Hardware Emulations

using 5G Toolkit and SDRs: Hands-on

GIGAYASA

For academia only

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1 | PDCCH Implementation and Blind Decoding in 5G Networks

In 5G New Radio (NR), the **PDCCH (Physical Downlink Control Channel)** plays a crucial role in downlink transmission. It is like the heart of data communication. If the UE is unable to decode PDCCH, then no matter what radio conditions are, UE can never be able to know the downlink/uplink grants for Physical Downlink Shared Channel (PDSCH)/Physical Uplink Shared Channel (PUSCH) and hence a user can not decode data.
Consider a scenario where we are watching a video on our mobile phone. Now the question that comes to our mind is how does our mobile phone knows on what time-frequency resources my data is coming, what modulation order and code-rate that a BS picks for data transmission, how many number of layers where used for transmission etc. All this critical information is defined as **downlink control information (DCI)**. Now if our mobile phone fails to decode this information, then our mobile phone does not where to look for on a time-frequency resource grid and hence will not be able to display the video.

1.1 | What is the purpose of PDCCH?

- PDCCH carries downlink control information (DCI), which is essential for the user equipment (UE) to interpret and process the data transmitted on the Physical Downlink Shared Channel (PDSCH).
- Essentially, it is the channel that delivers critical instructions to the UE regarding resource allocation, scheduling, and other control information.

Typically, DCI contains scheduling information such as the time-frequency resources that a base station (BS) allocates for UE, PDSCH related parameters such as rank indicator (RI), which specifies the number of layers that a BS is configured to transmit, Modulation order (M) and code rate (r) etc.
3GPP specifies 5 DCI formats depending on the type of the content that it carries and configuration of the network. These formats are denoted with a number followed by another number which we denote with x. For instance, a DCI Format i_x, where $i \in 0, 1, 2, 3, 4$ and $x \in 0, 1, 2, 3, 4, 5, 6, 7$. Table 1.1 elaborates DCI formats supported. For instance, DCI format 1_0 carries scheduling information of PDSCH in a single cell and Format 2_0 specifies the slot format, available RB sets to a group of UEs. Since DCI carries crucial information, it must be decodable at UE regardless of how poor the channel conditions are. To ensure desired reliability requirements DCI is processed through a sequence of signal processing steps, which is defined as PDCCH Tx chain

1.2 | PDCCH Tx Chain

The block diagram is shown in the figure 1.1 which captures the sequence of signal processing steps. The detailed explanation of these steps is as follows

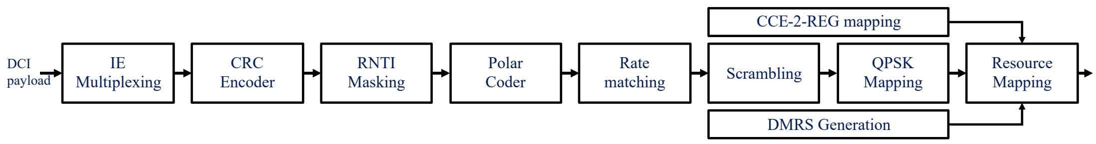

Figure 1.1: PDCCH transmitter chain

1. The first step is information element (IE) multiplexing, where a DCI payload bit sequences having different formats are multiplexed into a single bit sequence for further processing.
2. The next step is to cyclic redundancy check (CRC) encode the bits, which enables the receiver to detect any errors in the transmitted bits. In this step, a 24-bit CRC is attached to the multiplexed DCI payload bit sequence.
3. In the next step, the last 16 bits of CRC encoded DCI bit sequence is masked with a unique Radio Network Temporary Identifier (RNTI). The purpose of this step is to make a UE understand whether the transmitted DCI is intended to it or to some other UE under unicast transmission and to a group of UEs under multicast transmission.

