Course Introduction

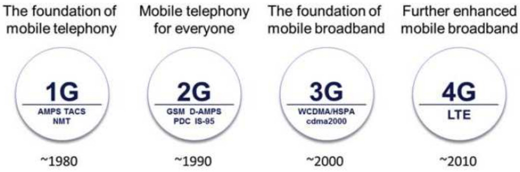
Rohit Budhiraja

Simulation-Based Design of 5G Standards

Brief history of wireless standards (1)

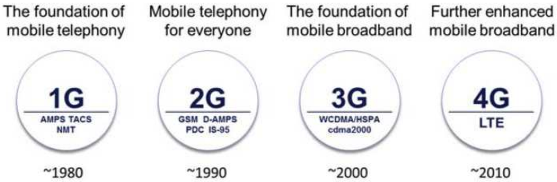
- 1G – based on analog transmission with the main technologies being
  - AMPS (Advanced Mobile Phone System) developed within North America,
  - NMT (Nordic Mobile Telephony) jointly developed by network operators of Nordic countries
  - TACS (Total Access Communication System) used in, for example, UK
- Limited to voice services and, for first time, made mobile telephony accessible to ordinary people

Brief history of wireless standards (2)



- 2G – saw the introduction of digital transmission on the radio link
- Target service was still voice – digital transmission allowed limited data services e.g., SMS
    - GSM - jointly developed by European countries
    - D-AMPS (Digital AMPS) developed within North America
    - PDC (Personal Digital Cellular) developed and solely used in Japan
    - CDMA-based IS-95 technology – developed at a somewhat later stage

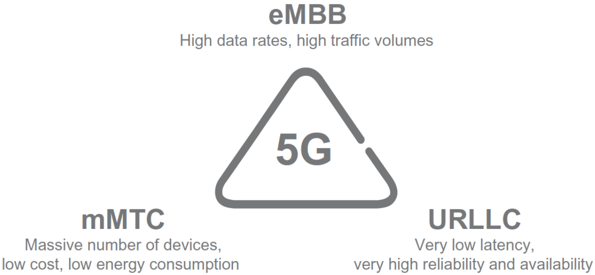
Brief history of wireless standards (3)



- 3G – true step to high-quality mobile broadband was taken, enabling fast wireless internet access
  - HSPA (High Speed Packet Access) – FDD, TD-SCDMA – TDD
  - CDMA-2000
- 4G – LTE supports both FDD and TDD operation
  - Unike 3G which had two different technologies
  - OFDM enables wider transmission bandwidths and advanced MIMO techniques

What Is 5G?

- 5G is being designed for the following use cases



- mMTC – remote sensors, and monitoring of various equipment
- URLLC – automatic control, factory automation

Evolving 4G LTE to 5G

- LTE technical specifications were (Release 8) introduced in 2009.
- Since then, LTE has evolved (through Release 9 to 14) to provide enhanced performance/features
  - Higher data rate by increasing number of tx/rx antennas
  - Enable truly low-cost devices with very long battery life, in line with massive MTC applications
  - Significant steps taken to reduce the LTE air-interface latency
- With these ongoing, and future evolution steps, LTE will be able to support a wide range of the use cases envisioned for 5G.

NR – The New 5G Radio-Access Technology

- Why are we developing 5G NR
  - Despite LTE being a capable technology, certain requirements cannot be met by LTE or its evolution.
  - LTE technical development was initiated a decade ago – advanced technical solutions are available
- To meet these requirements and to exploit new technologies, 3GPP initiated the development of a new radio-access technology known as NR (New Radio)
- First version of NR specifications was available by the end of 2017
  - to meet commercial requirements on early 5G deployments already in 2018
- NR reuses many of the structures and features of LTE
- Since NR serves broad use cases than LTE, uses a partly different set of technical solutions

Standardization of mobile communication (1)

- Multi-national technology specifications and standards – key to success of mobile communication.
  - Allows deployment and interoperability of devices and infrastructure of different vendors
  - Enables devices and subscriptions to operate on a global basis
  - 1G NMT technology was created on a multinational basis
    - Allowed for devices and subscription to operate over the national borders between the Nordic countries
- 2G GSM was jointly developed between European countries within ETSI (European Telecommunications Standards Institute).
  - GSM devices able to operate over a large number of countries – covering a large number of users
- True global standardization of mobile happened with 3G technologies, especially WCDMA

Standardization of mobile communication (2)

- Work on 3G was initially also carried out separately within
  - Europe (ETSI),
  - North America (TIA) – Telecommunication Industry Association
  - Japan(ARIB) – Association of Radio Industries and Businesses
- Although work was being done separately within different standard organizations
  - e.g., ETSI, TIA, ARIB – similar underlying technologies were being pursued
- Especially true for Europe and Japan – both were developing similar flavors of WCDMA

Standardization of mobile communication (3)

- Different regional standardization organizations came together and jointly created the Third-Generation Partnership Project (3GPP)
  - task of finalizing the development of 3G technology based on WCDMA
- A parallel organization (3GPP2) was later created to develop an alternative 3G technology,
  - cdma2000, as an evolution of second-generation IS-95.
- For a number of years, 3GPP and 3GPP2, with their respective 3G technologies (WCDMA and cdma2000) co-existed
- Over time 3GPP came to completely dominate and has,
  - despite its name, continued into the development of 4G (LTE, and 5G) technologies.
- Today, 3GPP is only significant organization developing specifications for mobile communication

Books

- 5G NR: The Next Generation Wireless Access Technology
  - Erik Dahlman, Stefan Parkvall, and Johan Skold, Elsevier 2018 [ErikD]
- 5G NR Architecture, Technology, Implementation, and Operation of 3GPP New Radio Standards
  - Sassan Ahmadi, Elsevier 2019[SassanA]
- Reference for today's lecture: Chap1 of ErikD

Course evaluation and attendance

- MATLAB simulation assignments based on class material - 15%
- Two mid-term exams 30%
- End-sem 40%
- Take home tutorials – not graded, will hold tutorial classes to clarify doubts
- Attendance - 15

5G Spectrum and Key 5G Technologies

Rohit Budhiraja

Simulation-Based Design of 5G Wireless Standards (EE698H)

Agenda for today

- Spectrum for 5G
- Discuss one of the key technologies used in 5G-NR
- Reference – Chap3 of the 5G-NR book for spectrum discussion
- Reference – Chap10.1 and 10.2 of LTE Baker book for adaptive modulation and coding

3GPP documents

- 3GPP documents are divided into releases
  - Each release has a set of features added compared to the previous release
- LTE is defined from Release 8 and onwards
- Release 15 is New Radio (NR)
  - first set of the specifications was published in December 2017
  - full specifications were due in mid-2018
- 3GPP Technical Specifications (TS) are organized in multiple series
- Following series of specifications are of interest to us:
  - 38-series: Transceiver design aspects for NR.

Spectrum for mobile systems

- Frequency bands – operating frequency range
- Frequency band for 1G and 2G – around 800 to 900 MHz, but also in a few lower and higher bands
- When 3G (IMT-2000) was rolled out, focus was on the 2 GHz band
- With 3G and 4G, new bands were added at both lower and higher frequencies, presently spanning from 450 MHz to around 6 GHz
- Bands at different frequencies have different characteristics
- Bands at lower frequencies have good propgation properties
  - Good for wide-area coverage deployments, in urban, suburban, and rural environments
- Propagation properties of higher frequencies make them difficult to use for wide-area coverage
  - Used for boosting bit-rate in dense indoor deployments

Spectrum for 5G/NR

- With 5G, the eMBB usage scenario even higher data rates and high capacity in dense deployments
  - Frequency range 1 (FR1) includes all existing and new bands below 6 GHz
  - Frequency range 2 (FR2) includes new bands in the range 24.25 to 52.6 GHz
- Frequency bands where NR will operate are in both paired (FDD) and unpaired (TDD) spectra
- Operating bands have a number, where NR bands are numbered n1, n2, n3
- 3GPP Release 15 for NR specifies 26 operating bands in FR1, and 3 in FR2

Example NR frequency bands

- For frequency range 1 (FR1)

NR Band	Uplink Range (MHz)	Downlink Range (MHz)	Duplex Mode	Main Region(s)
n41	2496–2690	2496–2690	TDD	US, China
n50	1432–1517	1432–1517	TDD	
n51	1427–1432	1427–1432	TDD	
n66	1710–1780	2110–2200	FDD	Americas
n70	1695–1710	1995–2020	FDD	
n71	663–698	617–652	FDD	Americas
n74	1427–1470	1475–1518	FDD	Japan
n75	N/A	1432–1517	SDL	Europe
n76	N/A	1427–1432	SDL	Europe
n77	3300–4200	3300–4200	TDD	Europe, Asia
n78	3300–3800	3300–3800	TDD	Europe, Asia

- For frequency range 2 (FR2)

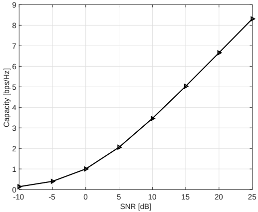
NR Band	Uplink and Downlink Range (MHz)	Duplex Mode	Main Region(s)
n257	26,500–29,500	TDD	Asia, Americas (global)
n258	24,250–27,500	TDD	Europe, Asia (global)
n259	37,000–40,000	TDD	US (global)

Key technologies of 4G/5G systems

- Adaptive modulation and coding
- OFDM
- MIMO
- Scheduling and Hybrid ARQ

Adaptive modulation and coding (AMC) (1)

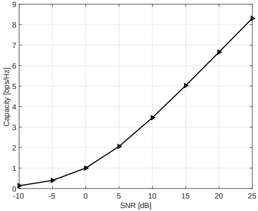
- Capacity of AWGN single-antenna channel $y = x + n$ is $\log(1 + \text{SNR})$ bps/Hz when x is Gaussian



- AMC helps us achieve capacity using discrete constellations e.g., M-QAM with $M = 2/4/16/64/256$
- If SNR is 5 dB, capacity is 2 bps/Hz, using 4-QAM achieves capacity, BLER ≈ 0 is achieved

Adaptive modulation and coding (AMC) (2)

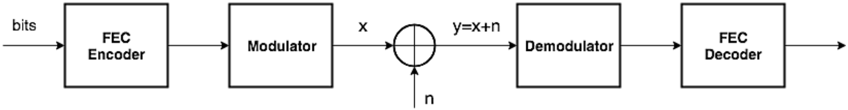
- Capacity of AWGN single-antenna channel $y = x + n$ is $\log(1 + \mathrm{SNR})$ bps/Hz when x is Gaussian



- If SNR is ≈ 12 dB, capacity is 4 bps/Hz, using 16-QAM achieves capacity, BLER ≈ 0 is achieved
- Idea of switching modulation, according to SNR is called adaptive modulation
- Achieve other points on capacity curve? For example, when SNR is 2.5 dB, capacity is 1.5 bps/Hz

Adaptive modulation and coding (AMC) (3)

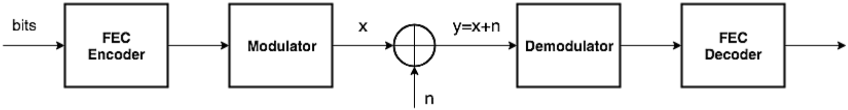
- All the points on capacity curve are achieved using adaptive modulation and (error control) coding
- Block diagram of capacity achieving transceiver



- FEC encoder code rate $r = \frac{\text{Number of FEC input bits}}{\text{Number of FEC output bits}}$
- FEC encoder code rate r is always ≤ 1

Adaptive modulation and coding (AMC) (4)

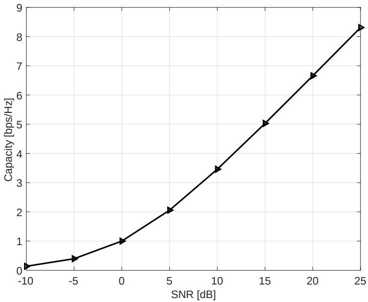
- All the points on capacity curve are achieved using adaptive modulation and (error control) coding
- Block diagram of capacity achieving transceiver



- FEC encoder adds parity bits to input message bits to guarantee a low BLER
- FEC encoder should use large code-block lengths to guarantee a low BLER
- If SNR is 2.5 dB, capacity is 1.5 bps/Hz, we will use 4-QAM with a code rate of 3/4

Capacity achieving codes

- 5G NR uses capacity achieving LDPC codes



- Capacity achieving – Provide low BLER with reasonable code block length at reasonable SNR offset from the capacity curve

AMC and OFDM in 5G-NR

Rohit Budhiraja

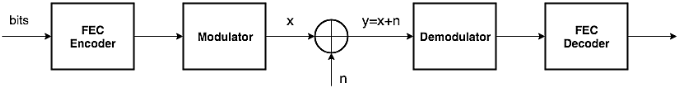
Simulation-Based Design of 5G Wireless Standards (EE698H)

