sentence but it is a technology of the present and future which is basically built on 3 major requirements[111] viz.

1. Ultra low latency and Reliable communication (EMMB)
2. Enhanced Mobile Broadband
3. Enhanced Machine type connectivity

#### Comparing 4G and 5G

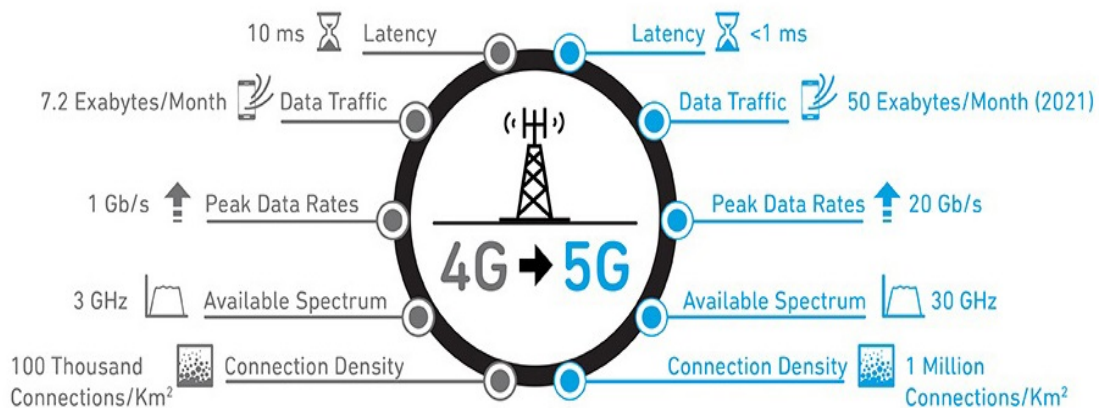


Figure 1.1: 4G to 5G evolution



Ultra low Latency and Reliable Communication aims at very less delay and low error rate in packets. Outstandingly fast applications with latency as low as 5ms or more for end-to-end communication must be achieved. EMMB will provide high spectral efficiency and higher throughput typically ranging from 1GBps to 10 GBps. Enhanced connectivity to devices will ensure longer battery life per device and support for 50-100 devices in network simultaneously.

3GPP is working to develop 5G since past few years. A major release was reached in December 2017 when the Non-standalone and the Standalone NR specification versions were completed and approved in June 2018. Key NR features include ultra-lean design for transmission, ultra low latency, advanced antenna systems, and high spectrum efficiency, compatibility between high and low frequency bands, and time division multiplexing (TDD) [1213].

LTE will evolve to support air interfaces of 5G since initially new air interfaces will not operate in similar frequency bands. 5G NR will enable dual-connectivity within LTE bands below 6GHz and new air interface in bands within the range 6GHz to 100GHz. The capabilities of 5G wireless access must evolve far beyond those of previous generations in order meet this requirement of inter-operability and previously mentioned features.

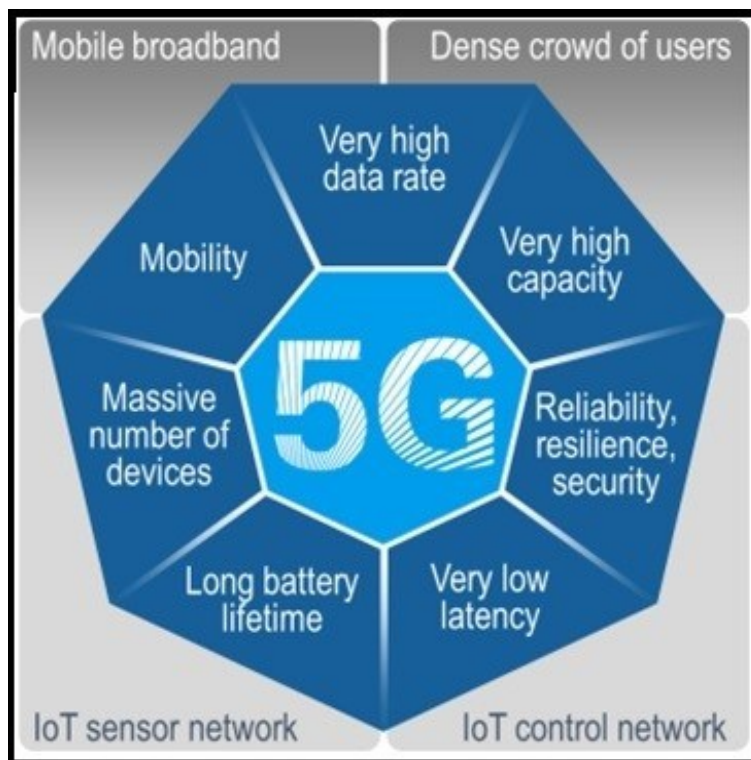


Figure 1.2: Features of 5G

## 1.1.2 Fundamentals of Physical Layer for 5G NR

### Frequency range and sub-carrier spacing

For any wireless Access Technology, radio waveform plays vital role in aspects of Bandwidth and complexity for implementation. 5G NR has a requirement of wide Bandwidth, very low complexity and support for Multiple Antenna systems (MIMO). Therefore, 3GPP has adopted Orthogonal Frequency Division Multiplexing (OFDM) with Cyclic Prefix for UL as well as DL.

There are two frequency ranges supported by NR:

- FR-1 : called as sub-6 GHz band ranging from 450MHz to 6GHz
- FR-2 : called as millimetre wave ranging from 24GHz to 52GHz

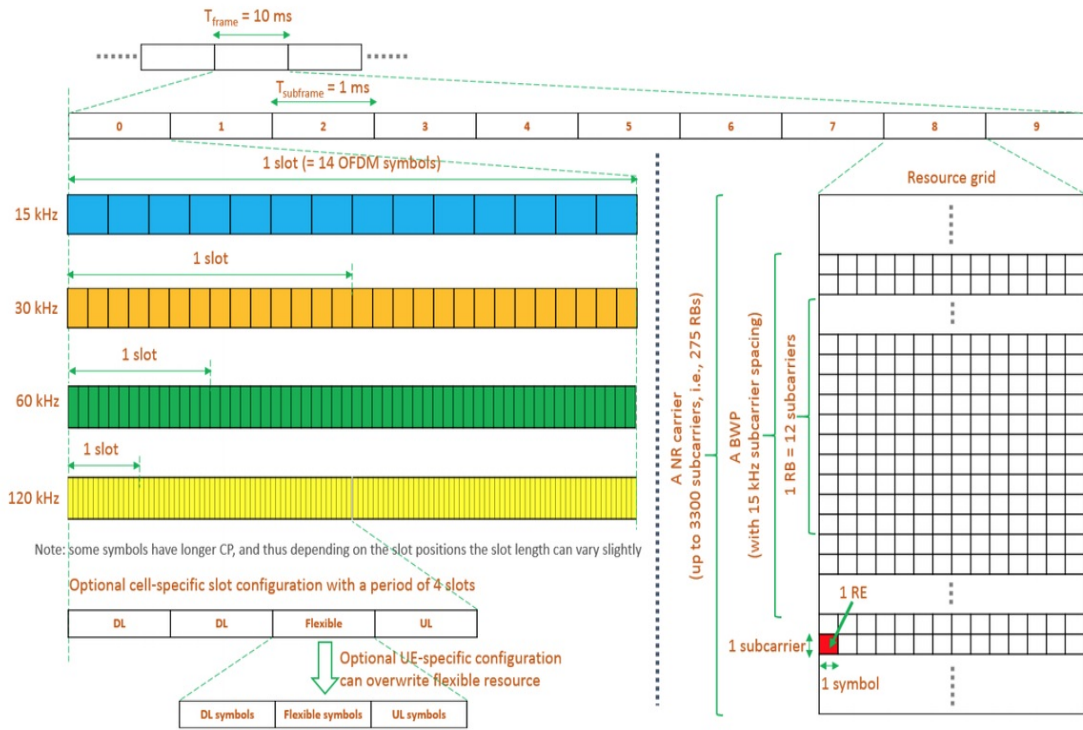


Figure 1.3: Frame Structure for 5G NR

OFDM Numerology is scalable in NR to support the wide spectrum and diverse scenarios. The sub-carrier spacing is flexible and can be scaled from basic 15kHz as in LTE to  $2^u \cdot 15\text{kHz}$ . Cell size is depended on the FR ranges. For FR1, the lower frequencies lead to larger cell size and hence sub-carrier spacings of 15kHz and 30kHz is suitable. for higher frequencies in FR2, the spacings used are 60, 120 and 240kHz for data and SSB channels.

The cell size can be smaller and delay spreads are shorter too. Hence the available spacings are sufficient.

Numerology	Sub-carrier spacing	CP type	Support for Physical channels	PRACH
0	15	Normal	Yes	Short Preamble
1	30	Normal	Yes	Short Preamble
2	60	Normal,Extended	Yes, not for Synch	Short Preamble
3	120	Normal	Yes	Short Preamble

Figure 1.4: Numerology supported for NR

### Frame, Resource blocks and Bandwidth part

A frame in NR has duration of 10ms as shown in Fig 1.3. It consists of 10 sub-frames each of 1ms duration. This structure is common to both LTE and NR. Each sub-frame has slots based on the numerology.

$$slots/subframe = 2^u \quad (1.1)$$

Each slot has 14 OFDM symbols forming a typical small unit of transmission for NR to schedule. so every frame consists of :

$$symbols/frame = 2^u * 14 * 10 \quad (1.2)$$

For example if u=2, then we have

- 1 Frame = 10 sub-frames
- 1 sub-frame =  $2^u$  slots = 2 slots
- 1 slot = 14 OFDM symbols

Therefore, 1 Frame =  $2*10*14=280$  OFDM symbols. Very low latency and minimum interference with other signals is achieved with such a short or mini slot transmission. These slots are in time domain but the data on sub-carriers is mapped in frequency domain called as Resource blocks(RBs).

