Implementaion of 5G NR
Medium Access Control - MAC

Internship report submitted in partial fulfilment of the requirements

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by

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Certificate

I, **NADIPINENI HEMANTH KUMAR**, with Roll No: **CED16I024** hereby declare that the material presented in the Project Report titled **Implementaion of 5G NR Medium Access Control - MAC** represents original work carried out by me in the **5G TESTBED LAB** at the **Indian Institute of Technology,Madras** during the months **May, 2020 - Oct, 2020**. With my signature, I certify that:

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Abstract

Medium Access Control (MAC) is a layer 2 protocol used in 5G NR Air interface. The MAC layer handles logical-channel multiplexing, hybrid-ARQ retransmissions, and scheduling and scheduling-related functions, including handling of different numerologies. It is also responsible for multiplexing/demultiplexing data across multiple component carriers when carrier aggregation is used. The MAC provides services to the RLC in the form of logical channels. 5G NR MAC and scheduler modules interact via well-defined APIs. The APIs ensure any scheduler implementation interworks with MAC. Hybrid ARQ with soft combining provides robustness against transmission errors. As hybrid-ARQ retransmissions are fast, many services allow for one or multiple retransmissions, and the hybrid-ARQ mechanism therefore forms an implicit (closed loop) rate-control mechanism.

Acknowledgements

I would like to express my special thanks of gratitude to my **Prof. Krishna Jagannathan** who gave me the golden opportunity to do this wonderful project on Implementation of MAC in Layer 2 Protocol in 5G NR , which also helped me in doing a lot of Research. I would also like to thank **Monisha Yuvaraj** who advised me through out the entire internship period. I came to know about so many new things I am really thankful to them.

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Abbreviations

3GPP	**T**hird **G**eneration **P**atnership **P**roject
5G	**F**ifth **G**eneration Mobile Communications
MAC	**M**edium **A**ccess **C**ontrol protocol
NG-RAN	**N**ext **G**eneration **R**adio **A**ccess **N**etwork
RAT	**R**adio **A**ccess **T**echnology
LTE	**L**ong **T**erm **E**volution
MAC	**M**edium **A**ccess **C**ontrol protocol
UMTS	**U**niversal **M**obile **T**elecommunications **S**ystem
GSM	**G**lobal **S**ystem for **M**obile communications
MIMO	**M**ultiple **I**nput **M**ultiple **O**utput
SDAP	**S**ervice **D**ata **A**daptation **P**rotocol
PDCP	**P**acket **D**ata **C**onvergence **P**rotocol
RLC	**R**adio **L**ink **C**hannel
MAC	**M**edium **A**ccess **C**ontrol
PHY	**PHY**sical Layer
RRC	**R**adio **R**esource **C**ontrol
API	**A**pplication **P**rogramming **I**nterface
UE	**U**ser **E**quipment
gNB	**gN**ode **B** (logical)
eNB	**e**volved **N**ode **B**
5GC	**F**ifth **G**eneration **C**ore
CU	**C**entral **U**nit
DU	**D**istributed **U**nit

CU-UP	**C**entral **U**nit **U**ser **P**lane
URLLC	**U**ltra-**r**eliable **l**ow-**l**atency **c**ommunication
SDU	**S**ervice **D**ata **U**nit
PDU	**P**rotocol **D**ata **U**nit
AMF	**A**ccess and **M**obility **M**anagement **F**unction
MME	**M**obility **M**anagement **E**ntity
HARQ	**H**ybrid **A**utomatic **R**epeat **R**equest
eMBB	**E**nhanced **M**obile **B**road**b**and
mMTC	**M**assive **m**achine **t**ype **C**ommunication
ROHC	**RO**bust **H**eader **C**ompression
CC	**C**omponent **C**arriers
TB	**T**ransport **B**locks
CRC	**C**yclic **R**edundancy **C**heck
RACH	**R**andom **A**ccess **Ch**annel
PRACH	**P**hysical **R**andom **A**ccess **C**hannel
DL	**Down** **L**ink
DL-SCH	**D**own **L**ink **Sch**eduler
TX RX	**T**ransmit **R**eceive
ASN	**A**bstract **S**yntax **N**otation
TA	**T**iming **A**dvance
PDCCH	**P**hysical **D**ownlink **C**ontrol **C**hannel
PUCCH	**P**hysical **U**plink **C**ontrol **C**hannel
PUSCH	**P**hysical **U**plink **S**hared **C**hannel
PDSCH	**P**hysical **D**ata **S**hared **C**hannel
DMRS	**D**emodulation **R**eference **S**ignal
LA	**L**ink **A**daption
BLER	**Bl**ock **E**rror **R**ate
MCS	**M**odulation and **C**oding **S**cheme
SRS	**S**ounding **R**eference **S**ignal
DCI	**D**ownlink **C**ontrol **I**nformation
SPS	**S**emi **P**ersistent **S**cheduling

Chapter 1

Introduction

5G NR is a new air interface being developed for 5G. 5G NR stands for 5th generation New Radio. It is a new **Radio Access Technology(RAT)**,the wireless standard that will become the foundation for the next generation of mobile networks.The standards for 5G NR are developed by **3GPP** organization.

5G is next big evolution of telecom network from it's previous technologies of **LTE**, **UMTS**, and **GSM**. 5G is named as 5G unlike 4G aka LTE, or 2G aka GSM. 5G claims to offer high throughput with low latency and increased number of connected devices.

Millimeter Wave, Small Cell, Massive MIMO, Beamforming, and Fullduplex are the foundations for 5G. Major changes seen in 5G architecture is with network elements, signal processing, interfaces between network elements and protocol stack.

1.1 5G NR RAN Protocol Stack

A protocol stack consists of many different individual protocols. Protocols can be simply described as set of rules that allow communication between corresponidng entities. 5G Protocol Stack is divided into many layers and sub-layers. **MAC** is one of the sub-layers.

The 5G NR radio access network is comprised of these protocol entities:

- Service data adaptation protocol (SDAP)
- Packet data convergence protocol (PDCP)
- Radio link control (RLC)
- Medium access control (MAC)
- Physical layer (PHY)

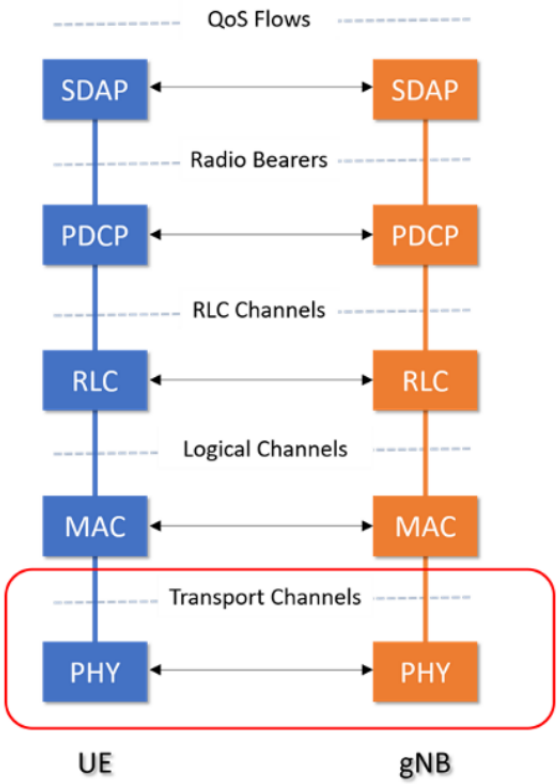


FIGURE 1.1: 5G NR RAN Protocol Stack

1.2 5G Architecture

The new 5G RAN architecture, as shown, supports the following topologies in order to enable diverse use cases:

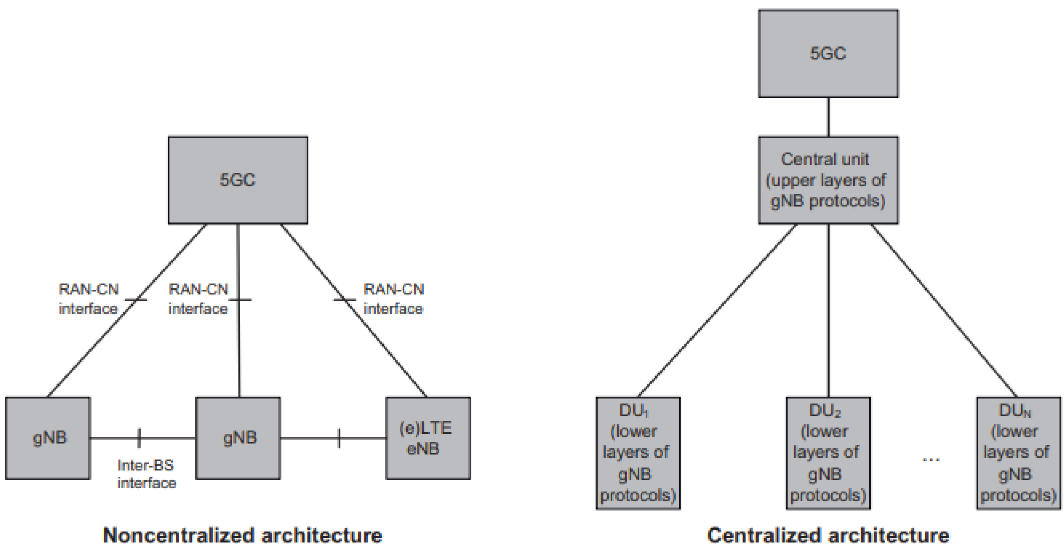


FIGURE 1.2: Non-centralized and centralized architectures

1) Non-centralized RAN architecture: In this scenario, full user-plane and control-plane radio protocol stacks are implemented at the gNB, for example, in a macrocell deployment or an indoor (public or enterprise) hotspot environment. The gNBs can be connected to each other using any transport mechanism (e.g., Ethernet, optical fiber). However, it is assumed that the gNB is able to connect to other gNBs or eLTE eNBs3 through standard interfaces defined by 3GPP.

2) Centralized RAN architecture: In this scenario, the upper layers of the radio protocol stack (PDCP and RRC layers) are implemented in the CU which is typically located in the edge cloud. Different functional splits between the CU and the DU(s) are also possible, depending on the transport layer configuration. High-performance transport mechanisms, for example, optical transport networks (OTN),4 between the CU and the lower layers of the stack located at the DUs would enable advanced coordinated multipoint (CoMP) transmission/reception schemes and inter-cell scheduling optimization, which could be useful in high-capacity scenarios, or scenarios where inter-cell coordination is desired. The higher layers of NR radio protocol stack can be moved to the CU, if a low performance transport mechanism is used between the CU and the DU (s), because in this case the requirements on the transport layer in terms of bandwidth, delay, synchronization, and jitter are relatively relaxed.

1.3 5G Deployment

Again, there are two different types of deployment scenarios:

1)Collapsed gNB deployment: In this scenario, all RAN protocols and functions are co-located within the same site. This deployment option corresponds to the current deployments of LTE systems and as such it ensures backward compatibility with the existing LTE deployments.

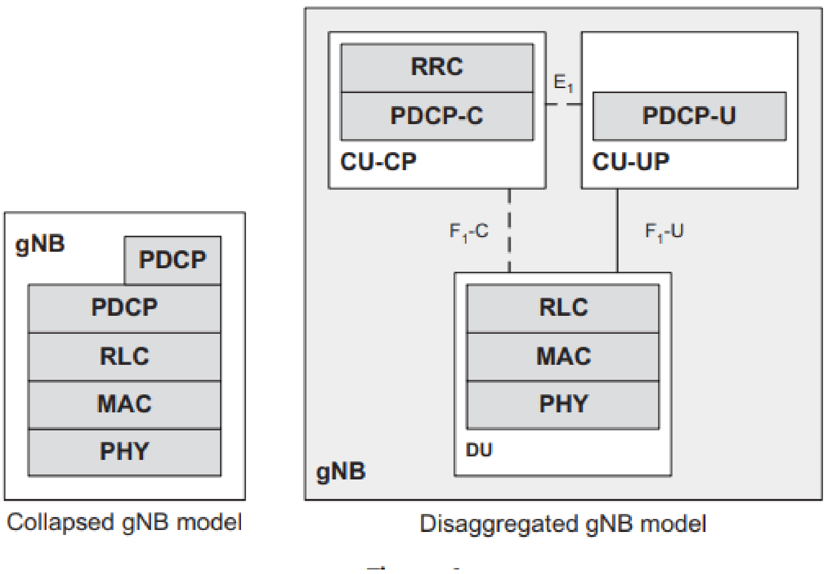


FIGURE 1.3: Collapsed and Disaggregated deployements

2)Disaggregated gNB deployment: In this scenario, RAN protocols and functions are distributed across different sites; that is, in a C-RAN architecture, the DU and the CU may be physically apart. The CU may be further divided into CP and UP entities. The DU hosts the RLC, MAC, and PHY protocols, the CU-CP entity hosts the PDCP-C and radio resource control (RRC) protocols whereas the CU-UP entity hosts the PDCP-U (and SDAP) protocols.

In the disaggregated gNB deployment, the separation of control-plane CU-CP and user-plane CU-UP entities offers the possibility of optimizing the location of different RAN functions based on the desired topology and performance. For example, the CU-CP can be placed in a location close to the DU entities. It could also be co-located with the DU, thus providing shorter latency for the critical CP procedures such as connection (re)establishment, handover, and state transition. On the other hand, the CU-UP can be centralized in a regional or national data center, thus favoring centralized implementations and providing a central termination point for the UP traffic in dual connectivity and tight interworking scenarios. An additional CU-UP can also be placed closer (or co-located) with the DU to provide a local termination point for the UP traffic for applications that require very low latency (e.g., URLLC traffic).