Agenda for today

- Finish discussion on AMC and discuss OFDM in context of 5G-NR
- Reference – Chap3 of the 5G-NR book for spectrum discussion
- Reference – Chap10.1 and 10.2 of LTE Baker book for adaptive modulation and coding
- Reference – Chap3 of the 4G LTE/LTE-A book for OFDM

Adaptive modulation and coding (recap)

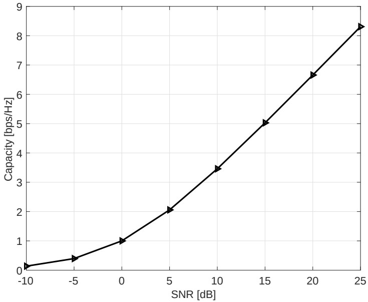
- 5G systems achieve capacity using adaptive modulation and coding
- Block diagram of capacity achieving transceiver



- FEC encoder adds parity bits to input message bits to guarantee a low BLER
- FEC encoder should use large code-block lengths to guarantee a low BLER
- FEC encoder code rate $r = \frac{\text{Number of FEC input bits}}{\text{Number of FEC output bits}}$
- FEC encoder code rate r is always ≤ 1
- If SNR is 2.5 dB, capacity is 1.5 bps/Hz, we will use 4-QAM with a code rate of $3/4$

Capacity achieving codes (recap)

- 5G NR uses capacity achieving LDPC codes



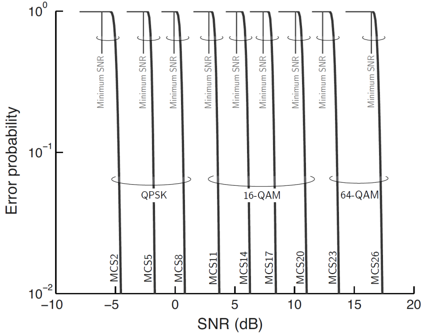
- Capacity achieving – Provide low BLER with reasonable code block length at reasonable SNR offset from the capacity curve

Adaptive modulation and coding in 5G NR (1)

MCS Index I_{MCS}	Modulation Order Q_m	Target Code Rate $1024 \times R$	Spectral Efficiency
		MCS Table I	
0	2	120	0.2344
1	2	157	0.3066
2	2	193	0.3770
3	2	251	0.4902
4	2	308	0.6016
5	2	379	0.7402
6	2	449	0.8770
7	2	526	1.0273
8	2	602	1.1758
9	2	679	1.3262
10	4	340	1.3281
11	4	378	1.4766
12	4	434	1.6953
13	4	490	1.9141
14	4	553	2.1602
15	4	616	2.4063
16	4	658	2.5703
17	6	438	2.5664
18	6	466	2.7305
19	6	517	3.0293
20	6	567	3.3223
21	6	616	3.6094
22	6	666	3.9023
23	6	719	4.2129
24	6	772	4.5234
25	6	822	4.8164
26	6	873	5.1152
27	6	910	5.3320
28	6	948	5.5547
29	2	Reserved	
30	4	Reserved	
31	6	Reserved	

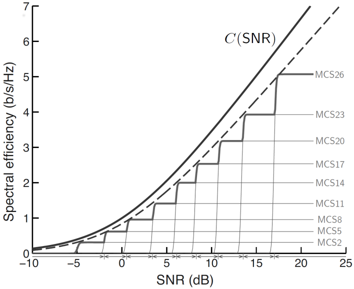
- UEs report MCS (modulation and coding scheme) to the BS instead of SNR

Adaptive modulation and coding in 5G NR (2)



- Above plots show BLER for LDPC with code block length of $N = 6000$

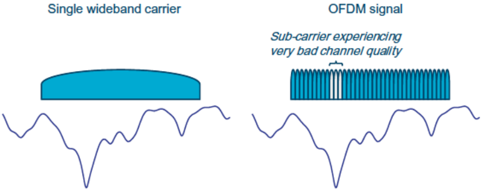
Adaptive modulation and coding in 5G NR(3)



- Cellular systems are designed to achieve capacity and use capacity-achieving FEC codes (uncoded cellular system do not exist)
- AMC achieves capacity by switching modulation and code rate

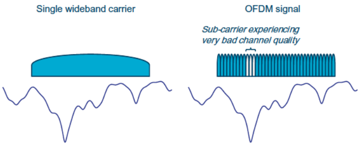
Key reasons why OFDM in 5G (1)

- Peak data rate = system bandwidth × peak spectral efficiency
- For a given spectral efficiency, peak data rate is scaled by increasing bandwidth
- For increased bandwidth, channel estimation and equalization is extremely complicated



- OFDM simplifies the channel estimation and equalization problem

Key reasons why OFDM in 5G (2)



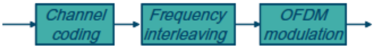
- UE calculates SNR for each subcarrier $\gamma_i = \frac{|h_i|^2 P}{N_0}$. Enables AMC implementation
  - UE averages SNR over a bunch of subcarriers to calculate a single SNR (MCS)
  - One popular way is Effective Exponential SNR (EESM)

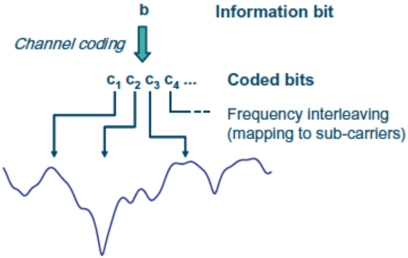
$$\gamma_{eff} = -\lambda \ln \left(\frac{1}{N_c} \sum_{i=1}^{N_c} e^{-\frac{\gamma_i}{\lambda}} \right)$$

  - λ is calibration parameter and N_c is the number of subcarriers

Key reasons why OFDM in 5G (2)

- Help in exploiting frequency diversity with channel coding





OFDM Transmitter

- Consider a system with T_u OFDM symbol duration and N_c subcarriers

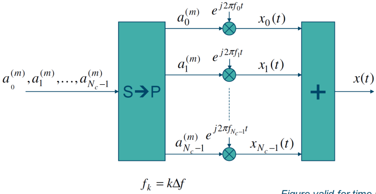


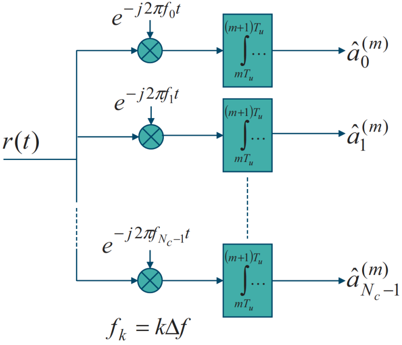
Figure valid for time interval $mT_u \le t < (m+1)T_u$

- Subcarrier spacing should be $\Delta f = 1/T_u$ for orthogonal subcarriers
- For two subcarriers $f_{k1} = k_1\Delta f$ and $f_{k2} = k_2\Delta f$, orthogonality implies

$$\int_{mT_u}^{(m+1)T_u} e^{j2\pi k_1 \Delta f t} e^{-j2\pi k_2 \Delta f t} dt = 0 \qquad \text{for } k_1 \neq k_2$$

OFDM receiver

- OFDM receive signal is $r(t) = x(t) + n(t)$



OFDM and HARQ

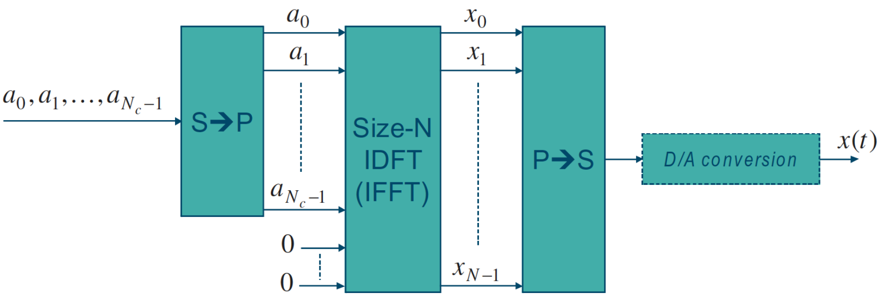
Rohit Budhiraja

Simulation-Based Design of 5G Wireless Standards (EE698H)

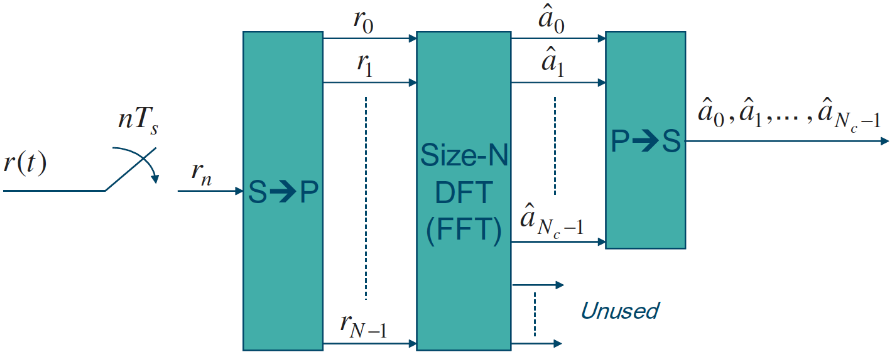
Agenda for today

- Finish discussing OFDM
- Discuss HARQ
  - Reference – Chap6 of the 4G LTE/LTE-A book

5G-NR baseband OFDM transmitter with IFFT



5G-NR baseband OFDM receiver with FFT



System dimensioning for 5G-NR

- NR baseband bandwidth = 100 MHz; Usable baseband bandwidth = 99 MHz
  - NR uses guard band of 1 MHz for 100 MHz bandwidth
- Subcarrier spacing $\Delta f = 30$ kHz
- Total subcarriers required $N_c = 3300$ $(30 * 3300 = 99$ MHz$)$
- (I)FFT size used $N = 4096$
- OFDM symbol duration $T_u = \frac{1}{\Delta f}$
  - OFDM symbol duration is fixed once subcarrier spacing is fixed
- Sampling time in the last slide $T_s = \frac{T_u}{4096}$
- Sampling rate

$$F_s = \frac{1}{T_s} = \frac{4096}{T_u} = 4096 \cdot \Delta F = 4096 \cdot 30 = 122.88 \text{ MHz}$$

- Sampling rate required according to Nyquist criteria = 99 MHz

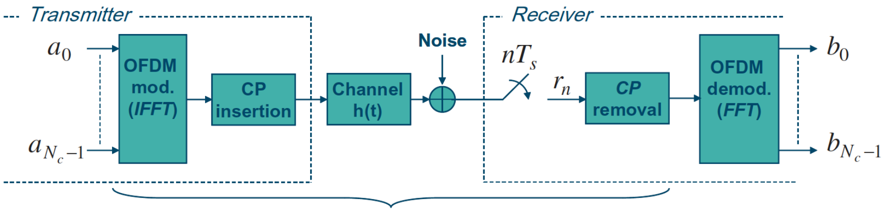
System dimensioning for 5G-NR (50 MHz)

- NR baseband bandwidth = 50 MHz; Usable baseband bandwidth = 49.5 MHz
  - NR uses guard band of 0.5 MHz for 50 MHz bandwidth
- Subcarrier spacing $\Delta f = 15$ kHz
- Total subcarriers required $N_c = 3300$ $(15 * 3300 = 49.5 \text{ MHz})$
- (I)FFT size used $N = 4096$
- OFDM symbol duration $T_u = \frac{1}{\Delta f}$
  - OFDM symbol duration is fixed once subcarrier spacing is fixed
- Sampling time in the last slide $T_s = \frac{T_u}{4096}$
- Sampling rate

$$F_s = \frac{1}{T_s} = \frac{4096}{T_u} = 4096 \cdot \Delta F = 4096 \cdot 15 = 61.44 \text{ MHz}$$

- Sampling rate required according to Nyquist criteria = 49.5 MHz

Equivalent OFDM system with channel



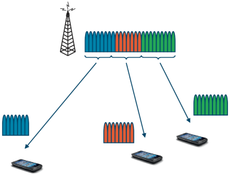
- System model for data on subcarriers

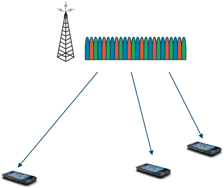
$$
\begin{aligned}
b_0 &= h_0 a_0 + n_0 \\
\vdots &= \vdots \\
b_{N_c-1} &= h_{N_c-1} a_{N_c-1} + n_{N_c-1}
\end{aligned}
$$

