UPLINK CHANNEL TRANSPORT PROCESSING AND PHYSICAL LAYER PROCEDURES

Module – 4

MODULE – 4 SYLLABUS

- **Uplink Channel Transport Processing:** Overview, Uplink shared channels, Uplink Control Information, Uplink Reference signals, Random Access Channels, H-ARQ on uplink (Sec 8.1 – 8.6 of Text).
- **Physical Layer Procedures:** Hybrid – ARQ procedures, Channel Quality Indicator CQI feedback, Precoder for closed loop MIMO Operations, Uplink channel sounding, Buffer status Reporting in uplink, Scheduling and Resource Allocation, Cell Search, Random Access Procedures, Power Control in uplink (Sec 9.1- 9.6, 9.8, 9.9, 9.10 Text).

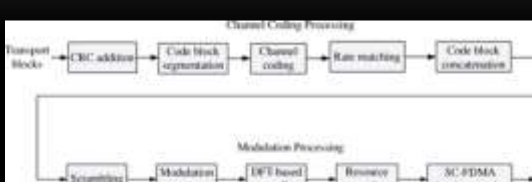
UPLINK CHANNEL TRANSPORT PROCESSING

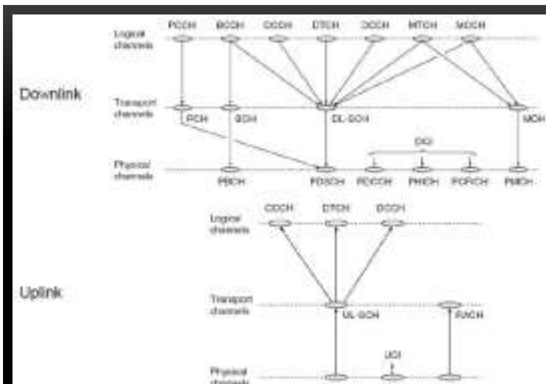
- Uplink is based on SC-FDMA due to its low peak-to-average power ratio (PAPR) compared to OFDMA
- Each UE can only be allocated contiguous resource blocks, unlike downlink where each UE can be allocated non-contiguous resource blocks in order to extract frequency diversity gain.
- In addition, the uplink only supports a limited number of MIMO modes compared to the downlink.

UPLINK CHANNEL TRANSPORT PROCESSING…

- There are *similarities* between the downlink and uplink transport channel processing.
  - the same ***channel coding processing*** is applied on both downlink and uplink
  - ***Time-frequency structure*** of the uplink resource blocks is similar to that of the downlink.
- There are also *interactions* between downlink and uplink transmissions.
  - The ***downlink control information*** carries **scheduling grants** for the ***uplink transmission***
  - the ***uplink control information*** provides necessary information such as **channel quality and channel rank** for ***downlink scheduling*** and ***transport format*** selection.

OVERVIEW OF UPLINK TRANSPORT CHANNEL PROCESSING





CHANNEL CODING PROCESSING

- The channel coding processing in the uplink is similar to that in the downlink:
  - I. CRC addition
  - II. code block segmentation
  - III. channel coding
  - IV. rate matching
  - V. code block concatenation.
- Unlike the downlink, the control information in the uplink can be mapped either to the Physical Uplink Shared Channel (***PUSCH***) or the Physical Uplink Control Channel (***PUCCH***).

- Usage of Channel Coding Scheme and Coding Rate for Uplink Transport Channels

Transport Channel	Coding Scheme	Coding Rate
UL-SCH	Turbo coding	1/3

- Usage of Channel Coding Scheme and Coding Rate for Uplink Control Information

Control Information	Coding Scheme	Coding Rate
UCI	Block coding	Variable
	Tail-biting convolutional coding	1/3

MODULATION PROCESSING

- For the modulation in the uplink, the various steps such as ***scrambling and modulation mapping*** are done in the ***same way as in the downlink***.
- ***Unlike downlink***, in uplink a ***UE-specific scrambling*** is applied in order to randomize the interference.
- Also, since spatial multiplexing is not supported in the uplink there is ***no layer mapping or MIMO precoding***.
- The main ***difference from the downlink comes from the nature of the SC-FDMA-based transmission,*** which is different from the OFDMA-based transmission that is used in the downlink.

