EE6143: Advanced Topics in Communications
Assignment 7
Understanding the Heart of the 5G Air Interface: An Overview of Physical Downlink Control Channel for 5G New Radio (NR)

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1 Introduction

In this assignment, we explore the Physical Downlink Control Channel (PDCCH) in 5G, by describing its physical layer, structure, monitoring mechanisms, beamforming, and the information carried, using the assignment provided by Takeda et. al. [1].

In the previous assignments, we have defined the three main use-cases of 5G: (i) eMBB, (ii) URLLC, and (iii) mMTC. As instituted by 3GPP (Third-generation partnership protocol), which includes frequencies previously unexplored. There are two main NR characteristics which achieve this:

- **OFDM with variable subcarrier spacing:** Previously in 4G, we had OFDM, but the subcarrier spacing was fixed to be 15 kHz. However, 5G allows variable subcarrier spacing, for spacings of 15, 30, 60, 120, 240 kHz and up to 3300 subcarriers can be used for OFDM. For each of these subcarrier spacings, it is crucial to have an appropriate cyclic prefix length, with a variable number of slots (one slot is 14 OFDM symbols) in each subframe (1ms time unit).
- **Flexible Bandwidth:** We know that using OFDM, we can aggregate up to 3300 subcarriers, for say $\Delta f = 120$kHz. For this case, the bandwidth can be up to $396MHz \approx 400MHz$. However, each UE doesn't need to use the whole bandwidth but can use a small part of it, called a *Bandwidth Part (BWP)*. An UE may have up to 4 BWPs and each of them can have a different OFDM numerology.

To accommodate all of this, we need a robust Physical Downlink Control CHannel (PDCCH). It has the following uses:

- DL scheduling assignments
- UL scheduling grants
- Slot format indication
- Preemption indication
- Power control

The information carried by the PDCCH (called Downlink Control Information (DCI)) contains scheduling and other control information for UL and DL transmissions.

2 What is Downlink Control Information (DCI)?

DCI is the *payload* of the PDCCH, i.e. the information which is transmitted through the PDCCH.

We consider the following DCI *formats*:

- The format 1_0 (fallback format) is used for Downlink scheduling assignments. The 1_0 format supports only basic `NR` features such as scheduling, paging, and system information changes.
- The format 1_1 (non-fallback format) is also used for Downlink scheduling assignments. The 1_1 format is highly configurable and supports advanced `NR` features also.
- The format 0_0 (fallback format) is used for Uplink Scheduling grants. The 0_0 format supports only basic `NR` features.
- The format 0_1 (non-fallback format) is also used for Uplink scheduling grants. The 0_1 format is supports all `NR` features.
- The format 2_0 is used for notifying the group of `UE` of the slot format indication that determines whether resources are used for UL or DL transmission.
- The format 2_1 is used for preemption indication that tells devices that some resources are pre-empted and hence not used for transmission.
- The format 2_2 is used for transmitting the power specifications for the uplink channels: PUSCH and PUCCH.
- The format 2_3 is used for transmitting power specifications for the sounding reference signal (SRS).

The DCI size can be different depending on the format, this is clarified more in subsequent sections.

3 Physical Layer Structure

3.1 DCI $\rightarrow$ PDCCH

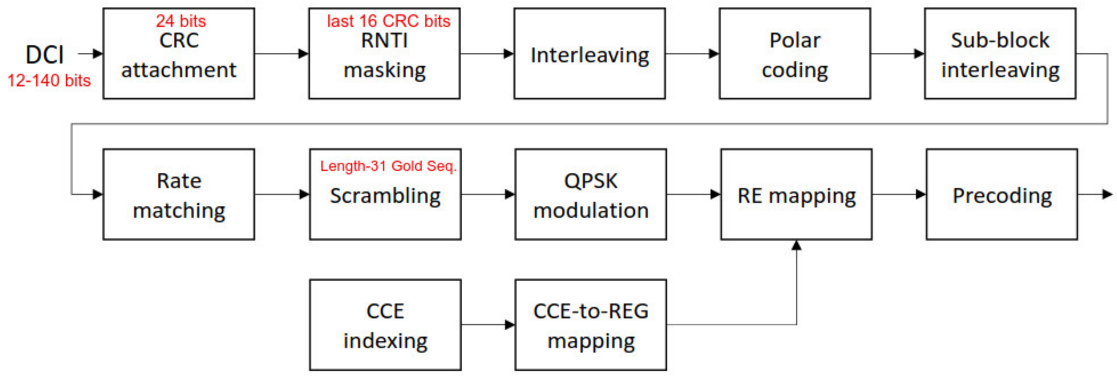

Figure 1: Procedure for generating PDCCH from DCI [1]

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Table 1 highlights the steps involved in converting DCI to PDCCH information, along with the technical details and details for the same. This is summarized in figure 1 also.

Steps	**Explanation**
Padding	If size of DCI less than 12 bits, zero padding is done
CRC	24-bit CRC is added
RNTI	Last 16 bits of CRC is masked with Radio Network Temporary Identifier (RNTI)
Interleaving	Converting Burst errors into Random Errors
Polar Coding	Error control coding
Sub-block interleaving and Rate Matching	Divides data into blocks, interleaves the blocks. The blocks themselves remain intact. After this, rate matching is done to match DCI information to the REs (Resource Elements)
Scrambling	Done by using a pseudorandom number initialized by cell or a `UE` specific scrambling identity.
QPSK	Quadrature Phase-Shift Keying Modulation Scheme
RE Mapping	Elaborated in subsection 3.1.1
Precoding	Narrowband / wideband precoding.