- Noise is independent across subcarriers

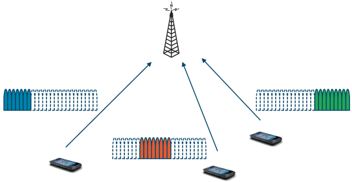
OFDM as multiple access scheme in 5G - downlink

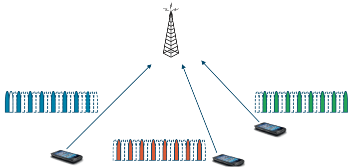
- OFDMA - Orthogonal frequency division multiple access
- Two types of subcarrier allocation - localized and distributed





OFDM as multiple access scheme 5G - uplink





Automatic repeat request (ARQ) protocol (1)

- Receiver uses an error detection code to check whether a receive data block is in error
- Error detection code is typically Cyclic Redundancy Check (CRC)
- If no error is detected in the received data block
  - the received data is declared error-free and
  - the transmitter is notified by sending a positive acknowledgement (ACK)
- If an error is detected,
  - the receiver discards the received data
  - and notifies the transmitter via a return channel by sending a negative acknowledgement (NAK)
  - In response to an NAK, the transmitter retransmits the same information

Automatic repeat request (ARQ) protocol (2)

- All modern communication systems, including 5G NR, employ a combination of FEC and ARQ
  - Known as hybrid ARQ (ARQ)
- HARQ uses FEC codes to correct a subset of all errors and relies on error detection to detect uncorrectable errors
- Erroneously received blocks are retained and receiver requests retransmissions of corrupted packets

HARQ And 5G Numerology

Rohit Budhiraja

Simulation-Based Design of 5G Wireless Standards

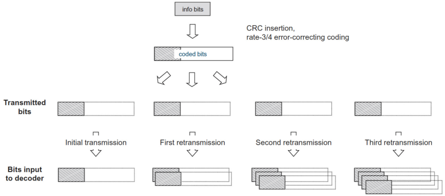
Agenda for today

- Finishing discussing HARQ
  - Reference – Chap6 of the 4G LTE/LTE-A book
- Will discussion 5G time/frequency frame structure
  - Section 7.1 to 7.4 of 5G NR book

Hybrid Automatic repeat request (HARQ) protocol

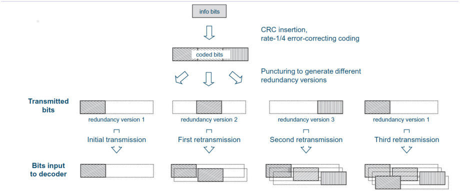
- 5G NR employs a combination of FEC and ARQ
  - Known as hybrid ARQ (ARQ)
- Erroneously received blocks are retained and receiver requests retransmissions of corrupted packets
- Two flavors of HARQ are used – Chase combining and Incremental redundancy

Hybrid ARQ – Chase combining



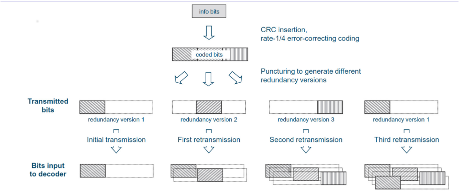
- Consider a code with rate 3/4
- Retransmissions consist of same set of coded bits as original transmission
- After each retransmission, the receiver combines each received channel bit with any previous transmissions of the same bit
- Combined signal is fed to the FEC decoder
- Effective code rate remain same

Hybrid ARQ – Incremental redundancy (IR) (1)



- Assume a basic rate-$1/4$ code. E.g., for 3 message bits, no. of o/p bits $= 12$
- For initial transmission, every third coded bit is only transmitted
  - Number of transmit bits $= 4 \Rightarrow$ Effective code rate $= 3/4$

Hybrid ARQ – Incremental redundancy (IR) (2)



- For 1st retransmission, 4 additional bits are transmitted, effective code rate $= 3/(4+4) = 3/8$
- For 2nd retransmission, 4 additional bits are transmitted, effective code rate $= 3/(4+4+4) = 1/4$
- For 3rd retransmission, 4 old bits are transmitted, effective code rate $= 3/(4+4+4) = 1/4$

Chase vs IR HARQ (1)

- Chase combining framework is easier to implement than IR but 5G NR provides a generic framework
- If all redundancy versions provide the same amount of information about the data packet
  - Order of the redundancy versions is not critical
- However, for some code structures, not all redundancy versions are of equal importance.
- E.g.,LDPC codes, where the systematic (message) bits are of higher importance than the parity bits
- Initial transmission should at least include all the systematic bits and some parity bits

Chase vs IR HARQ (2)

- In the retransmission(s), parity bits not in the initial transmission can be included
- If initial transmission was received with poor quality or not at all
  - A retransmission with only parity bits is not appropriate
  - As a retransmission of (some of) the systematic bits provides better performance
  - Better to use chase combining

5G NR numerology (1)

Subcarrier Spacing (kHz)	Useful Symbol Time, T_u (μs)	Cyclic Prefix, T_{CP} (μs)
15	66.7	4.7
30	33.3	2.3
60	16.7	1.2
120	8.33	0.59
240	4.17	0.29

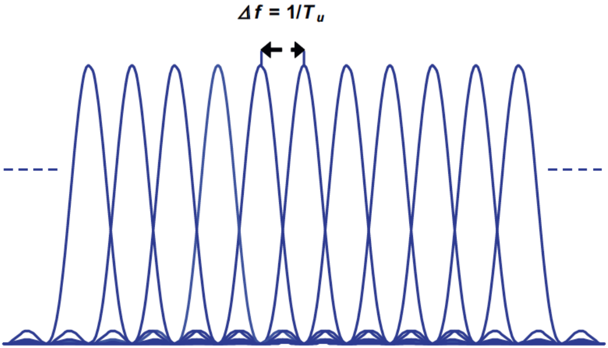
- Scalable subcarrier spacing $= 2^{\mu} \cdot 15$ kHz
- Important aspect of OFDM is numerology design – subcarrier spacing and the cyclic prefix length
- For a certain fixed cyclic prefix length requirement in microseconds
  - relative overhead increases with larger subcarrier spacing
  - smaller cyclic prefix is preferable from overhead perspective

5G NR numerology (2)

Subcarrier Spacing (kHz)	Useful Symbol Time, T_u (μs)	Cyclic Prefix, T_{CP} (μs)
15	66.7	4.7
30	33.3	2.3
60	16.7	1.2
120	8.33	0.59
240	4.17	0.29

- A large subcarrier spacing is beneficial from phase noise
- Subcarrier spacing therefore needs to balance cyclic prefix overhead and phase noise requirements

Phase noise in OFDM



5G Frame Structure

Rohit Budhiraja

Simulation-Based Design of 5G Wireless Standards

Agenda for today

- Will finish discussing 5G numerology
- Will discussion 5G time/frequency frame structure
  - Section 7.1 to 7.4 of 5G NR book by EricD

5G NR numerology (1)

Subcarrier Spacing (kHz)	Useful Symbol Time, T_u (μs)	Cyclic Prefix, T_{CP} (μs)
15	66.7	4.7
30	33.3	2.3
60	16.7	1.2
120	8.33	0.59
240	4.17	0.29

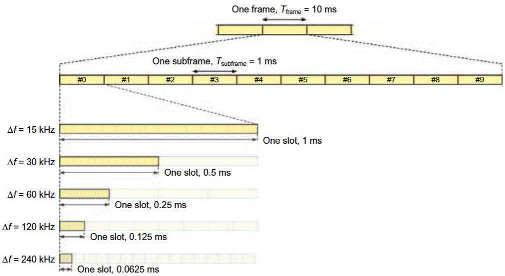
- Scalable subcarrier spacing $= 2^{\mu} \cdot 15$ kHz
- NR supports a wide range of deployment scenarios
  - from large cells with sub-1 GHz carrier frequency up to mm-wave deployments with wide bandwidths
- A single numerology for all these scenarios is not efficient or even possible

5G NR numerology (2)

Subcarrier Spacing (kHz)	Useful Symbol Time, T_u (μs)	Cyclic Prefix, T_{CP} (μs)
15	66.7	4.7
30	33.3	2.3
60	16.7	1.2
120	8.33	0.59
240	4.17	0.29

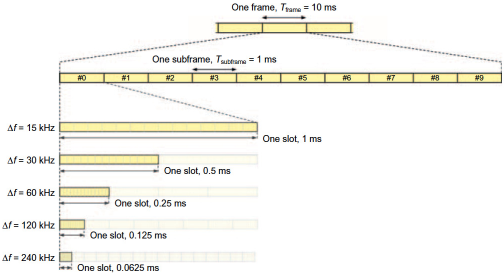
- For FR1, cell sizes can be relatively large and a couple of microseconds of cyclic prefix is necessary
  - to handle the delay spread expected in these type of deployments
  - subcarrier spacing of 15 - 30 kHz, is needed
- FR2 requires higher subcarrier spacings due to higher phase noise
- FR2 cell sizes will be smaller due to hostile channel
- FR2 consequently requires higher subcarrier spacing and a shorter cyclic prefix

Time domain structure (1)



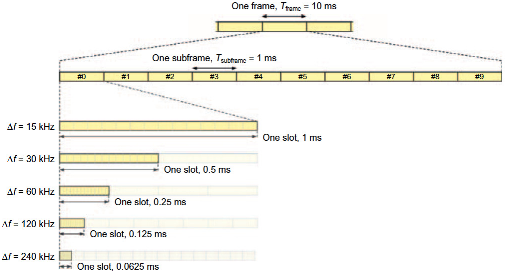
- NR transmissions are organized into frames of length 10 ms,
- Each subframe divided into 10 equal-sized subframes of length 1 ms

Time domain structure (2)



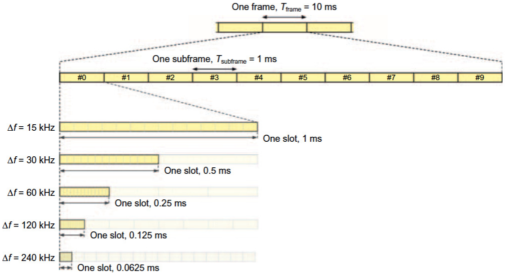
- A subframe is divided into slots consisting of 14 OFDM symbols each
  - Duration of a slot in milliseconds depends on the numerology
  - Slot is the typical dynamic scheduling unit
- Subframe in NR serves as a numerology-independent time reference

Time domain structure (3)



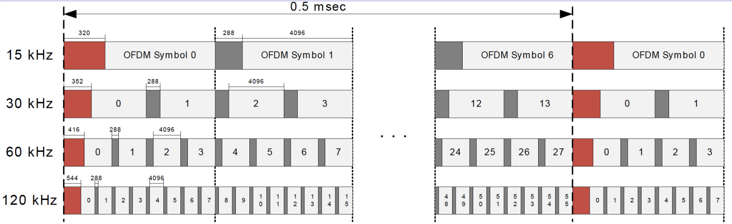
- A slot = 14 OFDM symbols – a higher subcarrier spacing leads to a shorter slot duration
- Can be used to support lower-latency transmission,
    - Cyclic prefix shrinks with increase in subcarrier spacing – not a feasible approach in all deployments

Time domain structure (4)



- Increase the cyclic prefix – increased overhead
- Reducing slot duration is a less efficient way of providing low latency
- Subcarrier spacing is primarily selected according to deployment scenario e.g., carrier frequency

Time domain structure in detail



- Recall for 100 MHz system: i) (I)FFT size $N = 4096$ ii) Number of CP samples: 288
- Total number of samples in 14 symbols: $14 \cdot (288 + 4096) = 61376$
- Recall sampling rate for 100 MHz system: 122.88 MHz. Samples generated in 0.5 msec=61440
- Extra samples $61440 - 61376 = 64$. 64 samples are added to CP of first symbol in each slot

5G Physical Layer Processing – CRC Attachment

Rohit Budhiraja

Simulation-Based Design of 5G Wireless Standards (EE698H)

Agenda for today

- Discuss 5G protocol architecture
  - Reference – Chap 2.1 of the 5G NR book by SassanA
- Discuss CRC calculation and an algorithm to implement it
  - Reference – Chap 4.1.5 of the 5G NR book by SassanA

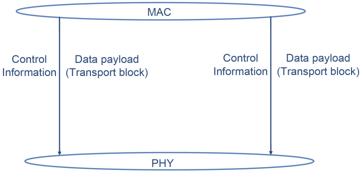
5G protocol architecture[1]

- Service data adaptation Protocol (SDAP)
  - Quality of Service (QoS) management
- Packet Data Convergence Protocol (PDCP)
  - Encryption to secure data
- Radio-Link Control (RLC)
  - duplicate detection
- Medium-Access Control (MAC)
  - hybrid-ARQ retransmission, uplink/downlink scheduling
- Physical Layer (PHY)
  - coding/decoding, modulation/demodulation, multi-antenna processing