Parameter / Numerlogy (u)	0	1	2	3	4
Subcarrier Spacing (Khz)	15	30	60	120	240
OFDM Symbol Duration (us)	66.67	33.33	16.67	8.33	4.17
Cyclic Prefix Duration (us)	4.69	2.34	1.17	0.57	0.29
OFDM Symbol including CP (us)	71.35	35.68	17.84	8.92	4.46

Figure 1.5: OFDM Symbol duration

Resource blocks comprises of 12 consecutive sub-carriers piled up in frequency domain as shown in the resource grid section in Fig 1.3. As per Release-15 specifications[2], an NR carrier has an upper limit of 3300 sub-carriers and 400MHz Bandwidth. The maximum Bandwidth in FR1 is 100MHz. As 30kHz is the maximum spacing available in FR1,  $3300*30\text{kHz}=99\text{MHz}$ , rounds up to 100MHz and in FR2, 120kHz is the highest spacing summing up a total of  $3300*120\text{kHz} = 396 \text{ MHz}$  which rounds up to 400MHz of total available Bandwidth per NR carrier.

A resource grid is made of radio resources in a NR carrier with sub-carriers over a duration of one sub-frame i.e. 1 ms. One resource element occupies a sub-carrier in an OFDM symbol as shown in Fig 1.3. For efficient power consumption, NR follows a concept called Bandwidth part[1321]. A single carrier has a large bandwidth which may be conditionally utilized to full extent depending on data-traffic conditions. Hence a User Equipment(UE) can switch to narrower Bandwidths or a part of total available spectrum per carrier to reduce power consumption. There are four Bandwidth parts that can be configured on UL and DL but at a particular transmission time and direction only one part can be active. Thus, depending on network conditions, the UE can switch dynamically between narrow and wide Bandwidths thus optimizing the power requirement.

#### **Modulation and Coding Schemes used in NR include:**

- BPSK and QPSK with Gray mapping[1]
- Orders of 16,64 and 128 QAMs with binary Gray mapping
- Controls channel data is coded with Reed Muller block codes and Polar codes
- Data channels use LDPC codes replacing turbo codes of LTE

#### **Duplexing options**

Frequency Division Duplexing(FDD), Time Division Duplexing(TDD) and dynamic TDD are included in duplexing techniques. Dynamic TDD is suitable for small cell size while static TDD is used in over-the-rooftop cells to mitigate interference efficiently. TDD operations are executed smoothly due to flexibility in slot configurations. NR allows a OFDM symbol to be UL, DL or flexible. Flexible symbols configured can be used both in UL and DL transmissions. If slot configuration is not predetermined, then every symbol is assumed to be flexible by default and dynamic TDD is implemented. In case of slot configurations, the Radio Resource Control (RRC) messages defined in 3GPP TS 38.331[2] determine allocations in UL and DL.

### **1.1.3 Physical channels and signals**

#### **Synchronization signal and Physical Broadcast channel**

The Synchronization signal(SS) and Physical Broadcast channel(PBCH) is collectively called Synchronization Signal Block (SSB) in NR. By receiving and decoding SS, UE identifies itself to the cell i.e. obtains cell identity. Time and frequency synchronization is achieved fro downlink and timing fro PBCH. PBCH carrier Master Information block which includes basic information of the system. SSB mapped to 4 OFDM symbols is transmitted as burst signal in 5ms window per NR

frame with a typical periodicity to achieve Beam Sweeping and minimize power consumption for UE to synchronize with the cell.

### **Physical Shared Channels**

PDSCH i.e. Physical Downlink shared channel is used to transmit the Downlink User data from gNB to UE, system information and other higher layer data. PDSCH transport block is coded with LDPC and support upto 2 code words mapped up on 4 MIMO layers. At the receiving end, UE can be informed of the unavailability of certain resources to decode PDSCH beforehand.

PUSCH i.e. Physical Uplink shared channel is used for transmission of shared data on uplink and 1/2 layer control information. The processing of Uplink data is similar at gNB as it is at the Downlink UE end for PDSCH.

### **Physical Control Channels**

PDCCH i.e. Physical Downlink Control Channel carries the Downlink Control Information (DCI) such as downlink and uplink scheduling grants. PDCCH is transmitted in a specific CORESET which is flexible and contiguous. UE follows a blind decoding process for maintaining flexibility to various DCI formats and aggregation levels.

PUCCH i.e. Physical Uplink Control channel carries the Uplink Control Information(UCI) such as HARQ, Channel state information(CSI) and scheduling requests.

### **Physical Reference Signals**

The reference signals for NR include

1. Demodulation Reference signal(DMRS) for Downlink and Uplink
2. Phase Tracking Reference signal (PTRS) for Uplink and Downlink
3. Channel State Information Reference signal (CSI-RS)
4. Sounding Reference Signal

Reference signals in NR are transmitted on demand and are time and frequency configurable which helps to reduce energy consumption and inter-cell interference. DMRS is used by the receiver to produce channel estimates to demodulate the data on the physical channel. PBCH, PDCCH, PDSCH, PUSCH and PUCCH are transmitted with DMRS and is UE specific. PTRS is used to track the phase of the local oscillator. at higher frequency operations i.e. millimeter wave FR2, the phase noise is dominant and PTRS helps to suppress the effect. CSI-RS is used for channel information at the UE. CSI-RS provides channel statistics, received signal power estimates, beam management and precoding for user data. SRS is transmitted for sounding of up link channel. It supports link adaptation and scheduling, precoder selection for DL and scheduling for multi-user MIMO.

This is brief introduction to basic and special features of 5G NR. The next chapter focuses on a physical signal, PBCH design and reception in base band.

# Chapter 2

## Physical Broadcast Channel (PBCH)

### 2.1 NR SSB Design

In NR, the Synchronization signal(SS), Demodulation Reference signal(DMRS) and Physical Broadcast Signal (PBCH) are combined together to form NR SS/PBCH Block (SSB). NR SSB design achieves

- flexible configuration for different numerologies
- beam sweeping
- low cell search latency
- ultra lean design to minimize power consumption

SSB is a periodic broadcast signal and sent multiple times in form of burst with sparse periodicity. In case of higher frequencies, the cell size is smaller. To ensure good coverage in this FR, NR implements SSB burst to sweep the beam accurately covering all users.

#### 2.1.1 SSB Design and Numerology

SS/PBCH block assists UE in performing initial cell search by which a UE acquires time and frequency synchronization with a cell and detects the physical layer Cell ID of that cell [2]. To ensure the detection of this cell ID, gNB periodically transmits SSB with a periodicity of at least 20 ms for a half frame (5ms). Each block includes Primary Synchronization Signal (PSS), Secondary Synchronization Signal (SSS) and PBCH data. PSS and SSS shall jointly convey physical layer cell ID. Master Information Block (MIB) is broadcasted over Physical Broadcast Channel (PBCH). DMRS support to decode MIB is provided.

The number of SSBs ( $L$ ) broadcasted within a half frame by gNB depends on the carrier frequency ( $f_c$ ). There are multiple periodicities supported for SS Bursts by NR viz. 5, 10, 20, 40, 80, 160 ms.

- if  $f_c < 3$  GHz :  $L=4$
- if  $3$  GHz  $< f_c < 6$ GHz :  $L=8$
- else if  $f_c > 6$  GHz :  $L=64$

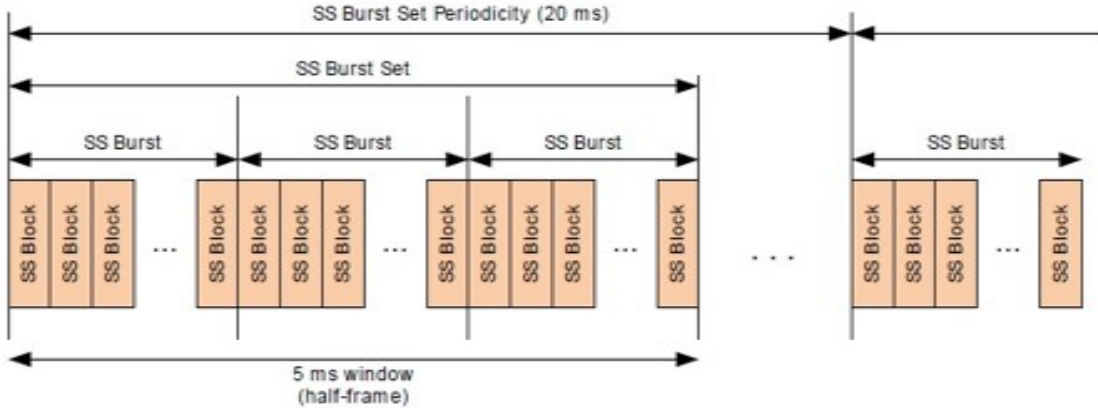


Figure 2.1: Burst mode and periodicity of SSB in NR frame

SSB Burst enables transmission of each such Block in different beams which are received by UE and used to manage beams of other channels following. UE scans all the SSBs in a burst to get the SSB index. The measurement from all the blocks received helps to decide the best beam for UE to receive other channels. In NR, unlike LTE, SSBs are flexibly placed i.e. the position can be configured based on numerology selected. A default burst period is 20ms but UE assumes the period to be 5ms if the burst set is not available. After successful detection of SSB, UE is equipped with cell ID and synchronized in time and frequency with gNB.