1.4 Data flow in 5G NR RAN Protocol Stack

There is a logical interface between each protocol module. The data will flow from one module to other through these interfaces. The interface between PDCP and RLC layers are called RLC Channels and the interface between RLC and MAC layers are called Logical Channels.

The data flows between UE and gNB. If the data flows from UE to gNB it is called uplink,and viceversa is known as downlink.

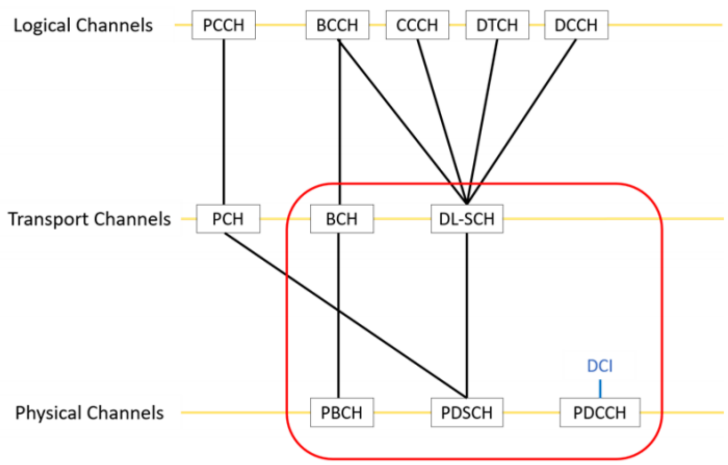


FIGURE 1.4: Uplink Channel Mapping

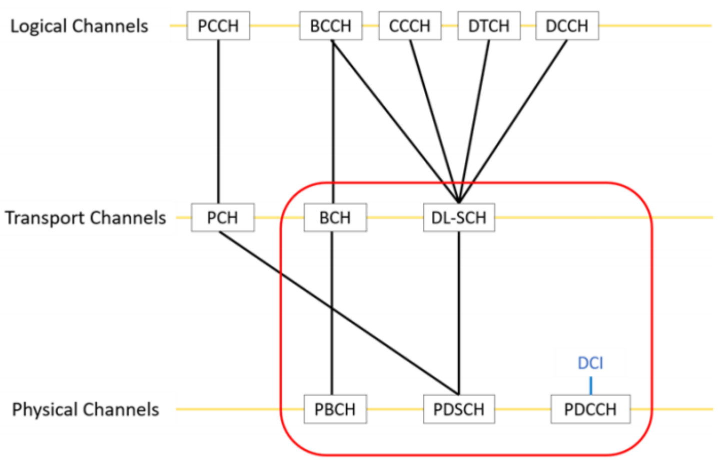


FIGURE 1.5: Downlink Channel Mapping

Data received by Nth layer from N+1th or N-1th layer is called Service Data Unit(SDU). This Nth layer will modify the data by performing required operations on the data and convert it into a Protocol Data Unit(PDU) which will be sent to N+1th or N-1th layer. Functions performed by one entity can be understood only by its peer entity. For example in the Fig 1.1, MAC in UE and MAC in gNB are peer entities.

1.5 Planes in 5G NR RAN Protocol Stack

5G NR Protocol Stack has two types planes based on the type of information it is transmitting. User plane protocols implement actual PDU Session service which carries

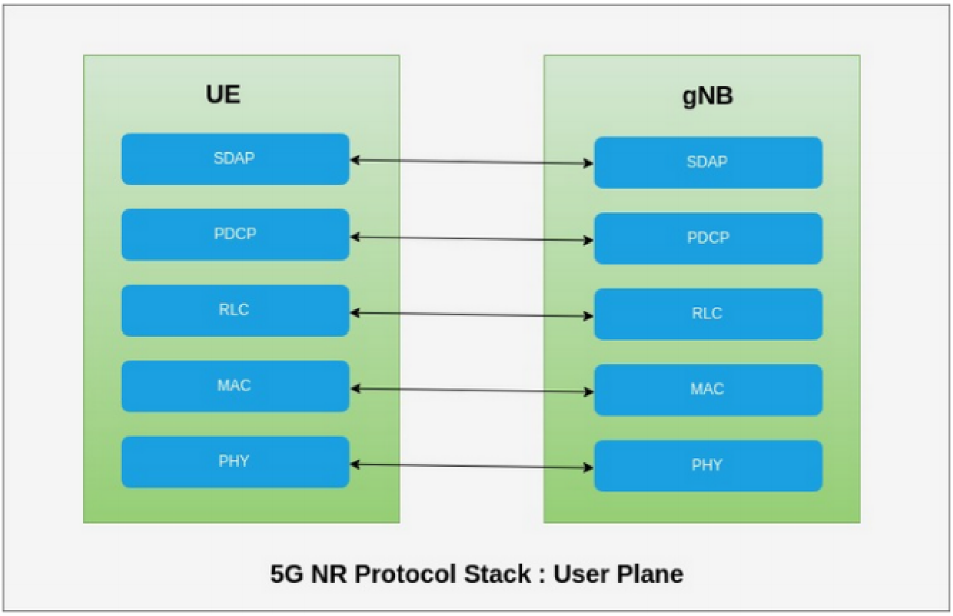


FIGURE 1.6: User Plane of 5G NR Protocol Stack

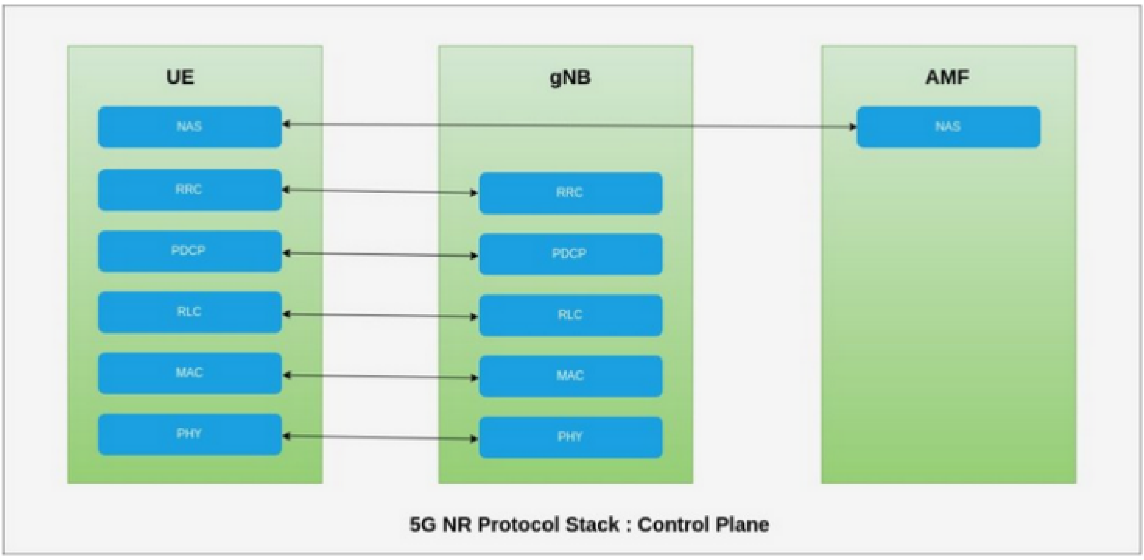


FIGURE 1.7: Control Plane of 5G NR Protocol Stack

user data through the access stratum. Control plane protocols control PDU Sessions and connection between UE and the network from various aspects which includes requesting the service, controlling different transmission resources, handover etc.
Data PDU'S flow through the User plane,whereas Control PDU'S will flow through the Control Plane.Data PDU consists of normal traffic data,where as Control PDU consists of information which be used for the configuration of other layers.