Table 1.1: DCI Formats

DCI format	Usage
0_0	Scheduling of PUSCH in one cell
0_1	Scheduling of one or multiple PUSCH in one cell, or indicating downlink feedback information for configured grant PUSCH (CG-DFI)
0_2	Scheduling of PUSCH in one cell
1_0	Scheduling of PDSCH in one cell
1_1	Scheduling of one or multiple PDSCH in one cell, and/or triggering one shot HARQ- ACK codebook feedback
1_2	Scheduling of PDSCH in one cell
2_0	Notifying a group of UEs of the slot format, available RB sets, COT duration and search space set group switching
2_1	Notifying a group of UEs of the PRB(s) and OFDM symbol(s) where UE may assume no transmission is intended for the UE
2_2	Transmission of TPC commands for PUCCH and PUSCH
2_3	Transmission of a group of TPC commands for SRS transmissions by one or more UEs
2_4	Notifying a group of UEs of the PRB(s) and OFDM symbol(s) where UE cancels the corresponding UL transmission from the UE
2_5	Notifying the availability of soft resources as defined in Clause 9.3.1 of [10, TS 38.473]
2_6	Notifying the power saving information outside DRX Active Time for one or more UEs
2_7	Notifying paging early indication and TRS availability indication for one or more UEs.
3_0	Scheduling of NR side-link in one cell
3_1	Scheduling of LTE side-link in one cell
4_0	Scheduling of PDSCH with CRC scrambled by MCCHRNTI/G-RNTI for broadcast
4_1	Scheduling of PDSCH with CRC scrambled by G-RNTI/GCS-RNTI for multicast
4_2	Scheduling of PDSCH with CRC scrambled by G-RNTI/GCS-RNTI for multicast

4. Following to this step the bits are polar coded, a forward error correction (FEC) code adopted in 5G for PDCCH. The purpose of this step is to ensure the receiver to correct errors introduced by the channel.

5. The next step is to rate match the polar coded bits. Rate matching ensures that the DCI bits fits into the allocated resources for transmission.

6. Next step is to scramble the rate matched bits. DCI payload is scrambled using a pseudo random sequence generated by cell-id and UE specific RNTI. Scrambling ensures that the interference among different UEs is randomized.

7. In the following step scrambled bits are QPSK modulated, where every 2 bits are mapped to a complex number.

8. Now the last step is to map these QPSK symbols into the resources allocated for PDCCH transmission. Resource mapping in PDCCH is always done in the units of control channel elements or CCEs. We will see the resource mapping in detail in the following section.

1.2.1 | Resource mapping in PDCCH

Resource mapping in PDCCH is always done in the units of CCEs. The notions of CCE, Aggregation Level (AL) and PDCCH candidate is crucial to understand the resource mapping. So, we will cover these concepts in detail next.

What is a CCE?