### Physical Layer cell ID

Physical layer cell ID broadcast is a two stage process involving PSS and SSS in the respective stages. There are 1008 distinct cell IDs in NR as compared to 504 in LTE.

$$N_{ID}^{cell} = 3N_{ID}^1 + N_{ID}^2 \quad (2.1)$$

Where  $N_{ID}^2$  is conveyed on PSS over a BPSK modulated signal.  $N_{ID}^1$  is broadcasted on SSS as BPSK modulated signal. Each PSS and SSS signal occupies 127 sub carriers in frequency domain.

$$N_{ID}^1 \in \{0, 1, 2, \dots, 33\}; N_{ID}^2 \in \{0, 1, 2\} \quad (2.2)$$

## 2.1.2 PBCH and NR frame mapping

A frame in NR is divided in two half frames of 5ms duration each, HF0 and HF1. UE undergoing the cell search assumes periodicity of 20ms. SS/PBCH block is spread over 4 OFDM symbols in the HF0 of the NR frame. Each of the synchronization signals, PSS and SS occupy 127 sub-carriers of the 1<sup>st</sup> and 3<sup>rd</sup> OFDM symbols of the SSB, respectively. PBCH occupies a total of 432 sub-carriers and DMRS for PBCH is mapped in 144 sub-carriers over the 2<sup>nd</sup>, 3<sup>rd</sup> and 4<sup>th</sup> OFDM symbol as shown in Fig 2.2.

240 sub-carriers are allocated in each OFDM symbol. Hence 2<sup>nd</sup> OFDM symbol in SSB is PBCH+DMRS, 3<sup>rd</sup> OFDM symbol in SSB is PBCH+SSS+DMRS. Here the SSS is the central part with 127 sub-carriers and there 48 sub-carriers of PBCH on either of the SSS. There are some unused carriers in-between for guard which are filled as nulls. For a half frame, the number of SSBs and index for 1<sup>st</sup> OFDM symbol of the block are determined by the Numerology assumed for the transmission.

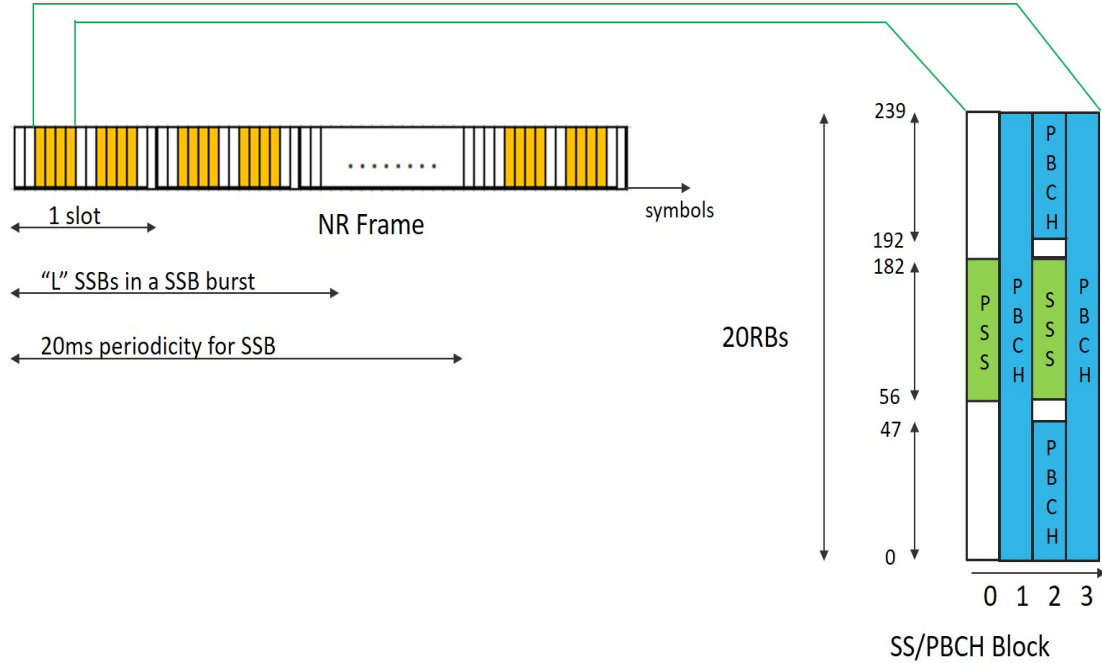


Figure 2.2: SS/PBCH in time and Frequency grid

The index and number of symbols in SSB are determined as below

- Case A – sub-carrier spacing is 15kHz. The indices for first symbols of candidate SSBs are given by  $\{2, 8\} + 14 * n$  where  $n = 0, 1$  for  $f_c \leq 3GHz$  and  $n = 0, 1, 2, 3$  for  $3GHz \leq f_c \leq 6GHz$
- Case B – sub-carrier spacing is 30kHz. The indices for first symbols of candidate SSBs are given by  $\{4, 8, 16, 20\} + 28 * n$  where  $n = 0$  for  $f_c \leq 3GHz$  and  $n = 0, 1$  for  $3GHz \leq f_c \leq 6GHz$
- Case C – sub-carrier spacing is 30 kHz. The indices for first symbols of candidate SSBs are given by  $\{2, 8\} + 14 * n$  where  $n = 0, 1$  for  $f_c \leq 3GHz$  and  $n = 0, 1, 2, 3$  for  $3GHz \leq f_c \leq 6GHz$



- Case D – sub-carrier spacing is 120 kHz. The indices for first symbols of candidate SSBs are given by  $\{4, 8, 16, 20\} + 28 * n$  where  $n = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18$  for  $f_c > 6GHz$
- Case E – sub-carrier spacing is 240 kHz. The indices for first symbols of candidate SSBs are given by  $\{8, 12, 16, 20, 32, 36, 40, 44\} + 56 * n$  where  $n = 0, 1, 2, 3, 4, 5, 6, 7, 8$  for  $f_c > 6GHz$

The positioning of SSB in frequency domain is determined by a higher layer parameter  $k_{SSB}$ .  $k_{SSB}$  for carrier frequencies greater than 6GHz is produced from higher layer and MSB of  $k_{SSB}$  is broadcasted to UE in the payload.

### PBCH Payload - Master Information Block

PBCH data includes a Payload of 32 bits. Among the 32 bits, the first 23 bits are the data of Master Information Block (MIB). MIB has a periodicity of about 80ms and within the 80 ms window has multiple transmissions.

NR MIB Characteristics are as follows :

- MIB is QPSK modulated
- It has a 24-bit payload with additional 8 bits to convey the System frame number
- MIB has a periodicity of 80ms with multiple transmissions within it.
- Decoding PBCH to obtain MIB helps UE to decode the SIB using the parameters provided by MIB

### Parameters of Master Information Block:

```
MIB := SEQUENCE {
    1. SystemFrameNumber          BIT STRING(SIZE(6)),
    2. subCarrierSpacingCommon    ENUMERATED{scs15or60,scs30or120},
    3. ssb-SubcarrierOffset       INTERGER(0,1.....15),
    4. dmrs-typeA-Position        ENUMERATED{pos2,pos3},
    5. pdcch-ConfigSIB1          INTEGER(0,1,...255),
    6. cellBarred                 ENUMERATED {barred,notBarred},
    7. intraFreqReselection       ENUMERATED{allowed,notAllowed},
    8. spare                       BIT STRING(SIZE(1))
}
```

Parameter Description:

- \* **systemFrameNumber** : The SFN for NR frame is a 10 bit number ranging from 0 to 1023 in value. The 6 MSBs of the SFN are a part of MIB and the remaining 4 LSB bits are part of extra bits padded after 24 bits of MIB in the transport block of PBCH.
- \* **subCarrierSpacingCommon** : carries the sub carrier spacing values 15 or 30 kHz for  $f_c < 6\text{GHz}$  and 60 or 120 kHz for  $f_c > 6\text{GHz}$  of SIB1, Message for initial access and System-Information Messages.
- \* **ssb-subcarrierOffset** : this field gives the frequency domain offset between SSB and the Resource grid in the value of number of sub-carriers. It helps to determine whether the cell provides SIB1 and common CORESET.
- \* **dmrs-TypeA-Position** : Indicates Position of Downlink DMRS corresponding to the L1 parameter
- \* **pdccchConfigSIB1** : It is the RMSI-PDCCH-Config in TS38.213 [13], section 4.1 which provides the Bandwidth for PDCCH/SIB, CORESET, a common search space and required PDCCH parameters. if the `ssb-subcarrierOffset` field is indicating absence of SIB1, then this field gives the frequency positions where UE will receive SS/PBCH block with SIB1 or where the network does not provide it.
- \* **cellBarred** : it gives the status whether the cell allows the UE to camp
- \* **intraFreqReselection** : indicates whether cell reselection is allowed or notAllowed. It controls the reselection to intra-Frequency cell when the highest ranked cell is barred by UE as in **1223**

### 2.1.3 PBCH and DMRS signal Generation and Mapping

PBCH data generation involves five important stages. MIB data obtained from higher layer is processed through following operations sequentially.

- (a) PBCH Payload Generation
- (b) Scrambling
- (c) CRC addition
- (d) Polar Coding
- (e) Rate Matching

The higher layer data comes to L1 in the form of a transport block every 80 ms.