---

[1] Chap2.1 of 5G NR SassanA

Our focus – 5G MAC-PHY interface at BS and UE



- MAC layer will pass data and control to PHY layer to process
- Control information – MCS index,
- PHY has a transport block (data payload) which needs to be
  - First encoded at a particular rate and
  - Later mapped using 4/16/64/256-QAM
- Data payload in 5G language- Physical Downlink Shared Channel (PDSCH)
- Control information in 5G language - Physical Downlink Control Channel (PDCCH)

PHY layer processing of data payload – Overview

- Minimum transport block size (for MCS-0 and 1 RB)- 24
- Maximum transport block size (for MCS-27 and 275 RBs)- 319784
- At the PHY layer, 24/16 bit CRC is attached to the transport block
- CRC performs error detection – does not correct
- An *n*-bit CRC, applied to a data block of arbitrary length, will typically detect
  - any single error burst of length n bits or less
- Essential for HARQ implementation

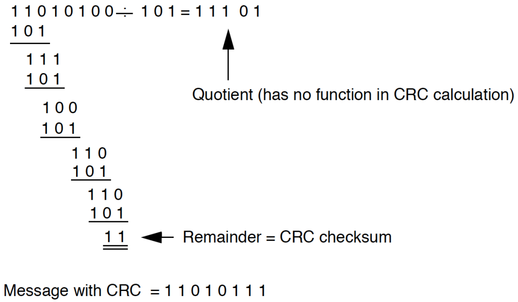
CRC algorithm[2]

- Transport block is treated by the CRC algorithm as a binary number
- This binary number (after appending necessary zeros) is divided by another binary number
  - Called generator polynomial
  - Division is modulo-2
- Remainder of the division is the CRC checksum, which is appended to the transport block
- Receiver divides the transport block (and appended CRC) by same polynomial used by transmitter
  - If the result of this division is zero, then the transmission was successful
  - If the result is not equal to zero, an error occurred during the transmission

[2] Reference - Wikipedia

Example of CRC generation

- An example six-bit transport block is 1 1 0 1 0 1
- Consider a generator polynomial $= D^2 + 1$ denoted as 1 0 1
- CRC length is equal to the degree of the polynomial
- Append two zeros to the end of the transport block and divide



Example of CRC validation

- Transmit transport block is 1 1 0 1 0 1 1 1
- Recall receiver divides the received transport block by same polynomial used by transmitter

1 1 0 1 0 1 1 1 ÷ 1 0 1 = 1 1 1 0 1

Quotient

```
1 1 0 1 0 1 1 1 ÷ 1 0 1 = 1 1 1  0 1
1 0 1
-----
  1 1 1
  1 0 1
  -----
    1 0 0
    1 0 1
    -----
        1 1 1
        1 0 1
        -----
          1 0 1
          1 0 1
          -----
            0 0
            ===
```

0 0 ← Checksum is zero, therefore, no transmission error

CRC in polynomial form

- Generator polynomial $= D^2 + 1$ is given as 1 0 1
- Input six-bit transport block 1 1 0 1 0 1 denoted as $a_0 \cdots a_5$
  - In polynomial form $a_0 D^5 + a_1 D^4 + a_2 D^3 + a_3 D^2 + a_4 D^1 + a_5$
- CRC 1 1 is denoted as $p_0\ p_1$ in polynomial form $p_0 D + p_1$
- Eight-bit transmit transport block is 1 1 0 1 0 1 1 1
  - In polynomial form $(a_0 D^5 + a_1 D^4 + a_2 D^3 + a_3 D^2 + a_4 D^1 + a_5) D^2 + p_0 D + p_1$
- Standard specifies the in above polynomial form – See section 5.1 of 38.212-f20.doc

5G PHY Layer Processing – Transport Block Segmentation

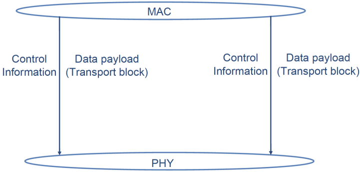
Rohit Budhiraja

Simulation-Based Design of 5G Wireless Standards (EE698H)

Agenda for today

- Discuss transport block segmentation
  - Section 5.2.2 of 36.218
- Very very briefly LDPC encoding
  - Reference – Chap 4.1.7.3 of 5G NR by SassanA for LDPC

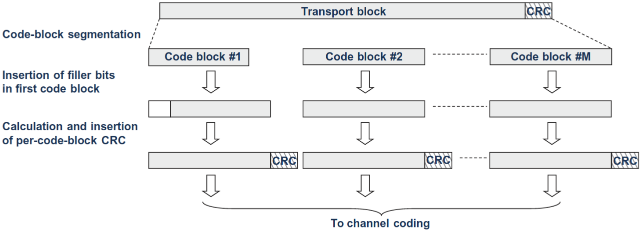
Recap – 5G MAC-PHY interface at BS and UE



- MAC layer will pass data and control to PHY layer to process
- Control information – MCS index,
- PHY has a transport block (data payload) which needs to be
  - First encoded at a particular rate and
  - Later mapped using 4/16/64/256-QAM
- Data payload in 5G language- Physical Downlink Shared Channel (PDSCH)
- Control information in 5G language - Physical Downlink Control Channel (PDCCH)

Transport block segmentation

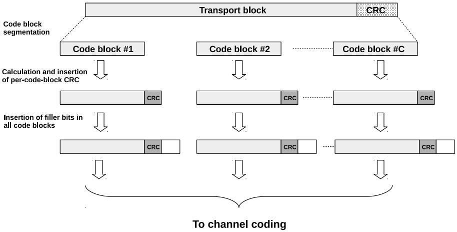
- Maximum input code block size which 5G LDPC encoder can process $(= K_{cb})$ – 8448/3840
- Transport block size can be greater than LDPC code block size
  - Maximum Transport block size (for MCS-26 and 275 RBs)- 319874
- TB should be segmented if TB length + 24-bit TB-CRC $= B > K_{cb}$



CRC for segmented code blocks

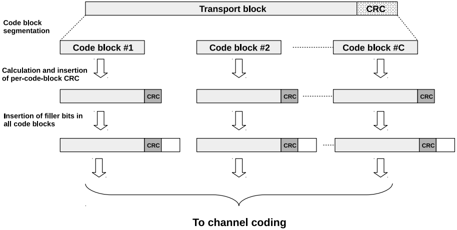
- Why not limit the maximum input code block size of LDPC encoder to largest TB size
  - Decoding complexity increases with increase in code block length
  - To reduce the encoding/decoding time by running multiple LDPC encoders/decoders in parallel
- CRC is computed for each segmented code block along with transport block
  - Allows error detection at the segmented code-block level and request for their retransmission
- Why do we need CRC for transport block when each segmented code-block has a CRC
  - Duplication of efforts?
  - Different polynomials for transport block CRC and segmented code-block CRC
  - Allows detection of any residual errors

Transport block segmentation (1)



- Maximum input code block size which 5G LDPC encoder can process ($= K_{cb}$) – 8448/3840
- Transport block (TB) size can be greater than LDPC code block size
  - Maximum TB block size (for MCS-27 and 275 RBs)- 319784,
- TB should be segmented if TB length + 24-bit TB-CRC $= B > K_{cb}$

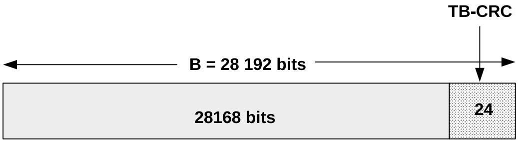
Transport block segmentation (2)



- C = total number of segmented code-blocks
- If $C = 1$, 24-bit TB-CRC is only used
- If $C > 1$, an additional CB-CRC of length ($L = 24$) is attached to each codeblock

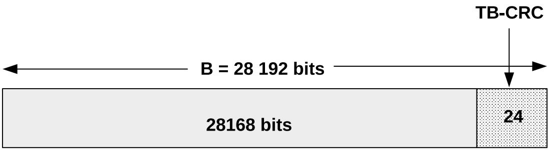
Wrong way of segmenting a transport block (1)

- Consider this system configuration which we use throughout today's class
  - Assume a user is allocated 70 resource blocks over a slot of 14 symbols
  - MCS-16 (16-QAM), which has a code rate of $658/1024 = 0.642$
- MAC will send a transport block of size 28168 bits
  - Will calculate later



- $B = 28192$ bits that include 28168 data bits and 24 bits transport block CRC (TB-CRC)

Wrong way of segmenting a transport block (2)



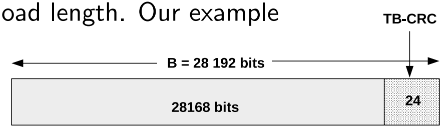
- Segment it into 3 code blocks of size 8448 bits and one of size $28192 - 8448 \times 3 = 2848$ bits
  - Coding gain is less
- Segmentation block ensures that a transport block is divided into equal size code-blocks
- BLER performance is limited by the smallest transport block size
  - Coding gain is less

Segmentation details – as in the standard

- Total number of code-blocks C is determined as below:

$$\text{if } (B > K_{cb}) \quad L = 24, \quad C = \lceil B/(K_{cb} - L) \rceil, B' = B + C \times L$$
$$\text{if } (B \leq K_{cb}) \quad L = 0, \quad C = 1, B' = B$$

- B' is effective payload length. Our example



$$C = \lceil B/(K_{cb} - L) \rceil = \lceil 28192/(8448 - 24) \rceil = 4$$
$$B' = B + C \times L = 28192 + 4 \times 24 = 28288$$

- Each code block size : $K' = \lceil B'/(C) \rceil = \frac{28288}{4} = 7072$. Not done like this.

5G PHY Layer Processing – Transport Block Segmentation (2)

Rohit Budhiraja

Simulation-Based Design of 5G Wireless Standards (EE698H)

Agenda for today

- Finish discussing transport block segmentation
  - Section 5.2.2 of 36.218
- Very very briefly discuss LDPC encoding
  - Reference – Chap 4.1.7.3 of 5G NR by SassanA
- Each code block size : $K' = \lceil B'/(C) \rceil = \frac{28288}{4} = 7072$. Not done like this.

LDPC Encoder details (1)

- An LDPC code is defined by parity check matrix H
- Each codeword $\boldsymbol{v}$ is chosen such that $\mathrm{H}\boldsymbol{v} = 0$
- A non-codeword (corrupted codeword) will generate a nonzero vector, which is called syndrome
- 5G NR uses a base graph matrix $\boldsymbol{u}$ to define the parity check matrix H

$$\mathbf{u} = \begin{bmatrix} 2 & 3 \\ 0 & 1 \end{bmatrix}, \quad \mathbf{I} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \rightarrow \mathbf{H} = \begin{bmatrix} \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} & \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} & \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \end{bmatrix} \rightarrow \mathbf{H} = \begin{bmatrix} 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 \end{bmatrix}$$

LDPC Encoder details (2)

- $\boldsymbol{u}$ needs to be transformed into a PC matrix H using a lifting factor Z_c
- Lifting – each (integer) entry of base graph $\boldsymbol{u}$ is replaced by a permuted $Z_c \times Z_c$ identity matrix
- To obtain H
  - Start with an identity matrix I and circularly shift its entries according to the base graph entry $\boldsymbol{u}_{ij}$
  - We considered an example 2×2 base graph matrix $\boldsymbol{u}$ and lifting factor $Z_c = 3$

LDPC lifting factor and base graph parameters (1)

- NR data channel supports two base graphs to ensure good performance
- Base graph 1 is optimized for large information block sizes and high code rates.
  - Designed for maximum code rate of 8/9 and may be used for code rates up to 0.95
- Base graph 2 is optimized for small information block sizes and lower code rates
  - Lowest code rate for base graph 2

Parameter	Base Graph 1	Base Graph 2
Minimum code rate R_{min}	1/3	1/5
Base matrix size	46×68	42×52
Number of systematic columns K_b	22	10
Maximum information block size K_{cb}	$8448(= 22 \times 384)$	$3840(= 10 \times 384)$
Number of non-zero elements	316	197

LDPC lifting factor and base graph parameters (2)

Parameter	Base Graph 1	Base Graph 2
Minimum code rate $R_{\min}$	1/3	1/5
Base matrix size	46×68	42×52
Number of systematic columns K_b	22	10
Maximum information block size K_{cb}	$8448 (= 22 \times 384)$	$3840 (= 10 \times 384)$
Number of non-zero elements	316	197

- Above table is Table 5.3.2-1 of 36.218-f20
- Fewer non-zero elements in H indicate lower decoding complexity for a given code rate
  - Base graph 2 has much lower decoding complexity than base graph 1

Segmented code block sizes (1)