1.6 Challenges and use cases

The key challenge in the design and deployment of 5G systems is not only about the development of a new radio interface(s) but also about the coordinated operation in a highly heterogeneous environment characterized by the existence of multi-RAT systems, multi-layer networks, multi-mode devices, and diverse user interactions. Under these conditions, there is a fundamental need for 5G to achieve seamless mobility and consistent user experience acrosstime and space. New business models and economic incentives with fundamental shift incost, energy, and operational efficiency are expected to make 5G feasible and sustainable. 5G also is going to offer value proposition to vertical businesses and consumers through the definition and exposure of capabilities that enhance today's overall service delivery.

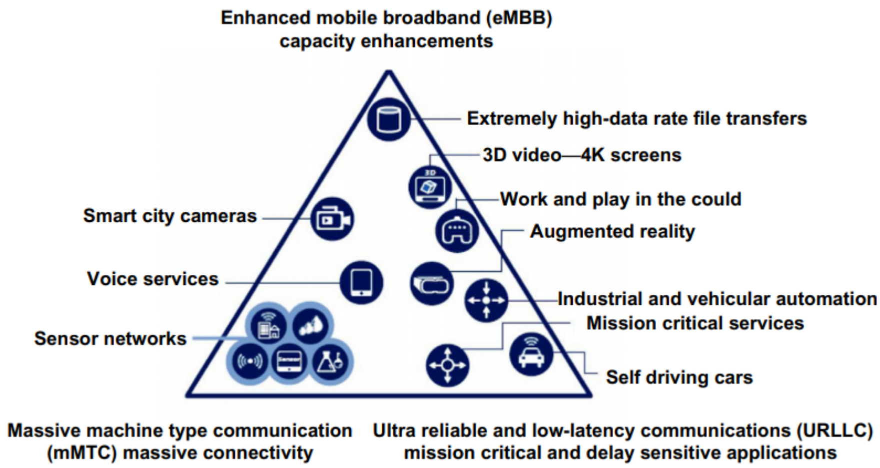


Figure 1.8: 5G use case categories

The breakthroughs in 5G network design are expected to sustain the extensive growth and enhancement of mobile Internet and the IoT services. The use of 5G technologies in the IoT and vertical industries are providing new business opportunities for network operators. In addition, expanded and enhanced mobile Internet services have been further improving consumer experience and satisfaction. To adequately support the enhancement and expansion of mobile Internet and IoT, 5G networks have to become the primary means of network access for person-to-person, person-to-machine, and machine-to-machine connectivity.

Chapter 2

Medium Access Control Sublayer

2.1 Overview

The MAC sublayer performs logical channel multiplexing and controls HARQ retransmissions. It also handles scheduling functions and is responsible for multiplexing/demultiplexing data packets across multiple component carriers when carrier aggregation is configured.

The services of MAC sublayer to the RLC sublayer are in the form of logical channels. A logical channel is defined by the type of information it carries and it is generally classified either as a control channel, for transmission of control and configuration information, or a traffic channel, for transmission of user data.
The MAC sublayer provides services to the physical layer in the form of transport channels. A transport channel is defined by how and with what characteristics the information is transmitted over the radio interface. The information traversing a transport channel is organized in the form of transport blocks.

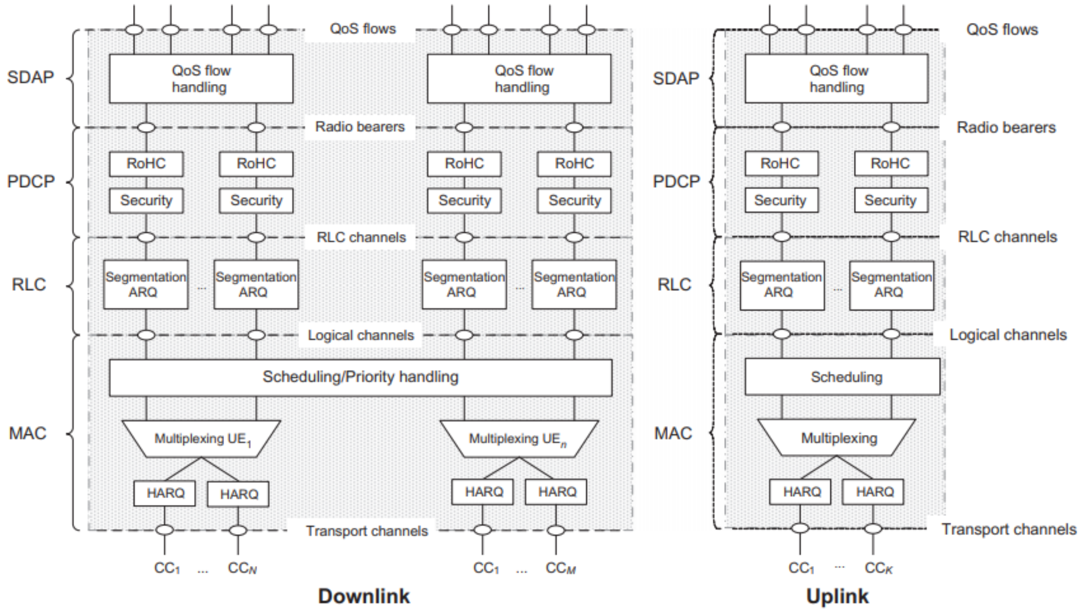


FIGURE 2.1: High Level View of NR MAC Layer

2.2 Functionalities

The MAC sublayer supports the following functions:

- mapping between logical channels and transport channels;
- multiplexing of MAC SDUs from one or different logical channels onto transport blocks (TB) to be delivered to the physical layer on transport channels;
- demultiplexing of MAC SDUs to one or different logical channels from transport blocks (TB) delivered from the physical layer on transport channels;
- scheduling information reporting;
- error correction through HARQ;
- logical channel prioritisation.