1 CCE = 6 REG = 72 RE
1 REG = 1 RB with 1 OFDM symbol = 12 RE

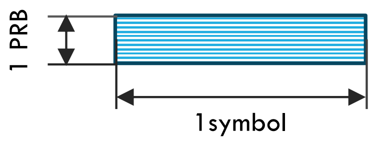

Figure 1.2: REG definition

On a downlink resource grid CCE-REG mapping is shown in the figure 1.3

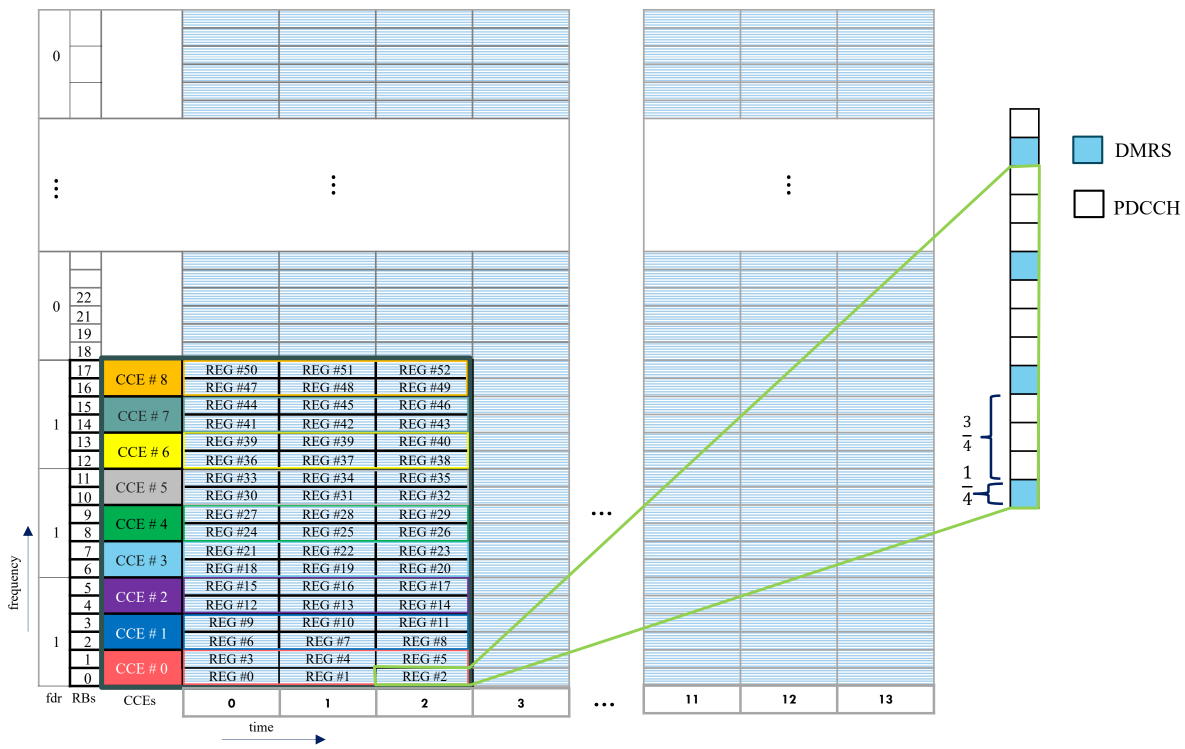

Figure 1.3: CCE-REG Mapping

What is Aggregation Level? The number of CCEs that a BS chose for the transmission of PDCCH is defined as Aggregation Level (AL) PDCCH occupies a specific number of resource elements (REs) according to the AL chosen by BS. Supported ALs are 1, 2, 4, 8 and 16.

BS always chose lower AL for users nearby (typically having LOS path with BS) having good coverage and higher AL for users far away having extreme coverage condition.

How the number of target bits are computed? The number of target bits are computed once the BS picks a particular AL depending on the coverage condition. The number of PDCCH symbol and its corresponding DMRS are functions of AL.
For an AL of L, BS choses L consecutive CCEs or 72L REs on a Downlink resource grid for the transmission of PDCCH including its DMRS. Among these 72L REs, 3/4th is allocated for actual PDCCH symbols and the rest 1/4th is allocated to its DMRS, and the number of target bits is 2 times the number of PDCCH symbols.
What is a PDCCH Candidate? L consecutive CCEs for an AL of L is defined as a PDCCH candidate. PDCCH is transmitted through PDCCH candidates and are located within a CORESET. We will explain the CORESET in detail in the next section 1.2.2. The position of different PDCCH candidates for each

AL is determined using a hash equation.

$$L.\left\{\left(Y_{p,n^{\mu}_{s,f}} + \left\lfloor \frac{m^{(L)}_{s,n_{CI}}.N_{CCE,p}}{L.M^{(L)}_{s,max}} \right\rfloor + n_{CI}\right) mod \left\lfloor \frac{N_{CCE,p}}{L} \right\rfloor\right\} + i \tag{1.1}$$

where $i = 0, 1, ..., L-1$.

1.2.2 | CORESET

CORESET or Control Resource Element Set is defined as the set of REs where PDCCH is transmitted. The number of RBs and the number of OFDM symbol that a CORESET occupy is configured through higher layer parameters *frequencyDomainResources*, *duration* respectively.