- Each code block size : $K' = \lceil B'/(C) \rceil = \frac{28288}{4} = 7072$. Not done like this.
- Standard specifies different lifting sizes to design parity check matrix H

Set Index i_{LS}	Set of Lifting Sizes Z_C
0	{2,4,8,16,32,64,128,256}
1	{3,6,12,24,48,96,192,384}
2	{5,10,20,40,80,160,320}
3	{7,14,28,56,112,224}
4	{9,18,36,72,144,288}
5	{11,22,44,88,176,352}
6	{13,26,52,104,208}
7	{15,30,60,120,240}

- Minimum value of Z_c from Table 5.3.2-1 such that

$$\begin{aligned} K_b \times Z_c &= K \geq K' \\ \Rightarrow 22 \times 352 &= \underbrace{7744}_{K} \geq \underbrace{7072}_{K'} \end{aligned}$$

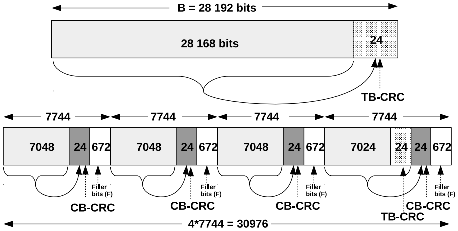
Segmented code block sizes (2)

- When segmented transport block size is not matched to suitable lifting size, filler bits are added
- Number of filler bits

$$F = K - K' = 7744 - 7072 = 672$$

- Total of four code block of size $K = 7744$ bits with filler bits $F = 672$
- Note the corresponding set index i_{LS} also - input to the LDPC encoder

Summary of transport block segmentation



- Input bit sequence to codeblock segmentation is denoted as:
  $b_0, \ldots, b_{B-1}, \quad B > 0$
- Bits output from codeblock segmentation are denoted as:
  $c_{r0}, c_{r1}, c_{r2}, c_{r3}, \ldots, c_{r(K_r-1)}$
  - r is codeblock number, and K_r is number of bits for rth codeblock
- Filler bits (usually denoted as -1) are added to the end of each codeblock

Transport block segmentation as in standard[1]

- Number of code blocks $C = 4$;
- Code block size without filler bits $K' = 7072$ bits
- Code block size with filler bits $K = 7072 + 672 = 7744$ bits
- CRC size $L = 24$ bits

The bit sequence c_{rk} is calculated as:

$s = 0$;

for $r = 0$ to $C - 1$

for $k = 0$ to $K' - L - 1$

$c_{rk} = b_s$;

$s = s + 1$;

end for

[1] 38.212 Sec 5.2.2

Transport block segmentation as in standard[2]

if $C > 1$

The sequence $c_{r0}, c_{r1}, c_{r2}, c_{r3}, \ldots, c_{r(K'-L-1)}$ is used to calculate the CRC parity bits $p_{r0}, p_{r1}, p_{r2}, \ldots, p_{r(L-1)}$ according to Subclause 5.1 with the generator polynomial $g_{\mathrm{CRC24B}}(D)$.

for $k = K'-L$ to $K'-1$

$c_{rk} = p_{r(k+L-K')}$;

end for

end if

for $k = K'$ to $K-1$ -- Insertion of filler bits

$c_{rk} = \langle NULL \rangle$;

end for

end for

[2] 38.212 Sec 5.2.2

5G NR PHY Layer Processing – Rate Matching, Modulation

Rohit Budhiraja

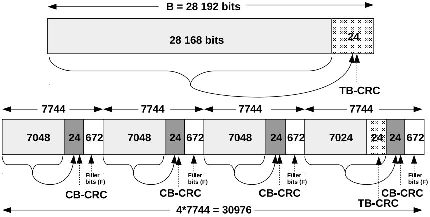
Simulation-Based Design of 5G Wireless Standards (EE698H)

Agenda for today

- Finish discussing LDPC encoding
    - Reference – Chap 4.1.7.3 of 5G NR by SassanA
- Rate matching
    - Reference – Chap 9.3 of 5G NR book by EricD
    - Section 5.4.2 of 38.212
- Modulation
    - Reference – Chap 9.5 of 5G NR book by EricD
    - Section 5.1.5 of 38.211

Example of transport block segmentation (recap)

- Our running example from last class
  - Assume a user is allocated 70 resource blocks over a slot of 14 symbols
  - MCS-16 (16-QAM), which has a code rate of $658/1024 = 0.642$

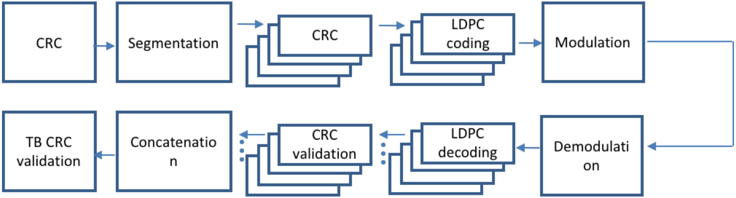


- Number of code blocks $C = 4$;
- Code block size without filler bits $K' = 7072$ bits
- Code block size with filler bits $K = 7072 + 672 = 7744$ bits
- CRC size $L = 24$ bits, lifting size $Z_c = 352$

LDPC coding in the standard

- LDPC encoder input $= K$ bits
- LDPC encoder output length
  - $N = 66Z_c$ bits for base graph 1
  - $N = 50Z_c$ bits for base graph 2
- For our example, LDPC encoder output for each segmented code block $N_r = 66 \times 352 = 23232$
- Filler bits are replaced with zeros while encoding and added back after encoding
- Rate of each code block $= 7744/23232 = 1/3$ - mother code-rate
- Bits input to LDPC encoder are denoted as $c_0, c_1, c_2, c_3, \ldots, c_{(K-1)}$
  - Subscript r is dropped while feeding data to LDPC encoder
- Bits output from LDPC encoder are denoted as $d_0, d_1, d_2, d_3, \ldots, d_{(N-1)}$

5G transceiver chain studied till now and to be studied today



- 5G NR allows 4/16/64/256-QAM modulation
- Demodulator detects bits from 4/16/64/256-QAM modulated symbols
- LDPC decoder works on the demodulated bits and not symbols
  - not practical to design decoder for different modulation schemes

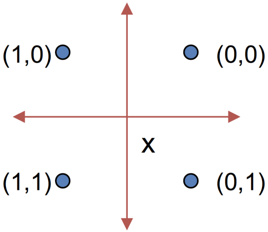
5G Modulation

- LTE allows 4/16/64/246-QAM for data. For example QPSK mapping

$b(i), b(i+1)$	*I*	*Q*
00	$1/\sqrt{2}$	$1/\sqrt{2}$
01	$1/\sqrt{2}$	$-1/\sqrt{2}$
10	$-1/\sqrt{2}$	$1/\sqrt{2}$
11	$-1/\sqrt{2}$	$-1/\sqrt{2}$

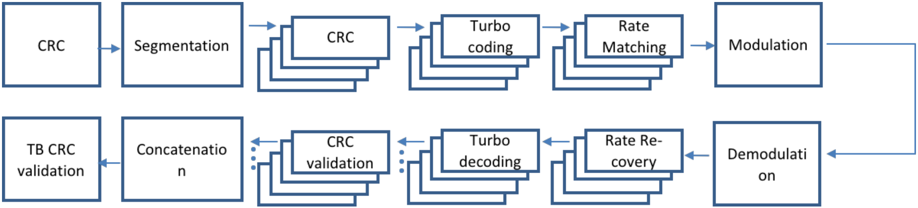
- Refer Section 5.1 of 38.211 for above mapping

QPSK demodulation



- Apply the nearest distance detection rule
- Threshold the equalized symbols to the nearest symbol
- Demap the symbols into bits

5G transceiver chain with rate matching/rate recovery



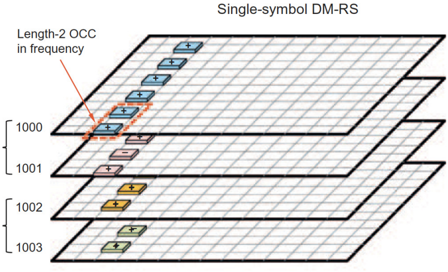
Objective of rate matching - first example

- Our running example
  - Assume a user is allocated 70 resource blocks over a slot of 14 symbols
  - MCS-16 (16-QAM), which has a code rate of $658/1024 = 0.642$
- One PRB over a slot consisting of 14 OFDM symbols will contain $12 \times 14 = 168$ subcarriers
- Out of 168 subcarriers, 6 are reserved for pilots. Subcarriers for transmitting data=162
  - Total number of bits which can be transmitted for 70 PRBS

$$G = 70(\text{NPRB}) \times 162(\text{RE}) \times 4(16\text{QAM}) = 45360$$

- Total number of segmented coded blocks $C = 4$
- Length of each rate-matched block $E = G/C = 45360/4 = 11340$
- Recall LDPC encoder output for each segmented code block $N = 66 \times 352 = 23232$

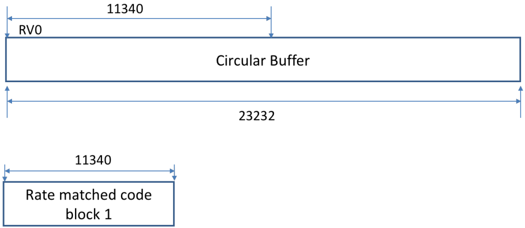
5G pilot structure



- Six subcarriers in a slot of 14 symbols are reserved for pilots
- One of the many pilots structures - will discuss in detail later

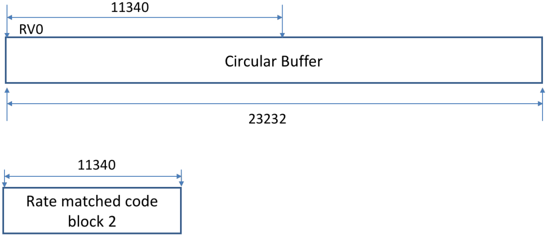
First RM example - RM for first code block

- Total number of segmented coded blocks $C = 4$
- Length of each rate-matched block $E = G/C = 45360/4 = 11340$
- Recall LDPC encoder output for each segmented code block $N = 66 \times 352 = 23232$



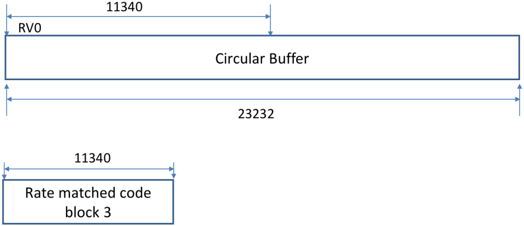
First RM example - RM for second code block

- Total number of segmented coded blocks $C = 4$
- Length of each rate-matched block $E = G/C = 45360/4 = 11340$
- Recall LDPC encoder output for each segmented code block
  $N = 66 \times 352 = 23232$



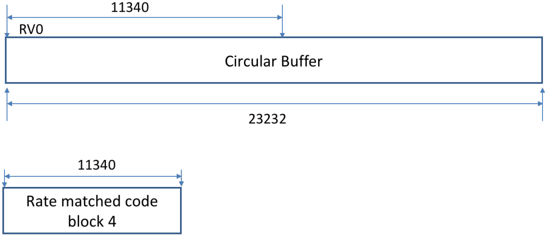
First RM example - RM for third code block

- Total number of segmented coded blocks $C = 4$
- Length of each rate-matched block $E = G/C = 45360/4 = 11340$
- Recall LDPC encoder output for each segmented code block $N = 66 \times 352 = 23232$



First RM example - RM for fourth code block

- Total number of segmented coded blocks $C = 4$
- Length of each rate-matched block $E = G/C = 45360/4 = 11340$
- Recall LDPC encoder output for each segmented code block $N = 66 \times 352 = 23232$



5G-NR PHY Layer Processing – Rate Matching (2)

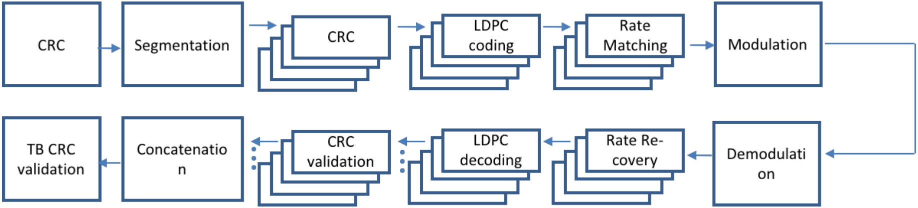
Rohit Budhiraja

Simulation-Based Design of 5G Wireless Standards (EE698H)

Agenda for today

- Finish discussing rate matching
    - References mentioned later in the slides

5G transceiver chain till rate matching/rate recovery



Second rate matching example (1)