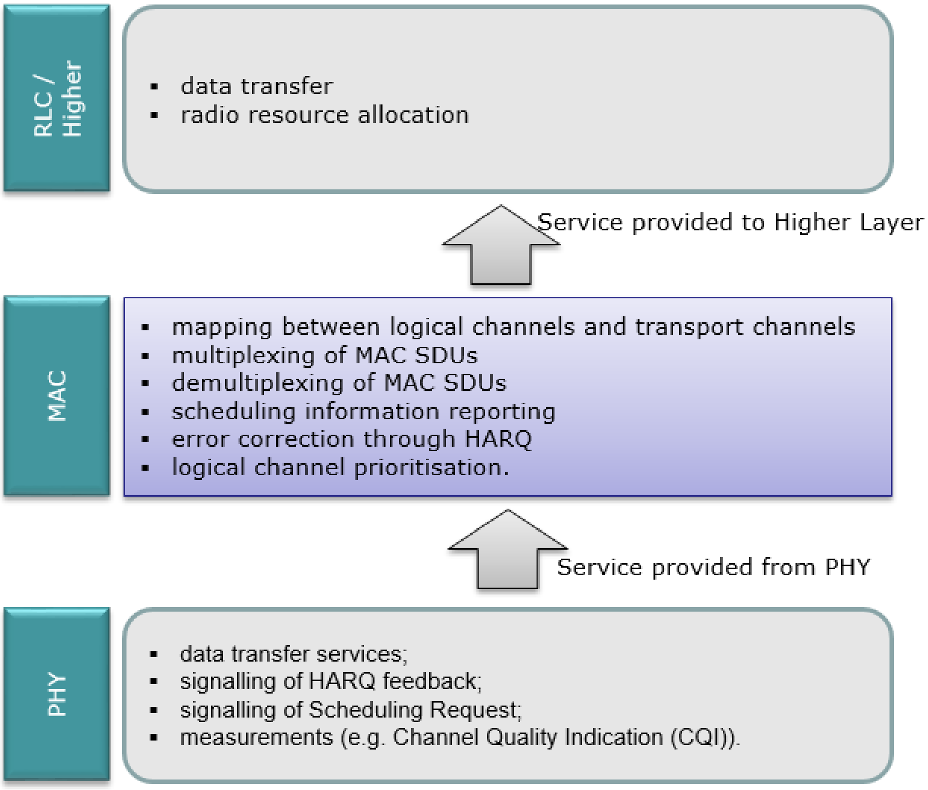


FIGURE 2.2: Functions of MAC sublayer

2.3 Uplink and Downlink of MAC

Both uplink and downlink physical layer processing of transport channels consists of the following steps as described in:

- mapping between logical channels and transport channels;
- multiplexing and demultiplexing of MAC SDUs from one or different logical channels onto transport blocks (TB) to be delivered to the physical layer on transport channels;
- Transport block CRC attachment;
- Code block segmentation and code block CRC attachment;
- Channel coding;

- Physical-layer hybrid-ARQ processing;
- Rate matching;
- Scrambling;
- Modulation;
- Layer mapping;
- Mapping to assigned resources and antenna ports

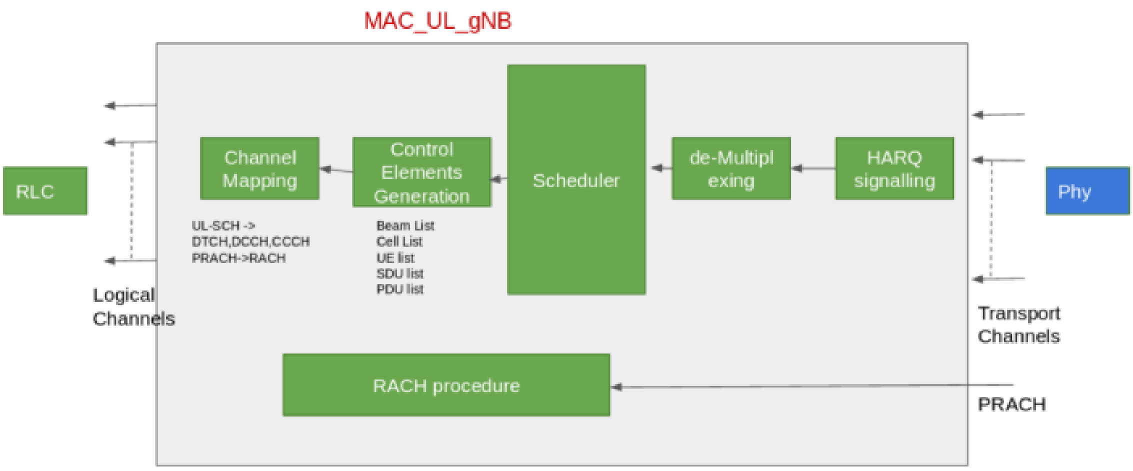


FIGURE 2.3: MAC Uplink

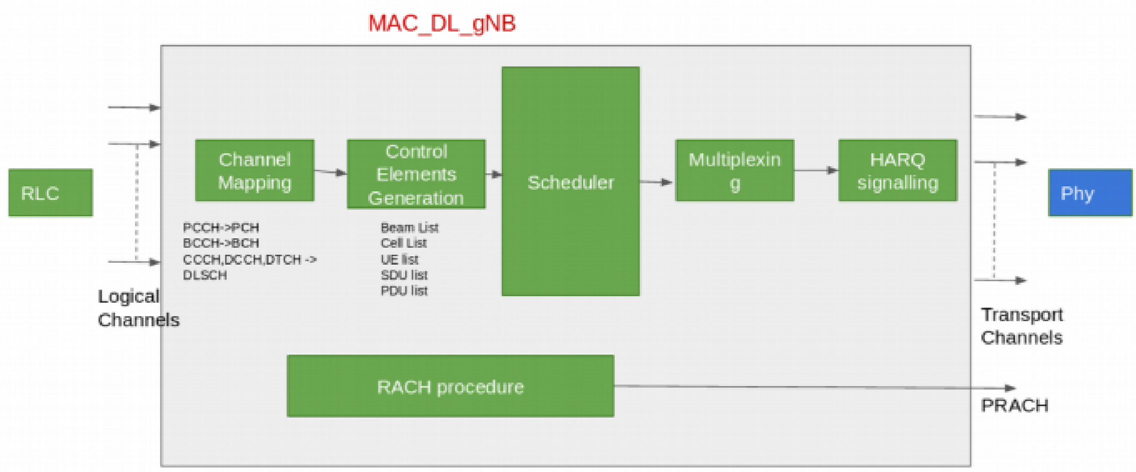


FIGURE 2.4: MAC Downlink

2.4 Scheduling

Scheduling is the process of allocating resources for transmitting data. As in LTE (actually in all cellular communication), NR scheduling is dictated by Network and UE is just following what network tells. Overall scheduling mechanism in NR is pretty much similar to LTE scheduling, but NR has finer granularity than LTE especially in terms of time domain scheduling at physical layer.

2.4.1 Dynamic downlink scheduling

In NR, the downlink scheduler is responsible for dynamically controlling the device(s) to transmit to. Each of the scheduled devices is provided with a scheduling assignment including information on the set of time-frequency resources upon which the device's DL-SCH is transmitted, the modulation-and-coding scheme, hybrid-ARQ-related information, and multi-antenna parameters.