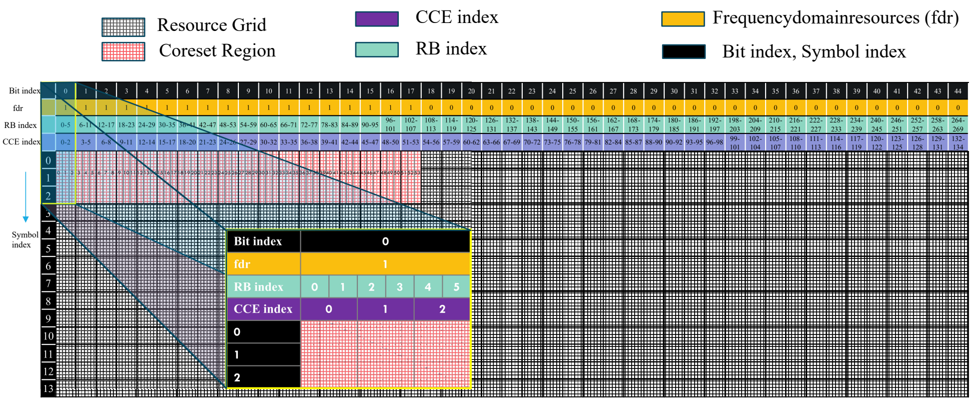

Figure 1.4: CORESET frequencyDomainResources

frequencyDomainResources is a bit string of length 45, where each bit correspond to 6 contiguous RBs and *duration* specifies contiguous time duration in number of OFDM symbols and can be either 1, 2, or 3 symbol.

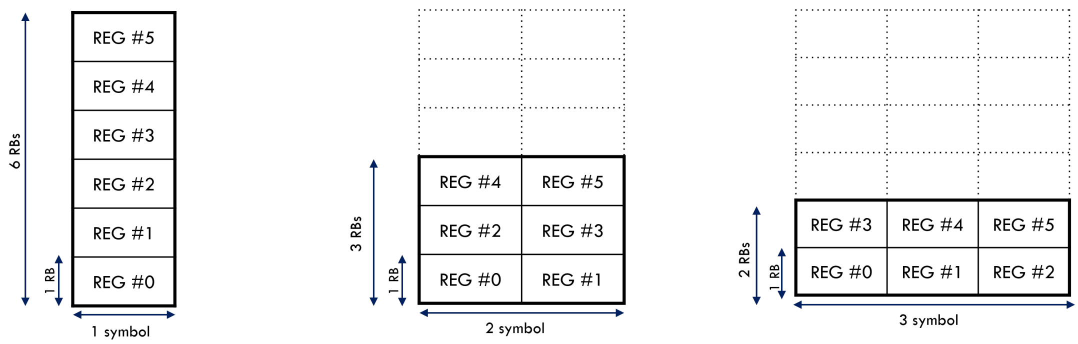

Figure 1.5: CORESET duration

Example:

$$
\begin{aligned}
\textit{frequencyDomainResources} &= [111111111111111111000000000000000000000000000] \\
\text{number of RBs} &= \text{number of 1s in } \textit{frequencyDomainResources} \times 6 \\
&= 18 \times 6 \\
&= 108 \\
\text{number of REGs} &= \text{number of RBs} \times \text{duration} \\
&= 108 \times 3 \\
&= 324 \\
\text{number of CCEs} &= \frac{\text{number of REGs}}{6} \\
&= \frac{324}{6} \\
&= 54
\end{aligned}
$$

1.2.3 | PDCCH Rx Chain

PDCCH Rx chain follows exactly opposite to PDCCH Tx chain as shown in the block diagram 1.6

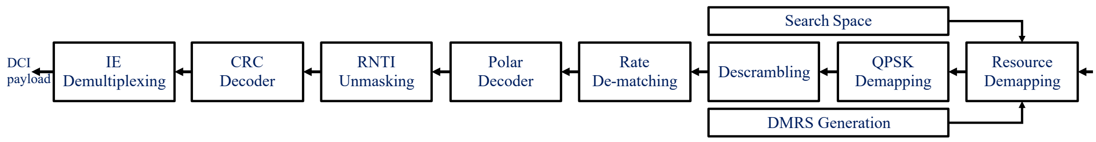

Figure 1.6: PDCCH Receiver Chain

1.2.4 | Search Space Set

The search space set is defined as the set of CCEs where a UE montiors for PDCCH continuously. The UE performs blind decoding of PDCCH candidates corresponding to the search space set. Search space set can be either a common search space set (CSS) or a UE specific search space set (USS). DCI that is common to a group of UEs are generally mapped to CSS and UE specific DCI is mapped to USS. BS generally use ALs 4, 8, 16 for CSS and 1, 2, 4, 8, 16 for USS.
Timing of CORESET is specified using search space set parameter known as *pdcchMonitoringSymbolsWithinASlot*, which is bit string of size 14 and each bit correspond to one symbol within a slot.
We have seen that the CORESET pareameter *duration* specifies the number of OFDM symbol that a CORESET occupies, but the start symbol is not specified. The start symbol of CORESET with in a slot is specified using *pdcchMonitoringSymbolsWithinASlot*.
If $\textit{pdcchMonitoringSymbolsWithinASlot} = 00100000000000$
Since a set bit exists at position 2 with a zero based indexing, the start symbol index of CORESET i is 2.