- MCS-0 (4-QAM) for which code rate is 120/1024. Consider $\mathrm{N}_{\mathrm{PRB}} = 10$ over one slot
- Effective transport block size $= 368 + 24 = 392$. Total number of coded blocks $= 1$;

Set Index i_{LS}	Set of Lifting Sizes Z_C
0	{2,4,8,16,32,64,128,256}
1	{3,6,12,24,48,96,192,384}
2	{5,10,20,40,80,160,320}
3	{7,14,28,56,112,224}
4	{9,18,36,72,144,288}
5	{11,22,44,88,176,352}
6	{13,26,52,104,208}
7	{15,30,60,120,240}

- Minimum value of Z_c from Table 5.3.2-1 such that

$$\begin{aligned} K_b \times Z_c &= K \geq K' \\ \Rightarrow 22 \times 18 &= \underbrace{396}_{K} \geq \underbrace{392}_{K'} \end{aligned}$$

Second rate matching example (2)

Set Index i_{LS}	Set of Lifting Sizes Z_C
0	{2,4,8,16,32,64,128,256}
1	{3,6,12,24,48,96,192,384}
2	{5,10,20,40,80,160,320}
3	{7,14,28,56,112,224}
4	{9,18,36,72,144,288}
5	{11,22,44,88,176,352}
6	{13,26,52,104,208}
7	{15,30,60,120,240}

- Filler bits are added to match to suitable lifting size, and its number is

$$F = K - K' = 396 - 392 = 4$$

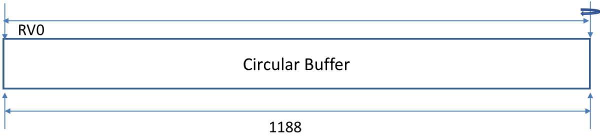
- Total of one code block of size $K = 396$ bits with filler bits $F = 4$
- LDPC encode output for each segmented code block $N_r = 66 \times 18 = 1188$

Second rate matching example (3)

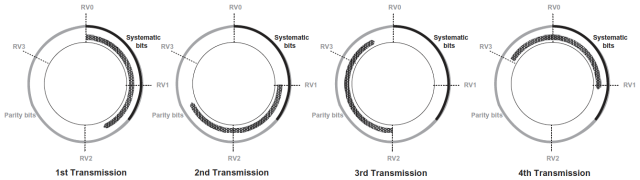
- LDPC encoder rate $= 396/1188 = 1/3$
- Total number of bits which can be transmitted for 10 PRBS

$$G = 10(\mathrm{NPRB}) \times 162(\mathrm{RE}) \times 2(4\mathrm{QAM}) = 3240$$

- Length of rate-matched block $E = G/C = 3240/1 = 3240$
- RV indices $k_0 = 0, 306, 594, 1008$

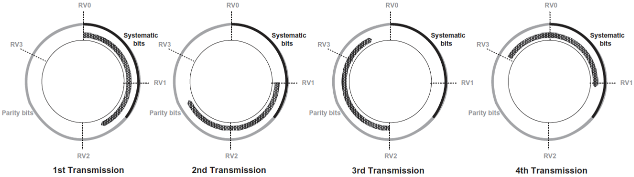


Objective of the rate matching block (1)



- Encoded output is directly written in a circular buffer
- Calculates number of bits to be read for each of the rate 1/3 encoded block
- Bits are read from buffer, starting from offset position and increasing bit index
- If bit index reaches its maximum, it is reset to the first bit in the buffer
- Redundancy version (RV) specifies a starting point in the circular buffer

Objective of the rate matching block (2)



- Different RVs are specified by defining different starting points
- Usually RV-0 is selected for initial transmission – sends large number of systematic bits
- Scheduler can choose different RVs to support Chase and IR HARQ
- Systematic bits are also punctured;enhances performance at high-code rates

RV position calculation in circular buffer

rv_{id}	k_0	
	LDPC Base Graph 1	LDPC Base Graph 2
0	0	0
1	$\left\lfloor \frac{17N_{cb}}{66Z_c} \right\rfloor Z_c$	$\left\lfloor \frac{13N_{cb}}{50Z_c} \right\rfloor Z_c$
2	$\left\lfloor \frac{33N_{cb}}{66Z_c} \right\rfloor Z_c$	$\left\lfloor \frac{25N_{cb}}{50Z_c} \right\rfloor Z_c$
3	$\left\lfloor \frac{56N_{cb}}{66Z_c} \right\rfloor Z_c$	$\left\lfloor \frac{43N_{cb}}{50Z_c} \right\rfloor Z_c$

- Consider $N_{cb} = N$ in our case
- RV index $k_0 = 0$,
- RV index $k_1 = \lfloor \frac{17N}{66Z_c} \rfloor = 5984$
- RV index $k_2 = 11616$
- RV index $k_3 = 19712$

Rate matching in the standard (1)[1]

- Recall bits output from LDPC encoder are denoted as $d_0, d_1, d_2, d_3, \ldots, d_{(N-1)}$
- Bits Input to rate matcher are denoted as $d_0, d_1, d_2, d_3, \ldots, d_{(N-1)}$
- Bits output of rate matcher are denoted as $e_0, e_1, f_2, e_3, \ldots, e_{(E-1)}$

[1](Sec 5.4.2 of 38.212)

Rate matching in the standard (2)

Denote by rv_{id} the redundancy version number for this transmission (rv_{id} = 0, 1, 2 or 3), the rate matching output bit sequence e_k, $k = 0,1,2,...,E-1$, is generated as follows, where k_0 is given by Table 5.4.2.1-2 according to the value of rv_{id} and LDPC base graph:

```
k = 0;
j = 0;
while k < E
    if d_{(k_0+j) mod N_cb} ≠ <NULL>
        e_k = d_{(k_0+j) mod N_cb};
        k = k + 1;
    end if
    j = j + 1;
end while
```

Rate matching in the standard (3)

Denoting by E_r the rate matching output sequence length for the r-th coded block, where the value of E_r is determined as follows:

Set $j = 0$

for $r = 0$ to $C-1$

if the r-th coded block is not scheduled for transmission as indicated by CBGTI according to Subclause 5.1.7.2 for DL-SCH and 6.1.5.2 for UL-SCH in [6, TS 38.214]

$E_r = 0$;

else

if $j \le C' - \mathrm{mod}(G/(N_L \cdot Q_m), C') - 1$

$$E_r = N_L \cdot Q_m \cdot \left\lfloor \frac{G}{N_L \cdot Q_m \cdot C'} \right\rfloor;$$

else

$$E_r = N_L \cdot Q_m \cdot \left\lceil \frac{G}{N_L \cdot Q_m \cdot C'} \right\rceil;$$

end if

$j = j + 1$;

end if

end for

Rate matching in the standard (4)

where

- N_L is the number of transmission layers that the transport block is mapped onto;
- Q_m is the modulation order;
- G is the total number of coded bits available for transmission of the transport block;
- $C'=C$ if CBGTI is not present in the DCI scheduling the transport block and C' is the number of scheduled code blocks of the transport block if CBGTI is present in the DCI scheduling the transport block.

5G PHY Layer Processing – receiver design (1)

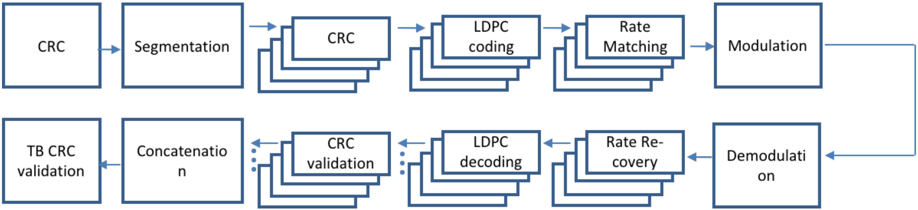
Rohit Budhiraja

Simulation-Based Design of 5G Wireless Standard (EE698H)

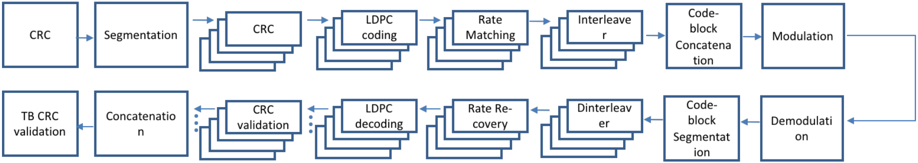
Agenda for today

- Discuss code block concatenation
  - References mentioned later in the slides
- Discuss receiver processing for the transmit chain discussed

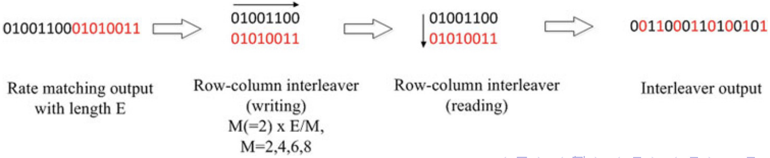
5G transceiver chain till rate matching/rate recovery



5G transceiver chain till code block concatenation



- Each rate matched codeblocks is interleaved using row-column interleaver



Pseudocode of interleaving[1]

- Row size depends on modulation order - avoid burst errors
- Bits output of rate matcher are denoted as $e_0, e_1, f_2, e_3, \ldots, e_{(E-1)}$
- Bits output of interleaver are denoted as $f_0, f_1, f_2, f_3, \ldots, f_{(E-1)}$

for $j = 0$ to $E/Q_m - 1$

  for $i = 0$ to $Q_m - 1$

    $f_{i+j \cdot Q_m} = e_{i \cdot E/Q_m + j}$;

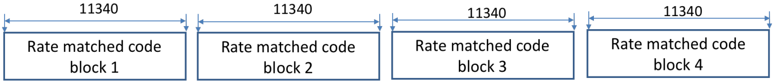
  end for

end for

[1] Sec 5.4.2.2 of 38.212

Concatenation of code blocks

- Rate matched codeblocks are sequentially concatenated when $C > 1$



- Rate matcher output is four code blocks of length 11340 bits
- Total rate matched output bits $11340 \times 4 = 45360$
- Recall total output bits allowed to transmit G= NPRB $\times$ RE $\times Q_m = 70 \times 162 \times 4 = 45360$
- Input and output bit sequence for the code block concatenation are

$$
\begin{aligned}
& f_{rj} \quad \text{for } r = 0, \ldots, \ (C-1) \text{ and } j = 0, \ldots, \ (E_r - 1) \\
& g_k \quad \text{for } k = 0, \ldots, \ (G-1)
\end{aligned}
$$

Pseudocode of code block concatenation[2]

Set $k = 0$ and $r = 0$

while $r < C$

    Set $j = 0$

    while $j < E_r$

        $g_k = f_{rj}$

        $k = k + 1$

        $j = j + 1$

    end while

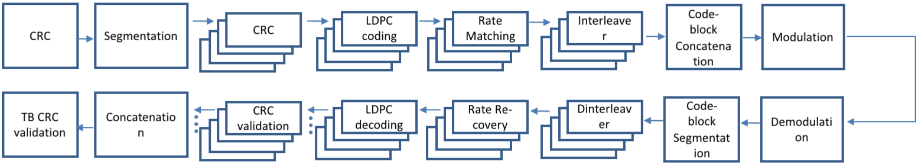
    $r = r + 1$

end while

---

[2] Sec 5.5 of 38.212

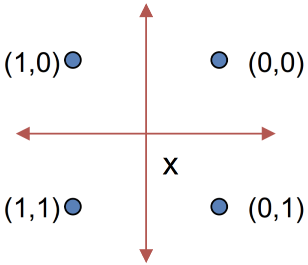
5G transceiver chain till modulation/demodulation[3]



- 5G NR allows 4/16/64/256-QAM modulation
- Demodulator detects bits from 4/16/64/256-QAM modulated symbols
- LDPC decoder works on the demodulated bits and not symbols
  - not practical to design decoder for different modulation schemes

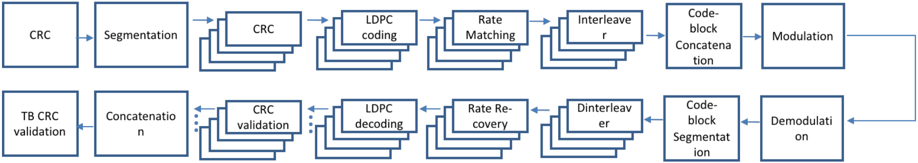
[3](Sec 5.1 of 38.211)

Receiver processing - QPSK demodulation

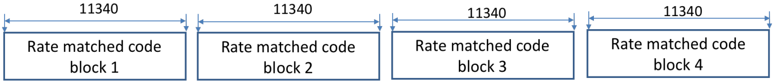


- Apply the nearest distance detection rule
- Threshold the equalized symbols to the nearest symbol
- Demap the symbols into bits