Different downlink schedulers may coordinate their decisions to increase the overall performance, for example, by avoiding transmission on a certain frequency range in one cell to reduce the interference towards another cell.

2.4.2 Dynamic uplink scheduling

The general downlink scheduling discussion is applicable to the uplink as well. However, there are some fundamental differences between the two. For example, the uplink power resource is distributed among the devices, while in the downlink the power resource is centralized within the base station. Furthermore, the maximum uplink transmission power of a single device is often significantly lower than the output power of a base station. This has a significant impact on the scheduling strategy.

Even in the case of a large amount of uplink data to transmit there might not be sufficient power available—the uplink is basically power limited and not bandwidth limited, while in the downlink the situation can typically be the opposite.

Hence, uplink scheduling typically results in a larger degree of frequency multiplexing of different devices than in the downlink.

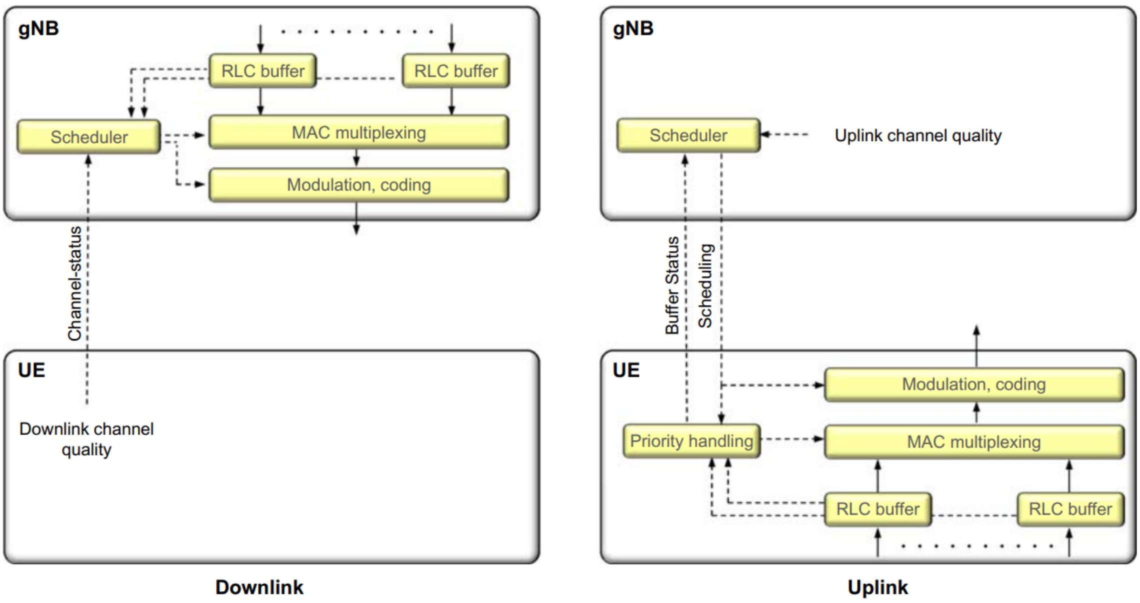


FIGURE 2.5: Downlink and uplink scheduling in NR

2.5 Hybrid ARQ

The hybrid-ARQ protocol is the primary way of handling retransmissions in NR. In case of an erroneously received packet, a retransmission is requested.

The basis for the NR hybrid-ARQ mechanism is, similarly to LTE, a structure with multiple stop-and-wait protocols, each operating on a single transport block. In a stop-and-wait protocol, the transmitter stops and waits for an acknowledgment after each transmitted transport block. This is a simple scheme; the only feedback required is a single bit indicating positive or negative acknowledgment of the transport block.

NR uses an asynchronous hybrid-ARQ protocol in both downlink and uplink.

2.5.1 Downlink Hybrid-ARQ

In the downlink, retransmissions are scheduled in the same way as new data that is, they may occur at any time and at an arbitrary frequency location within the downlink cell bandwidth. The scheduling assignment contains the necessary hybrid-ARQ-related control signaling—hybrid-ARQ process number, new-data indicator.

2.5.2 Uplink Hybrid-ARQ

The uplink uses the same asynchronous hybrid-ARQ protocol as the downlink. To differentiate between new transmissions and retransmissions of data, the new-data indicator is used. Toggling the new-data indicator requests transmission of a new transport block, otherwise the previous transport block for this hybridARQ process should be retransmitted.

Chapter 3

Work and Implementation

3.1 Objectives of the work

- Implementation of efficient scheduling algorithm for 5G MAC Sublayer.
- Implementation of Hybrid-ARQ for retransmission in 5G MAC Sublayer.

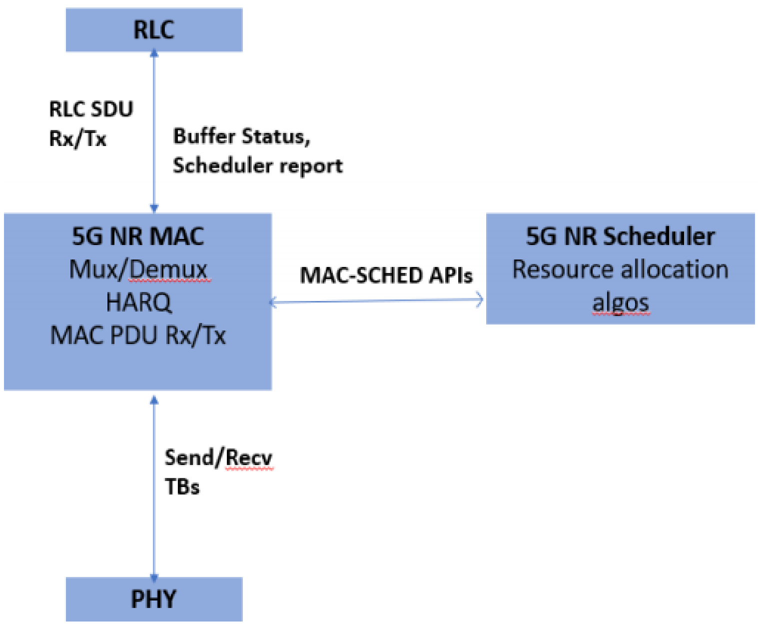


FIGURE 3.1: Harq and Scheduling Interface

3.2 Motivation

The motivations for the Implemenatation of 5G NR MAC are:

- Low Latency
- High Throughput

Throughput measures how long it would take to download a large file, while latency is determined by network and delays slow down responses in back-and-forth communication.

Low Latency and high Throughput are required to accquire enhanced mobile broadband (eMBB) where users can experience a minimum of 50-100 Mbps everywhere and see peak speeds greater than 10 Gbps with a service latency of less than 1ms while moving at more than 300 miles per hour.