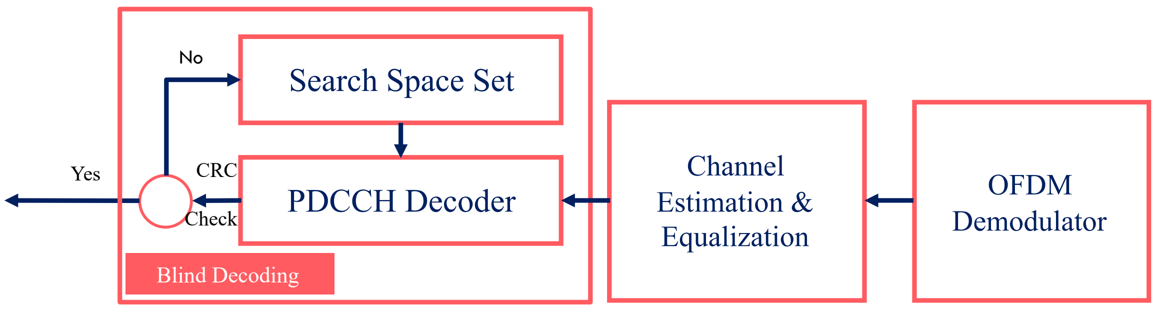

Figure 1.7: PDCCH blind decoding

1.2.5 | PDCCH Blind Decoding

UE blindly decodes PDCCH in the search space associated with a CORESET. If UE fails to decode the PDCCH, then UE will not know the location of PDSCH resources and it will keep attempting to decode the PDCCH using different set of PDCCH candidates.
UE blindly checks for CRC assuming that its DCI was mapped to a particular PDCCH candidate with each AL assocaited with in that search space. If it fails it repeats the same step of checking for CRC with next PDCCH candidate in sequence until the CRC check passes. Once CRC check passes, UE is able to decode its DCI. If a UE fails in CRC check of all the available candidates, then it must not be able to decode its DCI.
Example: Consider a CORESET size of 16 and the search space set associated with a CORESET is USS. Assume that the BS uses an AL of 2 and the number of PDCCH candidates that a UE has to search is 4. For simplicity we assume that all the candidates of AL other than 2 are 0. i.e., number of candidates per AL = [0, 4, 0, 0, 0, 0] and the CCE indices corresponding to candidates are [[0,1], [4,5], [8,9], [12,13]] as shown in 1.8. Also assume that BS maps the DCI corresponding to UE with CCE indices of [4,5] or candidate numbered 1 with a RNTI of 51585.

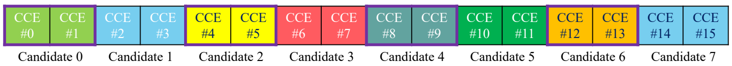

Figure 1.8: Blind Decoding of PDCCH Candidates

Now UE starts decoding blindly by CRC check assuming that its DCI was mapped to first candidate having CCE indices [0,1]. Since its DCI was not mapped to this candidate, CRC check fails as shown in 1.9 Since CRC check fails with the previous candidate, now UE repeats blind decoding with next

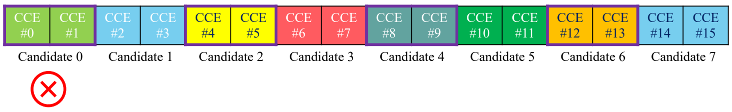

Figure 1.9: PDCCH blind decoding fails

candidate in sequence having CCE indices [4,5]. Here CRC check passes as this was the candidate that BS indeed used for mapping its DCI and UE is able to decode its DCI as shown in figure 1.10

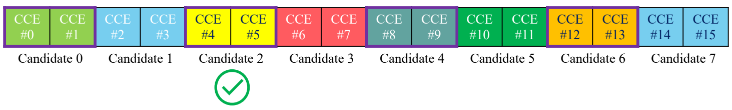

Figure 1.10: PDCCH blind decoding successful

1.3 | References

2 | References