Receiver Processing – code block segmentation

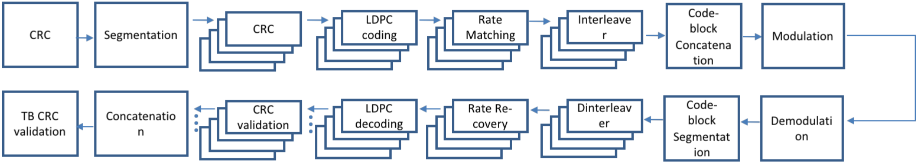


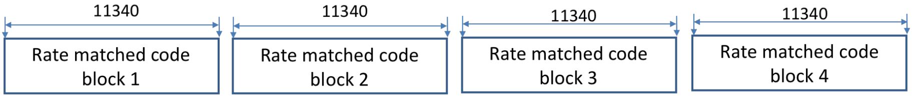
- Code block concatenation (recap)
- Rate matched codeblocks are sequentially concatenated when number of codeblocks $C > 1$



- Length of concatenated output $11340 \times 4 = 45360$

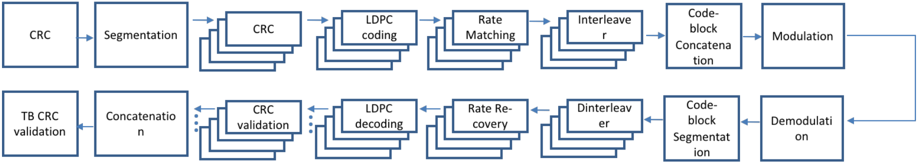
Receiver Processing – code block segmentation



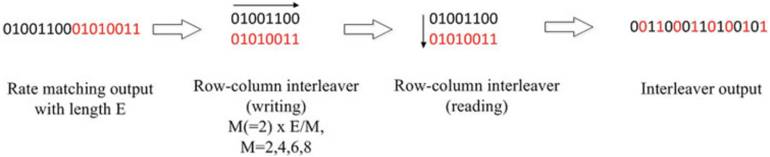


- Code block segmentation output is four code blocks of length 11340 bits
- Total output bits $= 11340 \times 4 = 45360$

De-interleaving of code blocks



- Each rate matched codeblock is interleaved using row-column interleaver



- De-interleave them by reading them appropriately

5G PHY Layer Processing – receive processing (2)

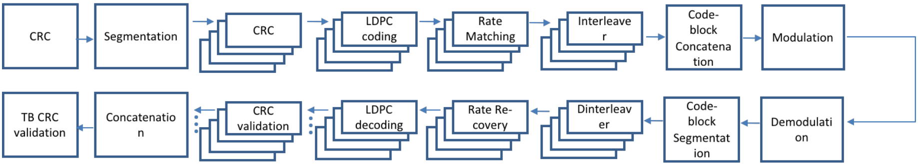
Rohit Budhiraja

Simulation-Based Design of 5G Wireless Standard (EE698H)

Agenda for today

- Discuss receiver processing for the transmit chain discussed
- Discuss scrambling
    - References mentioned later in the slides

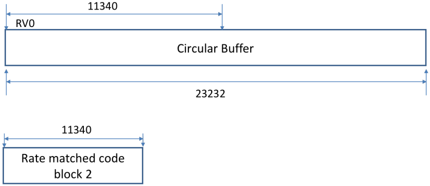
Receiver processing – rate recovery principles



- Rate matching
  - Puncturing/repeating bits to match the allocated resources
- Rate recovery
  - LDPC decoder works only for code rate of 1/3. Code rate should be reverted back to 1/3
  - Zeros are inserted in place of punctured bits
  - Repeated bits are combined

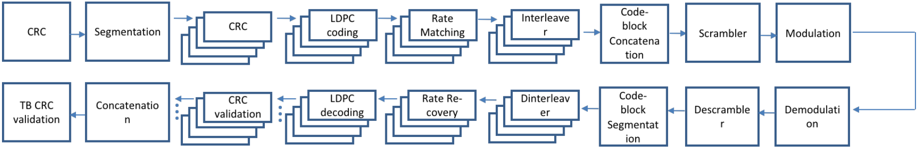
5G receiver Processing - rate recovery

- Rate recovery of code blocks e.g., second code block



- Write bits starting from RV0. Write neutral information for bits punctured at transmitter
- Feed rate recovered data to LDPC decoder. Validate CRC of each code block

5G transmit and receive chain upto scrambler



Scrambling principles

- Consider a concatenated block of G interleaved bits $b(0), \ldots, b(G-1)$
- Scrambled bits $\tilde{b}(0), \ldots, \tilde{b}(G-1)$ are given as

$$\tilde{b}(i) = b(i) \oplus c(i) \qquad i = 0, \ldots, (G-1)$$

- $c(i)$ is pseudo random sequence
- Example: 8-bit coded sequence $b = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$ and $c = [0\ 1\ 1\ 0\ 1\ 0\ 0\ 1]$

$$\tilde{b}(i) = [0\ 1\ 1\ 0\ 1\ 0\ 0\ 1]$$

- Scrambling is done to randomize the output of interleaver
  - both inner and outer signal points in the 16/64/256 QAM constellation to be used

De-scrambling principles

- For block of bits $b(0), \ldots, b(G-1)$, where G is the number of bits in code word
- Received scrambled bits $\tilde{b}(0), \ldots, \tilde{b}(G-1)$ were calculated as

$$\tilde{b}(i) = b(i) \oplus c(i) \qquad i = 0, \ldots, (G-1)$$

- Received descrambled bits $\tilde{b}(0), \ldots, \tilde{b}(G-1)$ can be recovered as

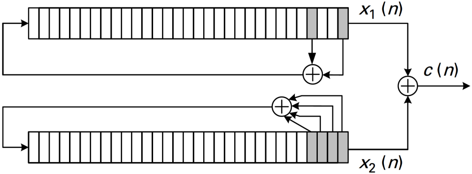
$$b(i) = \tilde{b}(i) \oplus c(i) \qquad i = 0, \ldots, (G-1)$$

- Example: 8-bit coded sequence $b = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$ and $c = [0\ 1\ 1\ 0\ 1\ 0\ 0\ 1]$

$$\begin{aligned} \tilde{b}(i) &= [0\ 1\ 1\ 0\ 1\ 0\ 0\ 1] \\ b(i) &= \tilde{b}(i) \oplus c(i) = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0] \end{aligned}$$

Pseudo random sequence generation in 5G[1] (1)

- Pseudo random sequences in 5G are defined by a length-31 Gold sequence



- Output sequence $c(n)$ of length G where $n = 0, 1, \ldots, G-1$

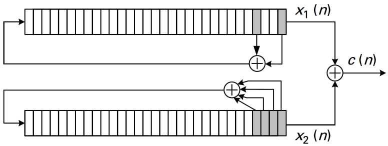
$$
\begin{aligned}
c(n) &= x_1(n) \oplus x_2(n) \\
x_1(n+31) &= x_1(n+3) \oplus x_1(n) \\
x_2(n+31) &= x_2(n+3) \oplus x_2(n+2) \oplus x_2(n+1) \oplus x_2(n)
\end{aligned}
$$

- Standard rejects first 1600 samples and uses $c'(n) = c(n+1600)$ instead

[1] Section 5.2 of 38.211

Pseudo random sequence generation in 5G (2)

- Pseudo random sequences in 5G are defined by a length-31 Gold sequence

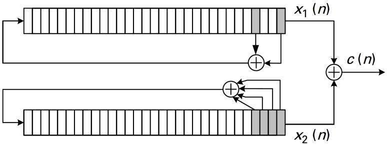


- Output sequence $c(n)$ of length G where $n = 0, 1, \ldots, G-1$
- First sequence $x_1(n)$ is initialized as

$$\begin{aligned} x_1(n) &= 1 \qquad n = 0 \\ &= 0 \qquad 0 < n \leq 30 \end{aligned}$$

Pseudo random sequence generation in 5G (3)

- Pseudo random sequences in 5G are defined by a length-31 Gold sequence



- Output sequence $c(n)$ of length G where $n = 0, 1, \ldots, G-1$
- Second sequence $x_2(n)$ is initialized by writing a constant c_{init} in binary form
- c_{init} is determined based on a cell ID and RNTI e.g, consider $c_{\text{init}} = 255$. Second sequence $x_2(n)$

$$
\begin{aligned}
x_2(n) &= 1 \qquad n \leq 7 \\
&= 0 \qquad 7 < n \leq 30
\end{aligned}
$$

5G PHY Layer – RF Processing

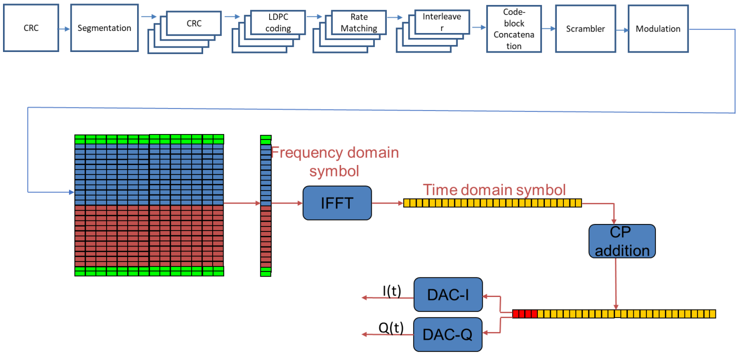
Rohit Budhiraja

Simulation-Based Design of 5G Wireless Standard (EE698H)

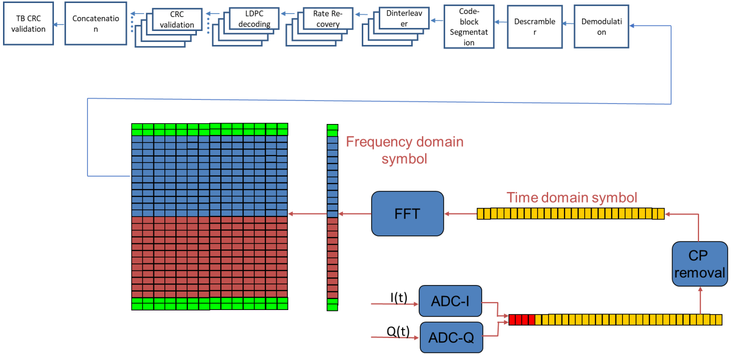
Agenda for today

- Finish discussing scrambler
- Discuss 5G radio RF transmitter and receiver
  - Any basic digital communications textbook

5G transmit chain

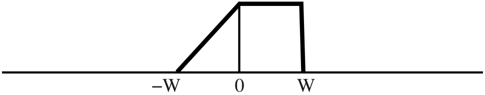


5G receive chain



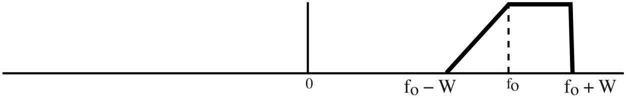
Baseband - passband system model

- Transmit complex waveform $s(t) = I(t) + jQ(t)$ is called as baseband signal
- $s(t)$ will have asymmetric spectrum around origin with bandwidth $-W$ to W



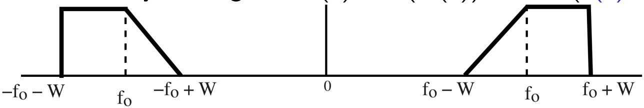
- Upconvert the baseband signal to desired center frequency f_o with $\omega_o = 2\pi f_o$

$$s_1(t) = s(t)\sqrt{2}e^{j\omega_0 t}$$



Transmit passband system model

- We can transmit only real signals $s^o(t) = \Re(s_1(t)) = \sqrt{2}\Re(s(t)e^{j\omega_0 t})$



- $s_1(t)$ is called passband/RF/upconverted transmit signal.
- Real transmit signal can equivalently be written as

$$
\begin{aligned}
s^o(t) &= \Re(s_1(t)) = \sqrt{2}\Re(s(t)e^{j\omega_0 t}) \\
&= \sqrt{2}\Re([I(t) + jQ(t)]e^{j\omega_0 t}) \\
&= \sqrt{2}I(t)\cos(\omega_0 t) - \sqrt{2}Q(t)\sin(\omega_0 t)
\end{aligned}
$$

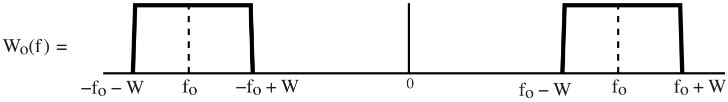
- Architecture is called balanced homodyne transmitter
- We assume that channel is not faded for today's discussion

Receive passband system model (2)

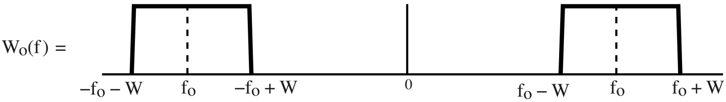
- Received signal is:

$$\begin{aligned} r_1(t) &= s^o(t) + n_w(t) \\ &= \sqrt{2}I(t)\cos(\omega_0 t) - \sqrt{2}Q(t)\sin(\omega_0 t) + n_w(t) \end{aligned}$$

- First step in recovering baseband signal – limit the bandpass noise $n_w(t)$.
- Filter the receive signal $r_1(t)$ using a band pass filter $W_0(f)$.