Proper Implemenation of MAC helps in accquiring above mentioned features.

3.3 Work Done

Scheduler for MAC is developed using 'C++' programming. The structures required for the MAC are provided in the 3GPP standard(38.322). Those structures are in the format of ASN.1.
ASN.1 stands for Abstract Syntax Notation number One is a standard that defines a formalism for the specification of abstract data types.It is a formal notation used for describing data transmitted by telecommunications protocols, regardless of language implementation and physical representation of the data.
At high level view, NR Scheduling is not much different from LTE scheduling in terms of overall concept. In this page, I will describe on the overview of NR Scheduling and the further details will be linked to several separate pages. The overall skelleton of this page is based on Based on "38.300 - 10 Scheduling".

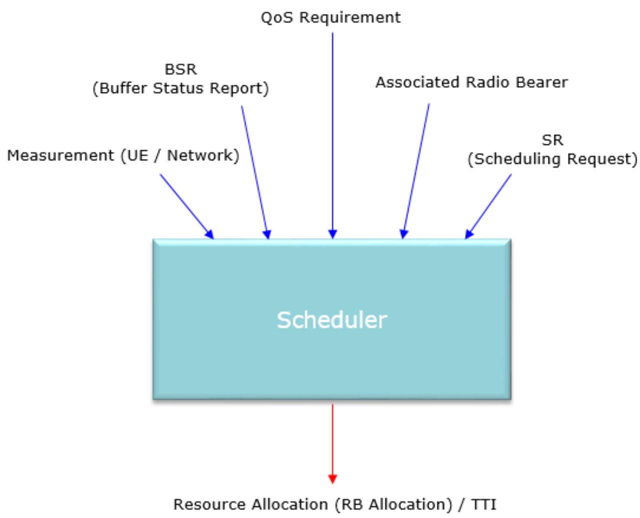


FIGURE 3.2: High level view of NR Scheduler

3.3.1 MAC scheduler components

It is assumed that the DU includes 40 complete MAC and scheduler functions implemented in the same physical platform.

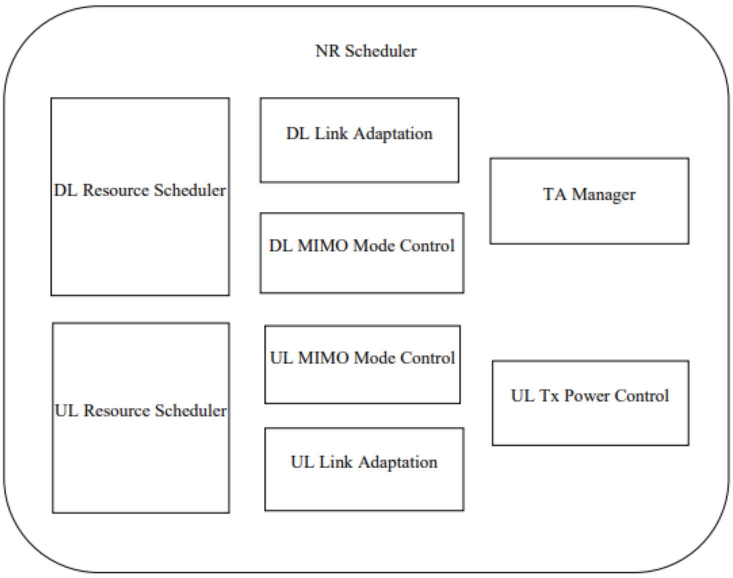


FIGURE 3.3: MAC scheduler components

NR Scheduler functional block has been further expanded into indicative smaller functional sub-blocks to capture the scheduler functionality:

- DL/UL Resource Scheduler: This corresponds to functionality of time-domain and frequency domain scheduling in DL and UL, respectively. Resource scheduling is performed per scheduling period and may be performed for a single slot or multiple slots. It may include functions such as beam selection, selecting of UEs and associated bearers per scheduling period, allocation of radio resources for PDCCH, PUSCH, PDSCH and associated channels like DMRS.
- DL/UL Link Adaptation (LA): This functionality performs per UE Link Adaptation in DL and UL, respectively. Link Adaptation may be performed based on channel quality reported by UE or estimated at gNB corrected by BLER. LA would return effective MCS to be used for channel allocation to the UE.
- UL Tx Power Control: Performs Closed loop UL power control for PUSCH, SRS and PUCCH. It may estimate the UL Tx power based on UE feedback (eg: Power Headroom Report) or measured UL channels
- DL/UL MIMO Mode Control: Determines per UE the MIMO mode, in DL and UL, respectively, to be used along with the corresponding precoding matrix.
- TA Manager: Estimating the TA Command for UE based on feedback from L1 using PUSCH, PUCCH and SRS

3.3.2 Scheduler Operation

- Taking into account the UE buffer status and the QoS requirements of each UE and associated radio bearers, schedulers assign resources between UEs;
- Schedulers assign resources taking account the radio conditions at the UE identified through measurements made at the gNB and/or reported by the UE;
- Schedulers assign radio resources in a unit of slot (e.g. one mini-slot, one slot, or multiple slots);

- Resource assignment consists of radio resources (resource blocks).

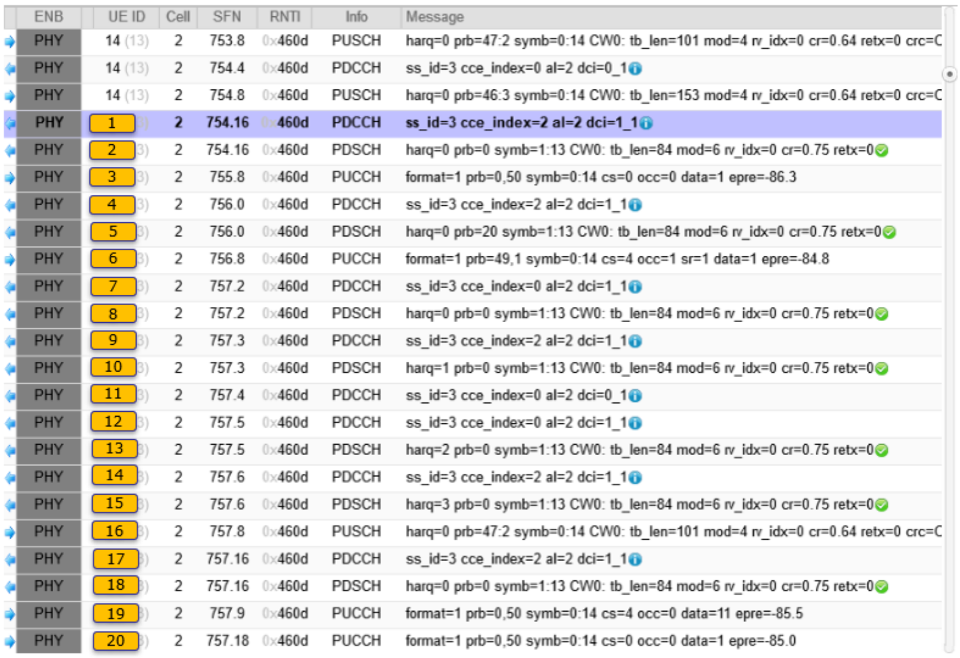
Implementation of Scheduler in MAC with above components and operations is achieved

3.3.3 Hybrid ARQ

Basic concept of HARQ in NR is similar to LTE HARQ.