**PBCH Transport process:**

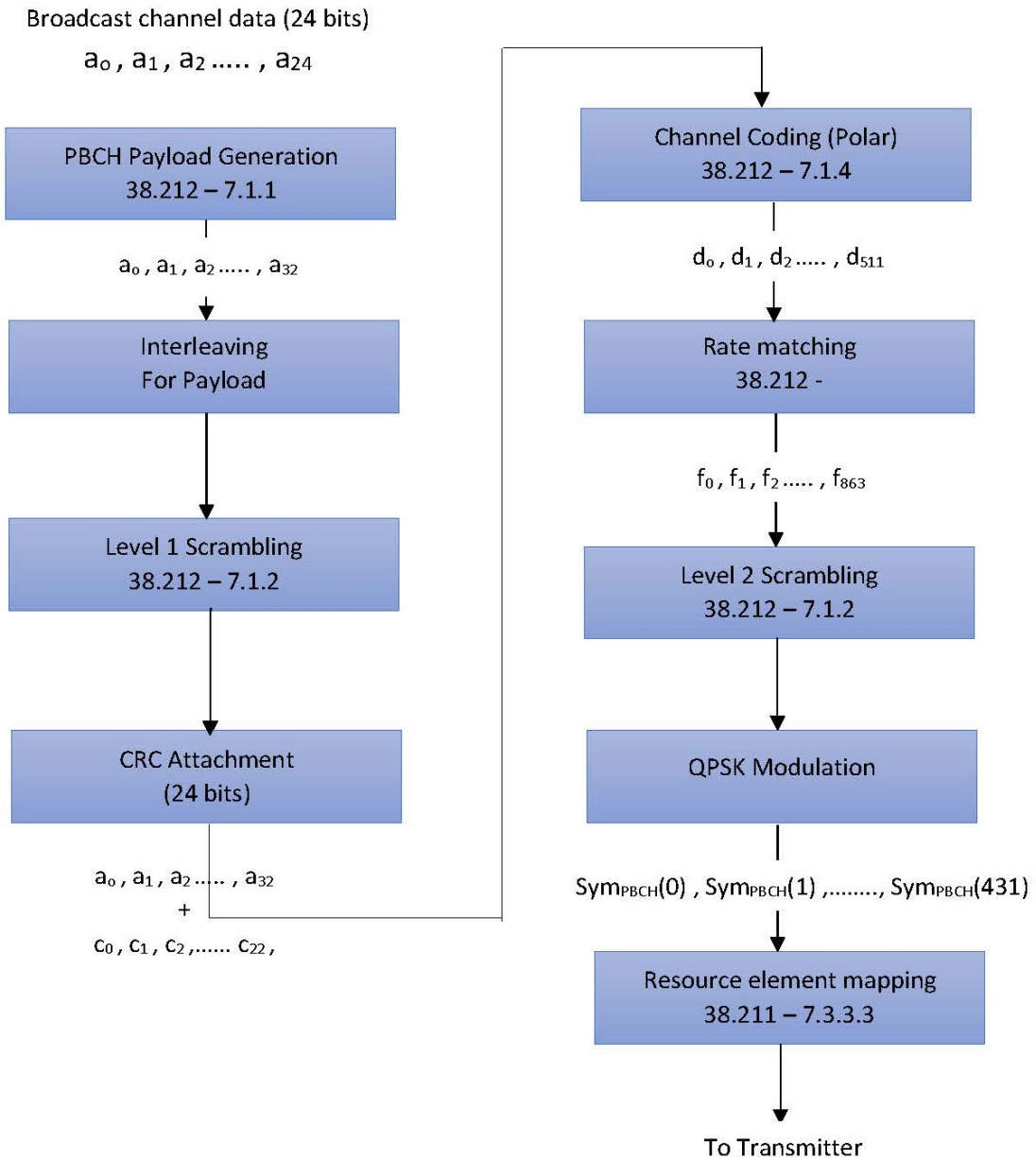


Figure 2.3: PBCH generation and mapping

## PBCH PAYLOAD and INTER-LEAVING

The payload MIB of 24 bits is obtained from higher layer viz.  $a_0, a_1, a_2, \dots, a_{23}$ . The total payload of PBCH builds up to 32 bits after adding the extra 9 bits for timing. Out of these 8 bits, 4 bits are LSBs of the System frame number (SFN), one bit signifies the half frame indication, and remaining three bits are LSB's of the index of SSB ( $k_0$ ) depending the carrier frequency (<6GHz or >6GHz). the 32-bit payload is interleaved with a 32 bit block inter-leaver given below:

<b>k</b>	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
<b>G(k)</b>	16	23	18	17	8	30	10	6	24	7	0	5	3	2	1	4
<b>k</b>	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
<b>G(k)</b>	9	11	12	13	14	15	19	20	21	22	25	26	27	28	29	31

Figure 2.4: 32 bit block Inter-leaver

## L1-SCRAMBLING

The interleaved payload is scrambled using level 1 Scrambler as in [1232]. The scrambled sequence  $a'_0, a'_1, a'_2, \dots, a'_{31}$  is obtained from  $a_0, a_1, a_2, \dots, a_{31}$  as,

$$a'_i = (a_i + s_i) \text{mod} 2 \quad (2.3)$$

where  $s_i$  are generated as

$$s_i = c(j + vM) \quad (2.4)$$

$s_i = 0$  for  $a_i$  corresponding to half frame bit index, and  $2^{nd}$  and  $3^{rd}$  least significant bits of the SFN

Here the scrambling sequence "c" is generated as follows: "c" is generic pseudo random sequence defined by length-31 Gold sequence[13253]. The output  $c(k)$  is obtained as, where  $k = 0, 1, 2, 3, \dots, M_{pn}$

$$c(k) = (x_1(k + N_c) + x_2(k + N_c)) \text{mod} 2 \quad (2.5)$$

$$x_1(k + 31) = (x_1(k + 3) + x_1(k)) \text{mod} 2 \quad (2.6)$$

$$x_2(k + 31) = (x_2(k + 3) + x_2(k + 2) + x_2(k + 1) + x_2(k)) \text{mod} 2 \quad (2.7)$$

where  $N_c = 1600$

$x_1(0) = 1, x_1(k) = 0$  for all other k

$$c_{init} = \sum_{i=0}^{31} x_2(i) \cdot 2^i$$

However "c" is initialized with  $c_{init} = N_{ID}^{cell}$  at the start of each SFN

Level 1 Scrambling helps in reducing blind decoding at UE. The scrambling sequence is generated in every frame in code base with indexing taken care of.

## CRC ATTACH

Error detection is achieved on the transport block of BCH through Cyclic Redundancy check(CRC). The parity of length  $L = 24$  for CRC are calculated using the entire payload. The generator

Polynomial  $g_{CRC24C}(D)$  is used to compute the parity and append it to the payload block. The total length  $B = 32+24=56$  bits viz  $c_0, c_1, c_3, \dots, c_{55}$  after CRC attachment are obtained and sent to channel coder.

## CHANNEL CODING

CRC attached sequence is polar encoded as in [2343]. The bit sequence denoted as  $c_0, c_1, c_3, \dots, c_{K-1}$ , where  $K$  is the number of bits to encode. After encoding using Polar coding we get  $d_0, d_1, d_2, \dots, d_{N-1}$ , where  $N = 2^n$ . The value of  $n$  is computed as follows:

Let  $E$  be the length of the output of rate matching, then  
if  $(K/E) < (9/16)$  and  $E \leq (9/8) \cdot 2^{(\lceil \log_2 E \rceil - 1)}$

$$n_1 = \lceil \log_2 E \rceil - 1 \quad (2.8)$$

else

$$n_1 = \lceil \log_2 E \rceil \quad (2.9)$$

if  $R_{min} = 1/8$ ;

$$n_2 = \lceil \log_2(K/R_{min}) \rceil; \quad (2.10)$$

$$n = \max\{\min\{n_1, n_2, n_{max}\}, n_{min}\} \quad (2.11)$$

where  $n_{min} = 5$

Here for PBCH  $K = 55$  and  $E = 864$ , hence the first if condition is satisfied.

We get  $n_1 = 9$  and  $n_2 = 8$ , thus the value of  $n$  is 9 and  $N = 2^n = 2^9 = 512$ .

The channel coded output bits  $d_0, d_1, d_2, \dots, d_{511}$  are forwarded to rate-matcher.

## RATE MATCHING

The channel encoded data is rate matched to 864 bits and then mapped to SS/PBCH block. The process is defined per block consisting of sub-block Interleaving, bit collection and bit interleaving.

For sub-block interleaving, the bit sequence from channel coder output  $d_0, d_1, d_2, \dots, d_{N-1}$  is divided into 32 sub-blocks as follows:

for  $n = 0$  to  $N-1$

$$i = \lfloor 32n/N \rfloor \quad (2.12)$$

$$J(n) = P(i)x(N/32) + \text{mod}(n, N/32) \quad (2.13)$$

$$y_n = d_{J(n)} \quad (2.14)$$

where the sub-block inter-leaver pattern  $P(i)$  is given by Fig.2.4

For bit-selection, the bit sequence  $y_0, y_1, \dots, y_{N-1}$  is loaded in a circular buffer of length  $N$ . If  $E$  is the rate to be matched, then the rate matching sequence  $e_1, e_2, e_3, \dots, e_{E-1}$  is obtained as follows:

```

if  $E \geq N$  — repetition of bits by padding
  for  $k = 0$  to  $E - 1$ 
     $e_k = y_{\text{mod}(k,N)}$ 
  end for
else
  if  $K/E \leq 7/16$  — puncturing if the rate is lower than channel coding output
    for  $k = 0$  to  $E - 1$ 
       $e_k = y_{k+N-E}$ 
    end for
  else — shortening
    for  $k = 0$  to  $E - 1$ 
       $e_k = y_k$ 
    end for
  end if
end if

Finally the sequence  $e_1, e_2, e_3, \dots, e_{E-1}$  is interleaved into bit sequence  $f_1, f_2, f_3, \dots, f_{E-1}$  to get the final rate matched bits of PBCH.