Receive passband system model (2)



- Received equivalent signal is

$$
\begin{aligned}
r(t) &= r_1(t) \circledast w_0(t) \\
&= (s^o(t) + n_w(t)) \circledast w_0(t) \\
&= s^o(t) + (n_w(t) \circledast w_0(t)) \\
&= s^o(t) + n(t)
\end{aligned}
$$

Receive baseband system model (1)

- Demodulate inphase signal $I(t)$

$$
\begin{aligned}
r_c(t) &= \left[r(t)\sqrt{2}\cos(\omega_0 t)\right]_{lpf} \\
&= \left[\left\{\sqrt{2}I(t)\cos(\omega_0 t) - \sqrt{2}Q(t)\sin(\omega_0 t) + n(t)\right\}\sqrt{2}\cos(\omega_0 t)\right]_{lpf} \\
&= \left[2I(t)\cos^2(\omega_0 t) - Q(t)\sin(2\omega_0 t) + \sqrt{2}n(t)\cos(\omega_0 t)\right]_{lpf} \\
&= \left[I(t) + I(t)\cos(2\omega_0 t) - Q(t)\sin(2\omega_0 t) + \sqrt{2}n(t)\cos(\omega_0 t)\right]_{lpf} \\
&= I(t) + n_c(t)
\end{aligned}
$$

Receive baseband system model (2)

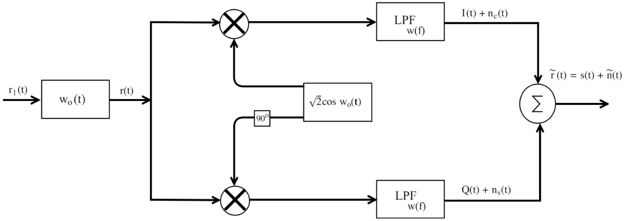
- Demodulate quadrature signal $Q(t)$ (multiply $r(t)$ with $-\sqrt{2}\sin(\omega_0 t)$)

$$
\begin{aligned}
r_s(t) &= -[r(t)\sqrt{2}\sin(\omega_0 t)]_{lpf} \\
&= -\left[I(t)\cos(2\omega_0 t) - Q(t)\sin^2(\omega_0 t) + \sqrt{2}n(t)\sin(\omega_0 t)\right]_{lpf} \\
&= Q(t) + n_s(t)
\end{aligned}
$$

Demodulator block diagram

- Demodulated complex baseband receive signal

$$
\begin{aligned}
\tilde{r}(t) &= r_c(t) + jr_s(t) \\
&= I(t) + jQ(t) + n_c(t) + jn_s(t) \\
&= s(t) + \tilde{n}(t)
\end{aligned}
$$



- Homodyne receiver architecture

5G Control Chain Details

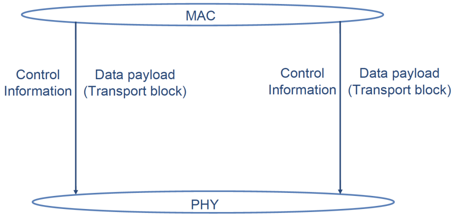
Rohit Budhiraja

Simulation-Based Design of 5G Wireless Standard (EE698H)

Agenda for today

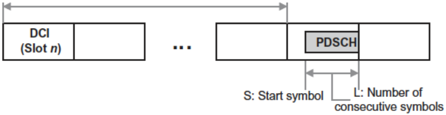
- Briefly discuss 5G control chain
    - Reference – Chap 10.1.4 and 10.1.11 of the 5G NR book by EricD
    - Reference – Chap 3.7.3 and 4.1.3.2.3 of the 5G NR book by SassanA

5G MAC-PHY interface



- MAC layer passes data payload and downlink control information (DCI) to PHY layer
- DCI – MCS index, number of resource blocks, location of resource blocks
- PHY layer first encodes DCI at a particular rate
- PHY layer later maps it using 4-QAM

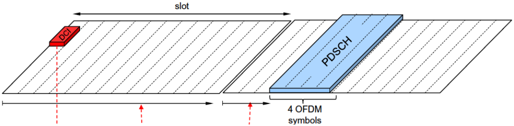
Resource allocation in time domain for downlink (1)



- Slot allocated for PDSCH is determined by $n + K_0$
  - K_0 is the slot offset relative to the slot where DCI was obtained

Resource allocation in time domain for downlink (2)

- Example allocation with start symbol $S = 3$ $L = 4$ consecutive symbols, and slot offset $K_0 = 1$



- Downlink – slot offsets from 0 to 3; uplink – slot offsets from 0 to 7 can be used
- Not all combinations of start and length fit within one slot,
    - for example, starting at OFDM symbol 12 and transmit during five OFDM symbols obviously results in crossing the slot boundary and represents an invalid combination

Time domain resource allocation table for downlink[1]

Row index	*dmrs-TypeA-Position*	PDSCH mapping type	K_0	*S*	*L*
1	2	Type A	0	2	12
	3	Type A	0	3	11
2	2	Type A	0	2	10
	3	Type A	0	3	9
3	2	Type A	0	2	9
	3	Type A	0	3	8
4	2	Type A	0	2	7
	3	Type A	0	3	6
5	2	Type A	0	2	5
	3	Type A	0	3	4
6	2	Type B	0	9	4
	3	Type B	0	10	4
7	2	Type B	0	4	4
	3	Type B	0	6	4
8	2,3	Type B	0	5	7
9	2,3	Type B	0	5	2
10	2,3	Type B	0	9	2
11	2,3	Type B	0	12	2
12	2,3	Type A	0	1	13
13	2,3	Type A	0	1	6
14	2,3	Type A	0	2	4
15	2,3	Type B	0	4	7
16	2,3	Type B	0	8	4

[1] Table 5.1.2.1.1-2 of 38.214. There are 3 more tables.

Resource allocation in time domain for uplink

- BS informs the user in the uplink when to transmit
- DCI is used to schedule users in the uplink also - informally called uplink scheduling grant

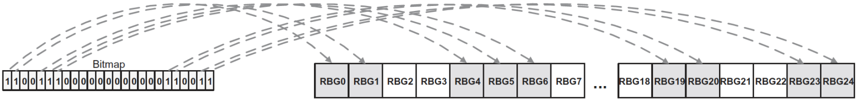
Time domain resource allocation table for uplink[2]

Row index	PUSCH mapping type	K_2	S	L
1	Type A	j	0	14
2	Type A	j	0	12
3	Type A	j	0	10
4	Type B	j	2	10
5	Type B	j	4	10
6	Type B	j	4	8
7	Type B	j	4	6
8	Type A	j+1	0	14
9	Type A	j+1	0	12
10	Type A	j+1	0	10
11	Type A	j+2	0	14
12	Type A	j+2	0	12
13	Type A	j+2	0	10
14	Type B	j	8	6
15	Type A	j+3	0	14
16	Type A	j+3	0	10

[2] Table 6.1.2.1.1-2 of 38.214

Downlink resource allocation in freq. domain (1)

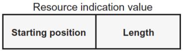
- A UE determines the frequency-domain resources on which it transmits or receives data by examining the resource-block allocation
- Base station can signal the allocated resources to a UE using resource allocation type 0 or type 1
- Type 0 is a bitmap-based allocation scheme

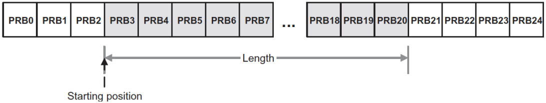


  - Indicates set of resource block groups that UE is supposed to receive in the downlink
  - Size of the bitmap is equal to the number of resource blocks group

Downlink resource allocation in freq. domain (2)

- Type 1 combines starting position and length of resource allocation values into a single value





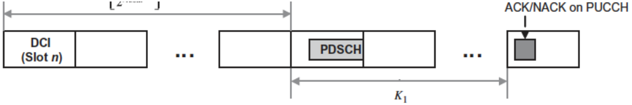
  - Referred to as resource indication value

Contents of DCI (1)

- DCI is used for both downlink and uplink scheduling
- Multiple DCI formats - e.g., “DCI Format 1_0”, which is used for downlink scheduling
- Length of this format is around 35 bits
  - Modulation and coding scheme (5 bits)
  - New data indicator (1 bit)
  - Redundancy version (2 bits)
  - Time-domain resource assignment (4 bits)
  - Frequency-domain resource assignment
  - VRB-to-PRB mapping (1 bit) - continuous / interleaved
  - Identifier for DCI format (1 bit) - downlink assignment / uplink grant

Contents of DCI (2)

- DCI is used for both downlink and uplink scheduling
- Multiple DCI formats - e.g., "DCI Format 1_0", which is used for downlink scheduling
- Length of this format is around 35 bits
  - PDSCH-to-HARQ feedback timing indicator (3 bits)
    - indicates HARQ ACK/ NAK timing relative to the PDSCH transmission



  - Few other fields

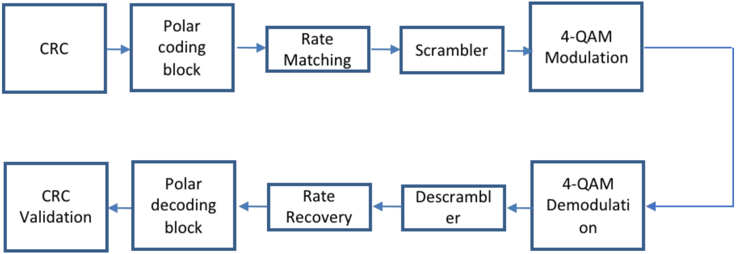
Comparison of two different DCI types for downlink

Field		Format 1–0	Format 1–1
Format identifier		•	•
Resource information	CFI		•
	BWP indicator		•
	Frequency domain allocation	•	•
	Time-domain allocation	•	•
	VRB-to-PRB mapping	•	•
	PRB bundling size indicator		•
	Reserved resources		•
	Zero-power CSI-RS trigger		•
Transport-block related	MCS	•	•
	NDI	•	•
	RV	•	•
	MCS, 2nd TB		•
	NDI, 2nd TB		•
	RV, 2nd TB		•
Hybrid-ARQ related	Process number	•	•
	DAI	•	•
	PDSCH-to-HARQ feedback timing	•	•
	CBGTI		•
	CBGFI		•
Multi-antenna related	Antenna ports		•
	TCI		•
	SRS request		•
	DM-RS sequence initialization		•
PUCCH-related information	PUCCH power control	•	•
	PUCCH resource indicator		•

Comparison of two different DCI types for uplink

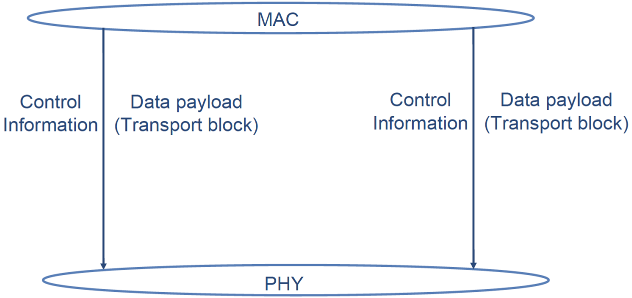
Field		Format 0–0	Format 0–1
Identifier		•	•
Resource information	CFI		•
	UL/SUL	•	•
	BWP indicator		•
	Frequency domain allocation	•	•
	Time-domain allocation	•	•
	Frequency hopping	•	•
Transport-block-related	MCS	•	•
	NDI	•	•
	RV	•	•
Hybrid-ARQ-related	Process number	•	•
	DAI		•
	CBGTI		•
Multi-antenna-related	DM-RS sequence initialization		•
	Antenna ports		•
	SRI		•
	Precoding information		•
	PTRS–DMRS association		•
	SRS request		•
	CSI request		•
Power control	PUSCH power control	•	•
	Beta offset		•

PHY layer processing of DCI – Overview



- Polar decoding block is the most complicated block
- Low BLER for short block lengths
- Low power and hardware consumption for PDCCH decoding, which a user performs

5G PHY processing summary



- Understood in detail PHY layer processing of PDSCH
- Had a overview of PDCCH PHY layer processing