Table 1: Tabular summary of the steps involved in converting DCI to PDCCH

3.1.1 RE Mapping

The RE Mapping is outlined in the below expressions.

$$\begin{aligned} 1 \text{ Physical Resource Block (PRB)} &= 12 \text{ Subcarriers} \\ 1 \text{ Resource Element Group (REG)} &= 1 \text{ PRB} \times 1 \text{ OFDM Symbol} \\ 1 \text{ Control Channel Element (CCE)} &= 6 \text{ REG} \\ 1 \text{ Downlink Channel Information (DCI)} &= AL \text{ CCEs} \end{aligned}$$

Here, AL (Aggregation Level) takes the values in the set $\{1, 2, 4, 8, 16\}$.
Thus, DCI consists of $AL \cdot 54$ REs, or $\boxed{AL \cdot 108 \text{ bits}}$.
The base station picks the value of the aggregation level based on the channel conditions.

3.2 What is a CORESET?

One CORESET consists of 6 PRBs on a six PRB frequency grid in the frequency domain and 1, 2, or 3 OFDM symbols in the time domain. A `UE` may be configured with up to three Control Resource Sets (CORESET) on each of up to four Bandwidth Parts (BWPs) on a serving cell, i.e. one `UE` might be mapped to up to 12 CORESETs.

CORESET 0: This is a special CORESET which is configured using a four-bit information element in the Master Information Block (MIB). Its configuration is restricted, but can be used even before other configurations are provided. Moreover, CORESET 0 may not be aligned with the six PRB frequency grid as in other CORESETs described above.

CORESETs are active only when their corresponding BWP is active, except CORESET 0, in accordance with the ultralean design principle.

3.3 PDCCH → CORESET

In the previous section, we saw how to map the DCI to a PDCCH. Now, we will define a CORESET and see how to map a PDCCH to CORESET.

1 DCI consists of AL CCEs (control channel elements), and the CCEs are mapped on a number of REGs in a CORESET. There are two types of CCE-to-REG mappings: interleaved or non-interleaved.

- **Interleaved CCE-to-REG mapping:** We saw that CORESETs can be made of 1, 2, or 3 OFDM symbols. An REG bundle is spans across all the OFDM symbols for a given CORESET. A block-interleaver converts CCEs to REG bundles, where we can think of the data being read in row-wise and read out column wise (the bundles).
- **Non-interleaved CCE-to-REG mapping:** All CCEs with some AL are mapped to consecutive REG bundles of the CORESET, there is no concept of row-in-column-out here.

After this, in `NR` there are two kinds of precodings:

- **Narrowband:** PDCCH Demodulation Reference Signals (DMRs) are transmitted only in the REG bundles actually used for the PDCCH transmission, and precoding is constant only within the REG bundle.
- **Wideband:** PDCCH DMRSs are transmitted in all contiguous REGs of a CORESET carrying the PDCCH using the same precoder.

4 PDCCH monitoring by `UE`

The `UE` needs to actively listen to the PDCCH to decode it. In this section, we highlight the technical details of how this is done.

The `UE` monitors using search-space (SS) sets:

- CSS (Common SS): Monitored by group of `UE`
- USS: (UE-specific SS): Monitored by a single `UE`.

One `UE` can be mapped to up to 4 BWPs, and each BWP can have up to 10 SS each, thus there can be a total of up to 40 SS sets. One SS is mapped to one CORESET.

SS Set 0: The SS set 0 can be monitored even before higher-layer configurations are provided, but it has limited configurations.

Mapping CCEs to SS set: This is done by a hash function, which randomizes the allocation of the PDCCH candidates within a CORESET.

Monitoring the SS set within a slot are configured by a bitmap parameter in the SS set configuration.

4.1 In Release 16

- Since URLLC is a primary goal of 5G, release 16 aims to optimize monitoring in this aspect. The PDCCH monitoring capability increases and the `UE` can monitor the PDCCH more often than in Rel 15.
- Low power consumption: As part of the ultra-lean design methodology, a wake-up signal is introduced to dynamically control the PDCCH's monitoring behaviour to reduce power consumption. This signals tells the `UE` if it can skip monitoring in a particular slot, thus the `UE` monitors the channel only when there is data.

5 Beamforming

Beamforming and massive MIMO (mMIMO) is a cornerstone of `5G`.

In *analog beamforming*, all the phase shifting and amplitude scaling happens in the analog domain, while in *digital beamforming* all this happens in the digital domain (precoding). *Hybrid beamforming* is a combination of these two techniques wherein phase shifters and amplitude weights on each antenna panel are used along with digital precoders.

PDCCH supports beamforming using TCI: Transmission Configuration Information. The UE can be configured with up to 64 TCI states for a CORESET to receive a PDCCH. Each TCI state contains parameters on:

- Reference Signals (RSs)
- QCL: Quasi co-location: Basically the similarity of the channel between the RS and the DMRS (demodulation reference signal)

Beam failure recovery: In this scenario, there is poor link quality between the BS and UE, usually since there is a miscommunication regarding the beamforming settings. In this case, the `UE` can tell how the beamforming should be done using random access.

Beam Collision: The number of analog beams received is upper bounded by the number of antenna panels supported on the `UE` side since analog beamforming is applied per antenna panel.

References

[1] Kazuki Takeda, Huilin Xu, Taehyoung Kim, Karol Schober, and Xingqin Lin. Understanding the heart of the 5g air interface: An overview of physical downlink control channel for 5g new radio (NR). *CoRR*, abs/1910.01711, 2019.