```

## L2-SCRAMBLING

Before modulating the final payload bit sequence  $f_1, f_2, f_3, \dots, f_{E-1}$ , it is scrambled on level-2 according to,

$$f'_i = (f_i + c(i + vM)) \text{mod} 2 \quad (2.15)$$

where  $c(i)$  is computed as described in subsection L1-Scrambling and is initialized with  $c_{\text{init}} = N_{ID}^{\text{cell}}$  at the start of each SSB where,

- for  $L=4$ ,  $v$  is the last 2 LSBs of the SSB index      - for  $L=8$  or  $64$ ,  $v$  is the 3 LSBs of the SSB index

## MODULATION

The scrambled bit sequence  $f'_1, f'_2, f'_3, \dots, f'_{E-1}$  is modulated by QPSK scheme into a block of complex-valued QPSK symbols carrying PBCH data,  $d_{PBCH}(0), d_{PBCH}(1), d_{PBCH}(2), \dots, d_{PBCH}(M_{\text{sym}} - 1)$ . Here  $M_{\text{sym}} = 864/2 = 432$ .

## Resource mapping

These 432 QPSK modulated symbols along with 144 DMRS symbols are mapped to the 576 sub-carriers which are the resource elements on the available Bandwidth part for PBCH transmission. The Resource mapping will be discussed in next section but lets first take a look at the Demodulation reference signal(DMRS) for the PBCH.

## DMRS signal generation

Demodulation Reference signal (DMRS) is used to decode PBCH signal at the receiver by helping in estimating the channel and noise values. DMRS symbols are QPSK modulated and generated from a PN sequence generator with  $c_{init}$  initialized as follows:

$$c_{init} = 2^{11}(\bar{i}_{SSB})(\lfloor N_{ID}^{cell}/4 \rfloor + 1) + 2^6(\bar{i}_{SSB} + 1) + (N_{ID}^{cell} \bmod 4) \quad (2.16)$$

where,

- for  $L=4$ ,  $\bar{i}_{SSB} = i_{SSB} + 4n_{hf}$
- for  $L=8$  or  $64$ ,  $\bar{i}_{SSB} = i_{SSB}$

and  $n_{hf}$  is the half-frame number in which the PBCH is present.

### 2.1.4 RESOURCE MAPPING

An SS/PBCH block is composed of 4 OFDM symbols in time domain numbered from 0 to 3 in which PSS, SSS and PBCH along with the DMRS symbols are mapped on the resource elements viz. sub-carriers.

An SSB consists of 240 contiguous sub-carriers numbered from 0 to 239 as shown in Fig.???. We have 432 symbols of PBCH and 144 symbols of DMRS to be mapped in available Bandwidth part for SSB. The Resource-mapping per OFDM symbol is given the following table, where  $k$  and  $l$  are frequency and time index respectively.

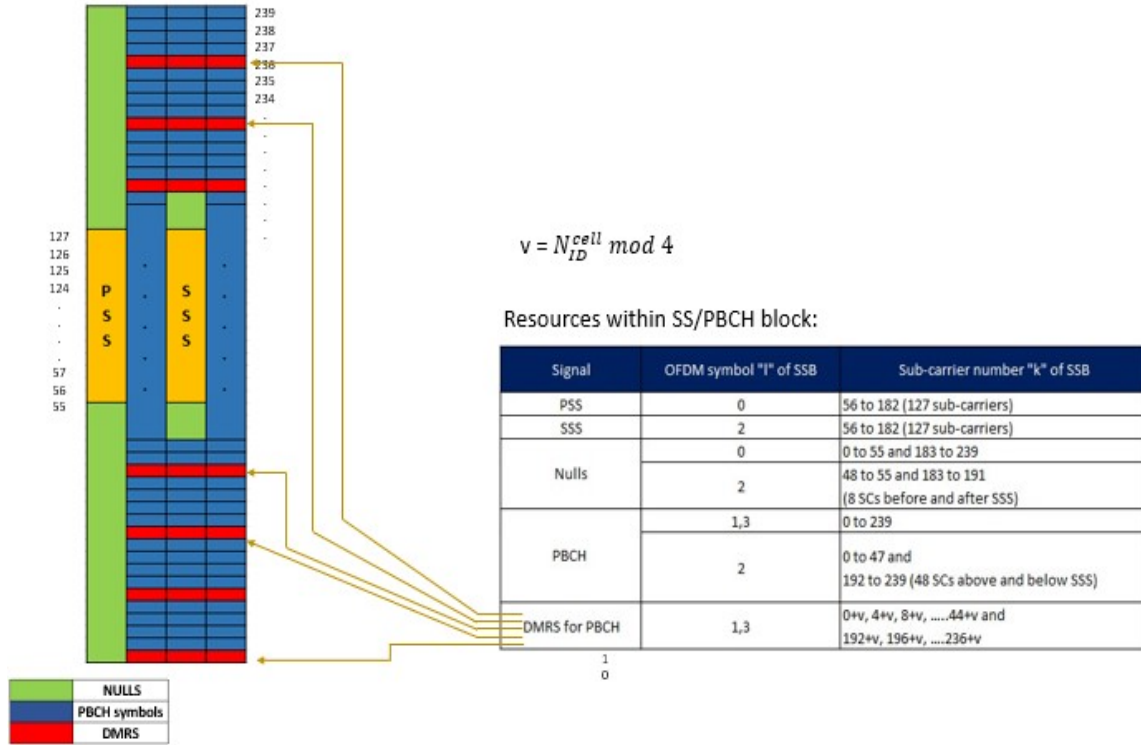


Figure 2.5: Resources within SS/PBCH block

In the above table, the value of  $v$  is obtained as :  $v = N_{ID}^{cell} \bmod 4$

For a SS/PBCH block, UE assumes the following features:

- $p=4000$  is the antenna port used for transmission
- cyclic prefix and sub-carrier is constant for all PSS, SSS and PBCH
- SSBs transmitted with the same ssb index on the same center frequency location are quasi co-located with respect to Doppler spread and shift, average gain, delay and delay spread and spatial receiver parameters.
- It shall never assume quasi co-location for any other SSB transmissions.

### Location shift of DMRS by $N_{ID}^{cell}$ value

The position of DMRS in SSB shifts vertically according to the value of  $N_{ID}^{cell}$  as shown below:

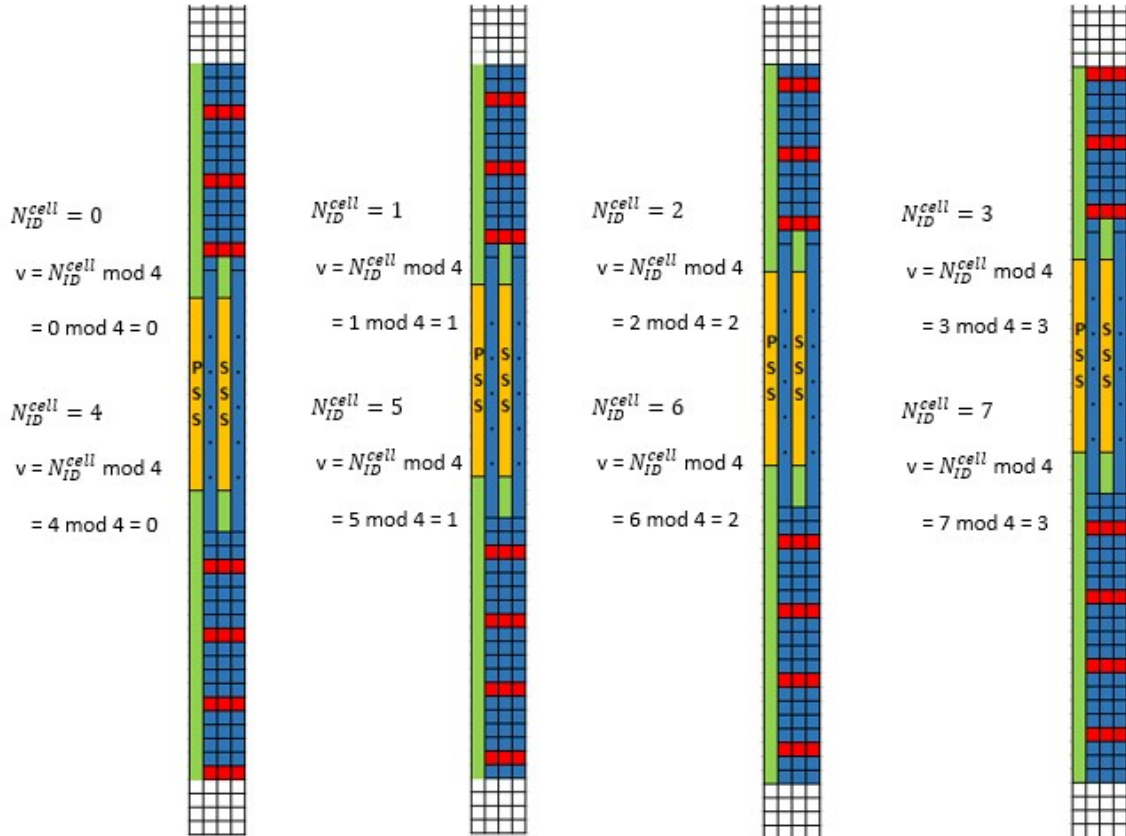


Figure 2.6: Shift in DMRS due to  $N_{ID}^{cell}$

The UE assumes the sequence of symbols  $d_{PSS}(0), d_{PSS}(1), \dots, d_{PSS}(126)$  constituting the PSS and  $d_{SSS}(0), d_{SSS}(1), \dots, d_{SSS}(126)$  constituting the SSS are mapped to resources  $(k, l)$  in increasing order of  $k$  where  $k$  and  $l$  are frequency and time indices respectively.