Two different types of Codebook determination algorithms called Type 1 and Type 2, are implemented. Each of these types are again divided into two cases depending on whether the HARQ ACK is reported in PUCCH (Physical Uplink Control Channel) or PUSCH (Physical Uplink Shared Channel). Which types of algorithm to use is determined by a couple of RRC parameters.

Following is a sample trace log showing sequences of HARQ



ENB	UE ID	Cell	SFN	RNTI	Info	Message
PHY	14 (13)	2	753.8	0x460d	PUSCH	harq=0 prb=47:2 symb=0:14 CW0: tb_len=101 mod=4 rv_idx=0 cr=0.64 retx=0 crc=C
PHY	14 (13)	2	754.4	0x460d	PDCCH	ss_id=3 cce_index=0 al=2 dci=0_1
PHY	14 (13)	2	754.8	0x460d	PUSCH	harq=0 prb=46:3 symb=0:14 CW0: tb_len=153 mod=4 rv_idx=0 cr=0.64 retx=0 crc=C
PHY	1	2	754.16	0x460d	PDCCH	ss_id=3 cce_index=2 al=2 dci=1_1
PHY	2	2	754.16	0x460d	PDSCH	harq=0 prb=0 symb=1:13 CW0: tb_len=84 mod=6 rv_idx=0 cr=0.75 retx=0
PHY	3	2	755.8	0x460d	PUCCH	format=1 prb=0,50 symb=0:14 cs=0 occ=0 data=1 epre=-86.3
PHY	4	2	756.0	0x460d	PDCCH	ss_id=3 cce_index=2 al=2 dci=1_1
PHY	5	2	756.0	0x460d	PDSCH	harq=0 prb=20 symb=1:13 CW0: tb_len=84 mod=6 rv_idx=0 cr=0.75 retx=0
PHY	6	2	756.8	0x460d	PUCCH	format=1 prb=49,1 symb=0:14 cs=4 occ=1 sr=1 data=1 epre=-84.8
PHY	7	2	757.2	0x460d	PDCCH	ss_id=3 cce_index=0 al=2 dci=1_1
PHY	8	2	757.2	0x460d	PDSCH	harq=0 prb=0 symb=1:13 CW0: tb_len=84 mod=6 rv_idx=0 cr=0.75 retx=0
PHY	9	2	757.3	0x460d	PDCCH	ss_id=3 cce_index=2 al=2 dci=1_1
PHY	10	2	757.3	0x460d	PDSCH	harq=1 prb=0 symb=1:13 CW0: tb_len=84 mod=6 rv_idx=0 cr=0.75 retx=0
PHY	11	2	757.4	0x460d	PDCCH	ss_id=3 cce_index=0 al=2 dci=0_1
PHY	12	2	757.5	0x460d	PDCCH	ss_id=3 cce_index=0 al=2 dci=1_1
PHY	13	2	757.5	0x460d	PDSCH	harq=2 prb=0 symb=1:13 CW0: tb_len=84 mod=6 rv_idx=0 cr=0.75 retx=0
PHY	14	2	757.6	0x460d	PDCCH	ss_id=3 cce_index=2 al=2 dci=1_1
PHY	15	2	757.6	0x460d	PDSCH	harq=3 prb=0 symb=1:13 CW0: tb_len=84 mod=6 rv_idx=0 cr=0.75 retx=0
PHY	16	2	757.8	0x460d	PUSCH	harq=0 prb=47:2 symb=0:14 CW0: tb_len=101 mod=4 rv_idx=0 cr=0.64 retx=0 crc=C
PHY	17	2	757.16	0x460d	PDCCH	ss_id=3 cce_index=2 al=2 dci=1_1
PHY	18	2	757.16	0x460d	PDSCH	harq=0 prb=0 symb=1:13 CW0: tb_len=84 mod=6 rv_idx=0 cr=0.75 retx=0
PHY	19	2	757.9	0x460d	PUCCH	format=1 prb=0,50 symb=0:14 cs=4 occ=0 data=11 epre=-85.5
PHY	20	2	757.18	0x460d	PUCCH	format=1 prb=0,50 symb=0:14 cs=0 occ=0 data=1 epre=-85.0

FIGURE 3.4: Trace log

Unlike LTE, in NR the max number of HARQ processor is configurable in RRC message as shown below. If this IE is not configured, it is assumed to be 8.
In LTE, the number of HARQ bits is determined by relatively simple factors like the number of transport block(number of Codeword) and number of carriers. In general, UE assigns 1 bits per one transport block. For example, for 4x4 MIMO or higher, a cell use two transport blocks (two code words). In case of carrier aggregation assuming that each carrier is using 4x4 MIMO or higher, the total number of HARQ bits is 2 x number of CCs.
In NR, this kind of simple method is used for a specific settings, but there are various other cases.

- < Case 1 >: Condition : PDSCH is received without corresponding PDCCH or PDCCH indcating a PDSCH release
  -> Number of HARQ Bit : 1 bit
- < Case 2 > : Condition : PDSCH-CodeblockGroupTransmission = Not Configured AND PDSCH
  -> Number of HARQ Bit : 1 bit per TB (Transport Block)
- < Case 3 > : Condition : PDSCH with DCI 1_0 or PDSCH
  -> Number of HARQ Bits : HARQ Ack only for the PDSCH or only for the SPS

Same cases for Uplink HarQ. Implementation of Hybrid ARQ is achieved using above cases.

Chapter 4

Conclusions and Extensions

4.1 Conclusions

Codes implemented are thoroughly reviewed and accepted into the final code base. Documentations are sent to our guide for further implementations if needed.

Read and understand the documentation of MAC and other documents which are required for the implementation of MAC in 5G NR Protocol Stack.
Make good understanding on the software tools and the programming languages required for the implementation of MAC in 5G NR Protocol Stack.

4.2 Extensions

This has to be integrated with other protocols of 5G NR. This has to be linked with RRC for entity establishment, re-establishment and send the messages through specified channels.

Bibliography

[1] E. Dahlman and S. Parkvall, *5G NR: The Next Generation Wireless Access Technology*. Academic Press publications, 2018.

[2] S. Ahmadi, *5G NR Architecture, Technology, Implementation, and Operation of 3GPP New Radio Standards*. Elsevier, 2019.

[3] *Base Station O-DU and O-CU Software Architecture and APIs*. O-RAN Working Group 8, 2017.

[4] *NR;Medium Access Control (MAC) protocol specification(Release 15)*. 3GPP TS 38.321 V15.8.0, 2019.