The UE assumes the sequence of complex valued symbols  $d_{PBCH}(0), d_{PBCH}(1), \dots, d_{PBCH}(431)$  carrying the PBCH data are mapped to resources  $(k, l)$  excluding the positions for DMRS mention in the table in Fig.2.5. Similarly the symbols for DMRS are mapped in the given resource locations.

## 2.2 PBCH transmitter

### 2.2.1 Transmitter design

The L number of SS/PBCH blocks thus obtained are centrally allocated in a grid of larger sub-carriers called as Bandwidth for the every OFDM symbol. Here the total sub-carrier per OFDM symbol is 3300. So the L number of 240x4 grid blocks of SS/PBCH data are mapped in frames with 3300 sub-carriers per OFDM symbol and L is obtained as discussed in section 2.1.1.

PBCH waveform is obtained by implementing CP-OFDM transmitter with scalable numerology. The scalable numerology leads to flexible sb-carrier spacing and cyclic prefix in both UL and DL upto 52.6GHz.

Subcarrier spacing	15kHz	30kHz	60kHz	$15 \times 2^n$ kHz ( $n=3,4,\dots$ )
OFDM symbol duration	66.67us	33.33us	16.67us	$66.67/2^n$ us
Cyclic prefix duration	4.69us	2.34us	7.17us	$4.69/2^n$ us
OFDM symbol with CP	71.35us	35.58us	17.84us	$71.35/2^n$ us
Number of OFDM symbols per slot	7or14	7or14	7or14	14
Slot Duration	500 or 1000us	250 or 500us	125 or 250 us	$1000/2^n$ us

Figure 2.7: Scalable Numerology for OFDM

OFDM symbol is formed by taking Inverse Fast Fourier Transform per 3300 sub-carriers. According to the assumed numerology, CP length is computed. For  $u=0$ , sub-carrier spacing =15kHz, CP = 288 and extended CP =  $288 + 32 = 320$  for every 7th OFDM symbol.

For PBCH Transmissions, NR uses  $p=4000$  as a single port to avoid the blind decoding of actual antenna ports used. If different antenna ports are used for SS and PBCH signals, then separate reference signals such as DMRS will be required. This will help in implementing flexible schemes for precoding with MIMO, but still a single antenna is preferred.

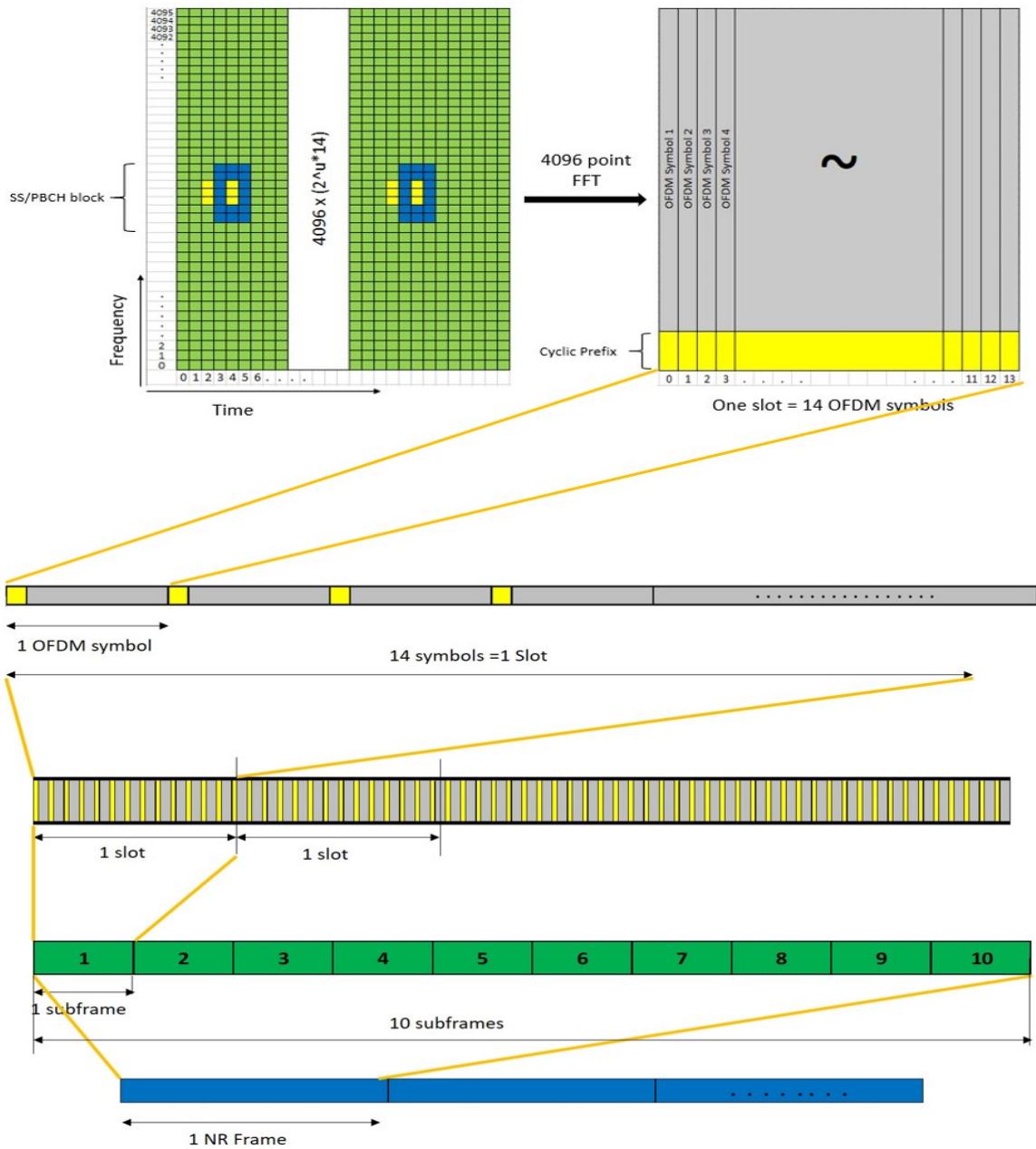


Figure 2.8: NR Frame Generation using OFDM

## 2.2.2 System Model

The PBCH baseband equivalent system model for air interface includes transmitted signal  $x(t)$ , wireless channel  $h(t-t_0)$ , AWGN and received PBCH signal  $y(t)$  depicted as follows:

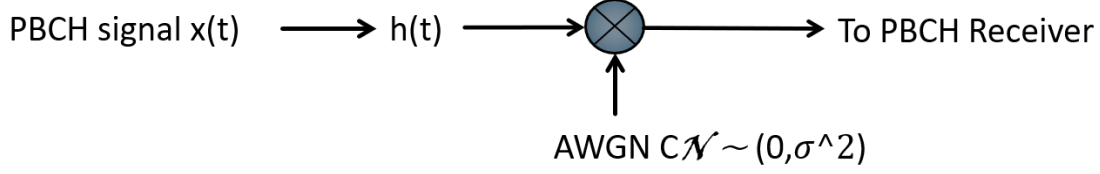


Figure 2.9: PBCH Communication model in Base-band

The PBCH signal is the NR frame generated in time domain as shown above in Fig.???. The signal is mapped to antenna port  $p=4000$  and the SSB beams are formed in air interface. Now the signal experiences attenuation, time delays and phase delays in multiple paths along with some random environment noise added to it before reaching the receiver antenna.

The signal that simulates the complete attenuation and delay in multi path is the wireless time varying channel  $h(t-t_0)$ . The random environment noise is characterized as Additive White Gaussian Noise with variation  $\sigma^2$ . The wireless channel gets convoluted with the PBCH signal and AWGN being additive is added to obtain the signal at receiver as  $y(t)$ .  $y(t)$  is a delay and attenuated version of  $x(t)$  affected in time and frequency both.

## 2.2.3 Wireless Channel Model

The wireless channel model considered is Tap Delay Line (TDL) model. TDL channel is easy to evaluate and defined for full frequency spectrum from 0.5 to 100GHz for non MIMO systems. There are 3 types of TDL such as TDL-A, TDL-B and TDL-C. The underlying fading distribution is Rayleigh for all three types.

As the channel is varying time, non LOS and also in mobile, there will be a shift in frequency as well leading to Doppler spread. The Doppler spectrum is characterized by using Jake's model simulation.

Maximum Doppler shift  $f_D$  is given by

$$f_D = |v|/\lambda \quad (2.17)$$

Each TDL model is scaled in delay to obtain the desired RMS delay spread. Parameter for TDL-C channel model is given as in the Fig 2.10 below: The scaled versions of delays are obtained as follows:

$$\tau_{scaled} = \tau x t_0 \quad (2.18)$$

where,

$\tau_{scaled}$  is normalized delay of TDL model

$\tau$  is new scaled delay of TDL model

$t_0$  desired Delay spread

TDL Model	$t_0$ (in ns)
Short Delay spread	30
Normal Delay spread	100
Long Delay spread	300
Very Long Delay spread	1000

Figure 2.10: Parameter for scaling of TDL model

Tap #	Normalized delays	Power in [dB]	Fading distribution
1	0	-4.4	Rayleigh
2	0.2099	-1.2	Rayleigh
3	0.2219	-3.5	Rayleigh
4	0.2329	-5.2	Rayleigh
5	0.2176	-2.5	Rayleigh
6	0.6366	0	Rayleigh
7	0.6448	-2.2	Rayleigh
8	0.6560	-3.9	Rayleigh
9	0.6584	-7.4	Rayleigh
10	0.7935	-7.1	Rayleigh
11	0.8213	-10.7	Rayleigh
12	0.9336	-11.1	Rayleigh
13	1.2285	-5.1	Rayleigh
14	1.3083	-6.8	Rayleigh
15	2.1704	-8.7	Rayleigh
16	2.7105	-13.2	Rayleigh
17	4.2589	-13.9	Rayleigh
18	4.6003	-13.9	Rayleigh
19	5.4902	-15.8	Rayleigh
20	5.6077	-17.1	Rayleigh
21	6.3065	-16	Rayleigh
22	6.6374	-15.7	Rayleigh
23	7.0427	-21.6	Rayleigh
24	8.6523	-22.8	Rayleigh

Figure 2.11: Parameter for TDL-C channel model

## Chapter 3

# Receiver for Physical Broadcast Channel

The UE may have one or more antenna to receive the Broadcasted information from the base station. As the UE is turned ON or woken up from a idle state, the first task of the equipment is to get synched up or identified to the serving cell. SS/PBCH block reception and decoding leads to the necessary synchronization and identification.

PBCH receiver designed as a part of this thesis includes extracting the data, channel estimation and equalization, decoding and demodulating to obtained the transmitted payload. Finally, the performance is analyzed based on the number of bits and block in error for varying values of channel repetitions and noise variances. The UE procedure to receive PBCH includes receiving the SSB burst transmitted from Base station. UE assumes the periodicity of the SSB to be 20ms and and each half frame of 0.5ms includes L number of SSBs configured based on carrier frequency and numerology. PBCH receiver procedures are triggered after attaining synchronization with the cell using the PSS and SSS in SS/PBCH block.

The Synchronization procedure takes of the timing and frequency offsets through some robust and high speed computation algorithm to obtain the starting index or position to extract PBCH data. The rest of the process flow is described in the sections followed.

### 3.1 PBCH Receiver

#### 3.1.1 Receiver design

The synchronization procedure outputs a position index value to extra the data of PBCH from. The receiver flow chart is as follows:

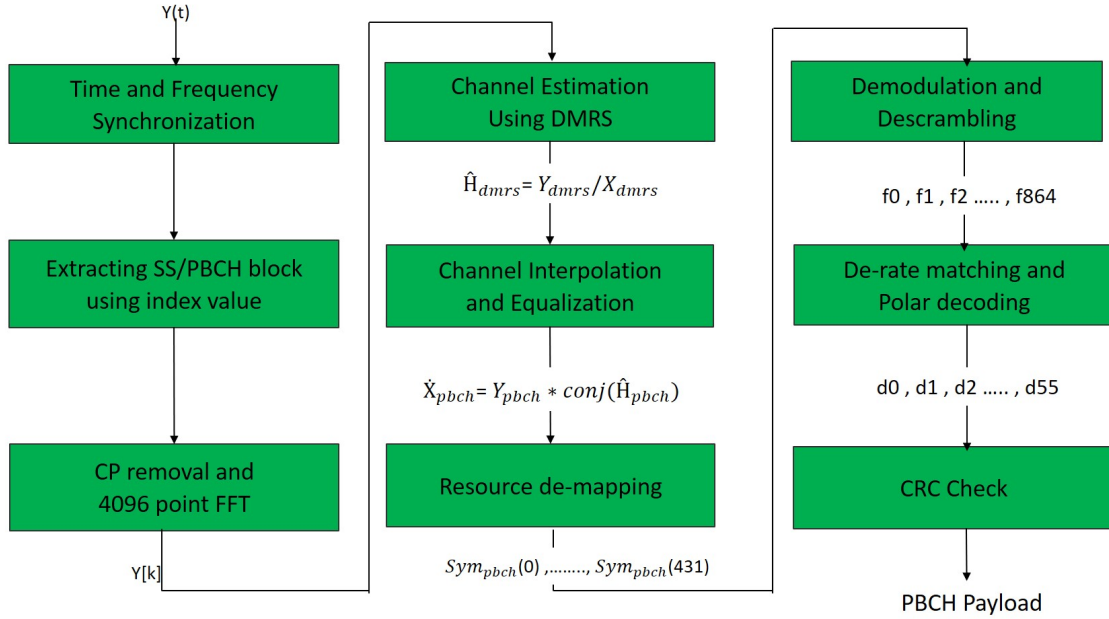


Figure 3.1: Receiver process flow for PBCH

### Extraction of PBCH

The data is received in the form of frames. These time domain frames obtained have OFDM symbols each 4096 long. For a frame with numerology "u" and carrier frequency " $f_c$ ", the PBCH location is obtained as discussed in section 2.1.2. If suppose,  $u=0$  and  $f_c = 2GHz$ , case A is satisfied and the first index for SS/PBCH block is "2". This index marks the third OFDM symbol in the frame. So, the output index of the synchronization procedure is

$$pssloc = 4096 + 288 + 4096 + 288 + 288 + 32 + 1 = 9089 \quad (3.1)$$

So from a received frame, the PBCH receiver must start extracting from 9089th value.

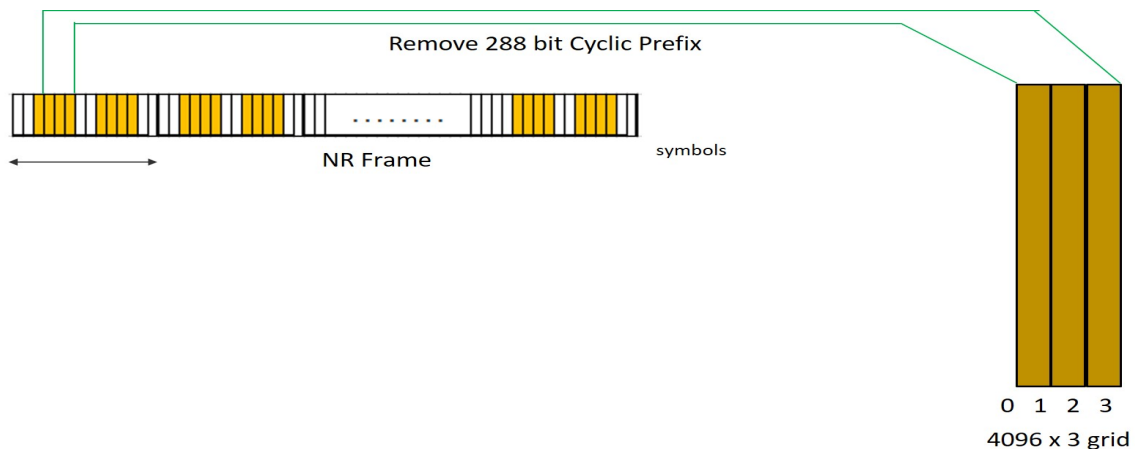


Figure 3.2: Extraction of OFDM symbols with PBCH data

### CP removal and FFT computation

Now SS/PBCH is a block of 4 OFDM symbols with PBCH located among 3 of them. Removing 288 bit Cyclic prefix prior to every symbol and extracting three such 4096 length symbols, a grid of 4096 x 3 is obtained.

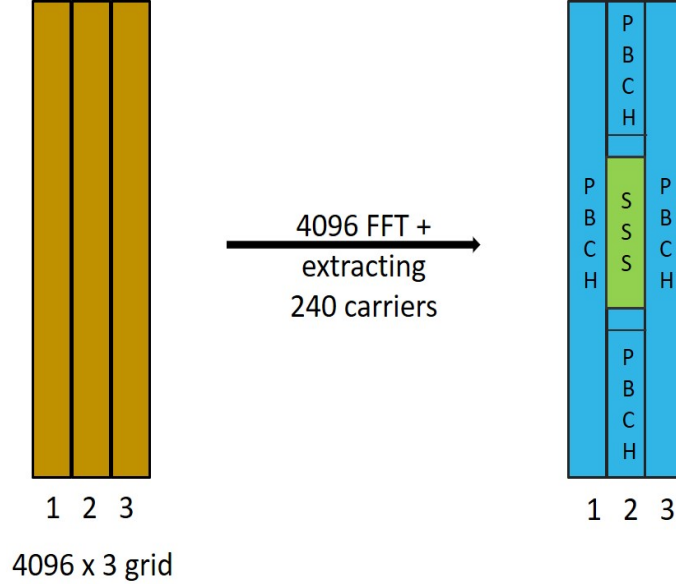


Figure 3.3: 4096 point FFT and extraction of SS/PBCH block

After obtaining the 4096x3 grid, the PBCH data carried by 240 subcarrier per symbol is extracted out and a grid of 240x3 is obtained. Let us say this is  $Y_{PBCH}$ . For a frame, we obtain L number of such  $Y_{PBCH}$  blocks.

### 3.1.2 Channel Estimation and Equalization

**Channel Estimation:** Demodulation reference signal is used to estimate the pilot values or the channel at the receiver. We have the received PBCH data  $Y_{PBCH}$  obtained as shown in Fig.???. Now the  $Y_{DMRS}$  of length 144 symbols is obtained from the DMRS positions mentioned in the table in Fig.???. Now, DMRS signal generation at the Transmitter end requires the  $N_{ID}^{cell}$  which is known to the receiver at this stage from synchronization block. Hence, using  $N_{ID}^{cell}$ , the DMRS is re-generated at the receiver. Lets call this as  $X_{DMRS}$ .

L number of such 144x1 vectors of  $X_{DMRS}$  will be obtained. The following algorithm is followed:

1. 144 x1 complex valued vector of  $Y_{DMRS}$  is extracted.
2. 144 x 1 complex valued vector of  $X_{DMRS}$  is computed using the known  $N_{ID}^{cell}$
3. L number of such vector of  $X_{DMRS}$  are generated to identify the optimum copy of estimation of received  $Y_{DMRS}$
4.  $Y_{DMRS}$  is co-related with every copy of  $X_{DMRS}$
5. DMRS with maximum value of correlation is used for channel estimation

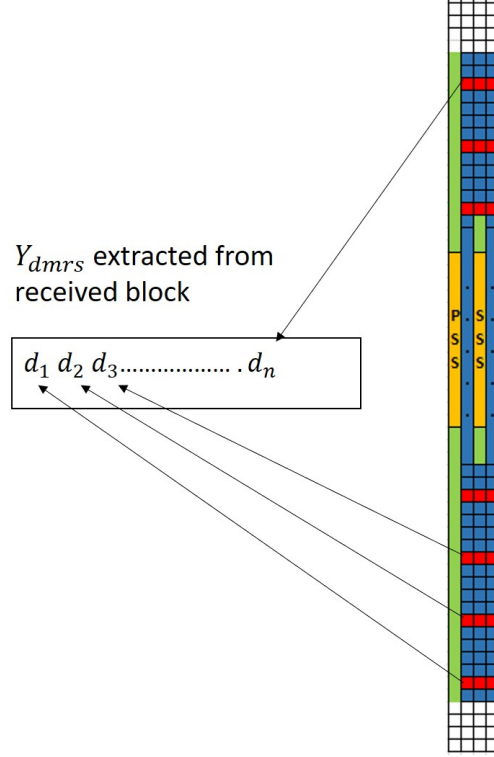


Figure 3.4: Extraction of  $Y_{DMRS}$

$Y_{DMRS}$  is the attenuated and delayed version of  $X_{DMRS}$  affected due to the Wireless channel model. The channel estimate  $\hat{H}_{DMRS}$  is obtained as

$$\hat{H}_{DMRS} = Y_{DMRS} * conj(X_{DMRS}) \quad (3.2)$$

**Channel Equalization:** The channel estimate thus obtained is re-mapped to the 240x3 grid. Now the channel experienced by the pilots is known but that for the PBCH is unknown. The channel values for the remaining positions of the block are obtained by simple interpolation technique.

#### Linear Interpolation for channel

- Linear Interpolation algorithm, two adjacent pilot subcarriers are used to determine the channel response for data subcarriers in between the pilot signals
- Linear interpolation has a low computational complexity.

The equation is as below:

$$\hat{H}(k) = \hat{H}_{DMRS}(kN + l) = \frac{\hat{H}_{DMRS}(k + 1) - \hat{H}_{DMRS}(k)}{N} + \hat{H}_{DMRS}(k) \quad (3.3)$$

here  $k=0,1,2,\dots,N$  and  $N=4$



Now,

$Y_{DMRS}$  : a 240x3 matrix of complex symbols of received PBCH

$\hat{H}$  : a 240x 3 matrix of channel estimates

Channel Equalization is performed by using Maximum Ratio combining (MRC) We have,

$$Y = HX + N \quad (3.4)$$

Estimate of PBCH data is given by:

$$\hat{X}_{PBCH} = conj(\hat{H}) * Y_{PBCH} \quad (3.5)$$

### 3.1.3 Resource de-mapping

The  $\hat{X}_{PBCH}$  obtained is in the form of a 240 x 3 grid with unwanted pilot estimates. The Resources are de-mapped as per the positions mentioned in Fig 2.5 to obtain a 432x1 vector of noisy complex values of PBCH estimate.

### 3.1.4 Demodulation and De-scrambling

- The 432 complex values are demodulated to obtain 864 length noisy values of PBCH. The demodulation is QPSK as the PBCH is QPSK modulated at the transmitter.
- The 864 values are LLR values which are then descrambled using the same pn sequence generated at the transmitter end. However, as the values are no more binary but LLR, the sequence are multiplied.

$$\hat{x}_{PBCH} = x_{scr} * \hat{X}_{PBCH} \quad (3.6)$$

### 3.1.5 De-rate Matching and Decoding

The 864 LLRs are de-rate matched to 512 in two stages: **bit de-selection** and **de-interleaving**. Bit de-selection process involves puncturing the last  $864-512 = 352$  values from the sequence and averaging it with the first 352 values of the original sequence to get a new sequence of 512 values. This is done to avoid the loss of received data and reversing the algorithm performed at the transmitter end. Similarly the de-interleaver uses the same table of interleaving pattern to rearrange the blocks of 32 values in the original positions to finally obtained the 512 values for Decoder.

The Receiver implements a Polar Decoder to obtain the 55 bit PBCH Payload with CRC attached.

# Chapter 4

## Simulation and Results

### 4.1 Performance testing

Every 55 bit PBCH Payload with CRC is checked for errors using CRC check algorithm. The algorithm is as follows:

if check = 0:

1. The decoded block is in error
2. increase the error count

if check = 1:

1. The decoded block is not in error
2. send to de-scrambler to obtain the 31 bit PBCH payload

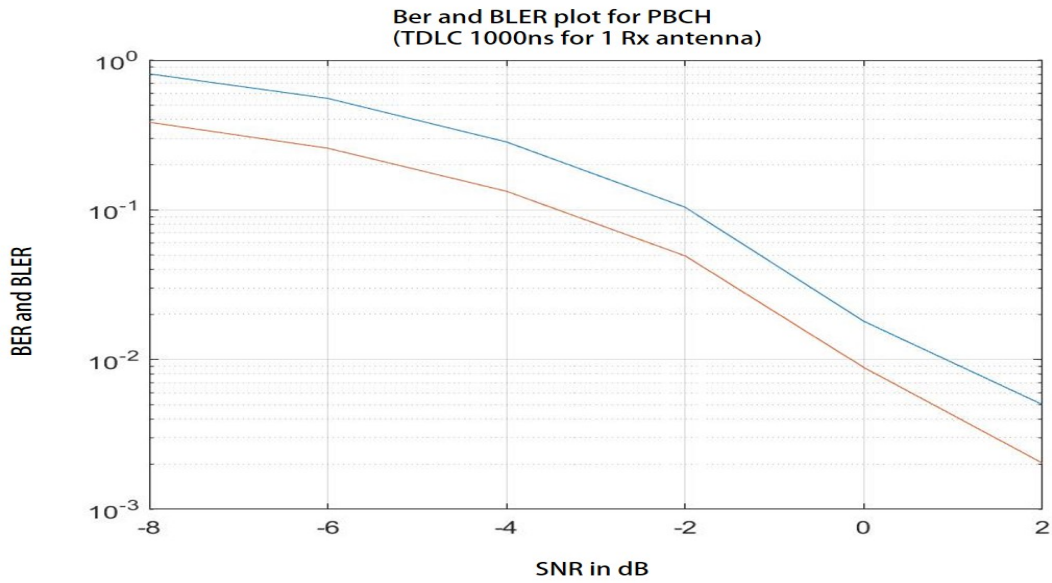
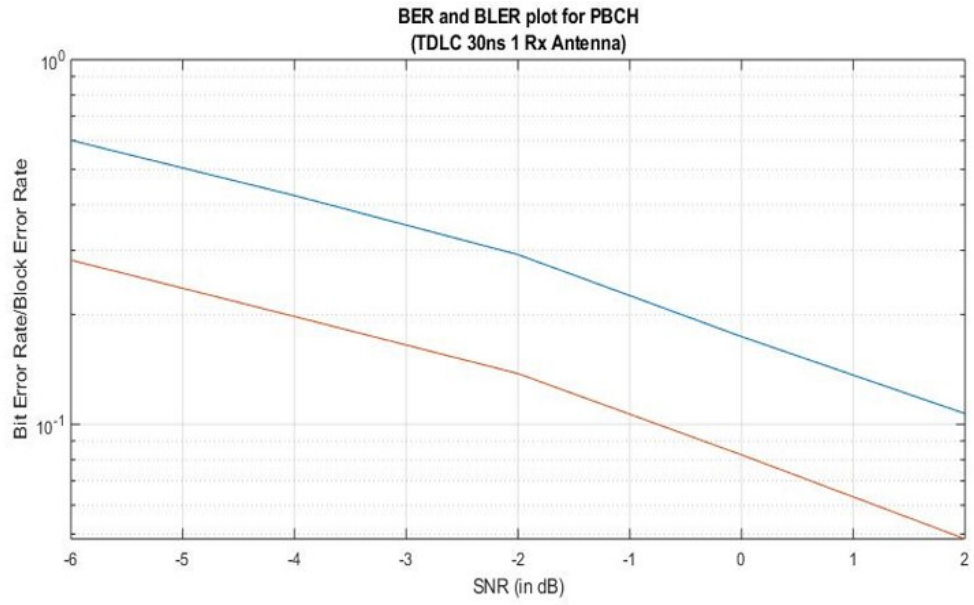
Here the error count updates by 1 for the complete block and not by the number of bits in error, hence the obtained error rate is a Block Error Rate (BLER).

### 4.2 Simulation table:

Parameter	Value
Carrier Frequency	2GHz
Numerology	0
Bandwidth	50MHz
Sub-carrier spacing	15Khz
FFT length	4096
Cyclic Prefix length	288
PBCH Payload size	24bits
Polar Coding rate	56/512
Channel Model	1. 30ns TDLC Rayleigh fading 2. 1000ns TDLC Rayleigh fading Simulated using Jake's model
Channel estimation	based on PSS, SSS and DMRS

Figure 4.1: Simulation parameters for analysis

### 4.3 Results



## 4.4 Conclusion

SSB in general including the SSB structure, mapping, burst set, and beam Sweeping was analysed. PBCH design is presented including the PBCH transmission scheme, DRMS patterns and the information carried by PBCH DMRS. PBCH channel estimation is achieved at low complexity and demodulation performance gain of more than 1dB is observed when PSS, SSS and PBCH DMRS are jointly used. Different channel models with varying delay spreads is simulated. Multiple path diversity is exploited to obtain a gain of about 1 dB from TDLC 30ns to 1000ns.

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