MODULATION PROCESSING

THE GENERATION OF THE SC-FDMA BASEBAND SIGNAL

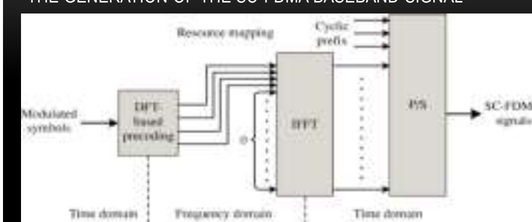


Fig: Generation of SC-FDMA baseband signals, where P/S denotes the parallel-to-serial converter

Note that the generation of the SC-FDMA signal shares the similar structure as that for the OFDMA signal, with an additional DFT operation.

MODULATION PROCESSING

THE GENERATION OF THE SC-FDMA BASEBAND SIGNAL

1. First, the DFT-based precoding is applied to the block of complex-valued modulation symbols, which transforms the time-domain signal into the frequency domain.
   - In LTE, the DFT size is constrained to be products of the integers two, three, and five, which is a tradeoff between the complexity of the implementation and the flexibility on the assigned bandwidth.
   - The DFT size also depends on the number of resource blocks assigned to the UE.
2. Then the output of the DFT-based precoder is mapped to the resource blocks that have been allocated for the transmission of the transport block.
   - In LTE, only localized resource allocation is supported in the uplink, that is, contiguous resource blocks are assigned to each UE.

MODULATION PROCESSING

THE GENERATION OF THE SC-FDMA BASEBAND SIGNAL

3. The baseband signal $s_l(t)$ in SC-FDMA symbol l in an uplink slot is defined by:

$$s_l(t) = \sum_{k=-\lfloor N_{RB}^{UL} N_{sc}^{RB}/2 \rfloor}^{\lceil N_{RB}^{UL} N_{sc}^{RB}/2 \rceil - 1} a_{k^{(-)},l} \cdot e^{j2\pi(k+1/2)\Delta f(t - N_{CP,l} T_s)}$$

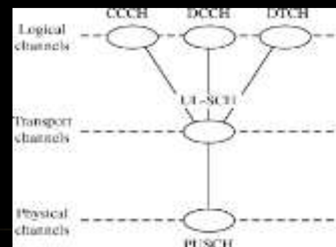
- for $0 \le t < (N_{CP,l} + N) \times T_s$, where $k^{(-)} = k + \lfloor N_{RB}^{UL} N_{sc}^{RB}/2 \rfloor$, N is the FFT size,
- Δf = 15kHz, and $a_{k,l}$ is the content of resource element (k, l).

MODULATION PROCESSING

- It is generated with an IFFT operation, after which the cyclic prefix (CP) is inserted.
- Different from the OFDM baseband signal in the downlink, the DC SC-FDMA subcarrier is used in the uplink.
- Direction conversion will introduce distortion in the DC subcarrier, and in LTE uplink all the subcarriers are shifted by half a subcarrier spacing to reduce this influence.
- The operation combining DFT-based precoding and IFFT applies to all uplink physical signals and physical channels except the physical random access channel.

UPLINK SHARED CHANNELS

- In the uplink, the UL-SCH is the only transport channel that carries traffic data.
- It can also be used to transfer control signals for higher layers.



UPLINK SHARED CHANNELS

CHANNEL ENCODING AND MODULATION

- The channel coding scheme for data streams on the UL-SCH is the same as that for the DL-SCH.
- A rate 1/3 turbo encoder is used to encode the transport block.
- Effective code rates other than 1/3 are achieved by either puncturing or repetition of the encoded bits, depending on the transport block size, the modulation scheme, and the assigned radio resource.
- The encoded symbols are scrambled prior to modulation, which is done to randomize the interference.

UPLINK SHARED CHANNELS

CHANNEL ENCODING AND MODULATION….

- Instead of using a cell-specific scrambling as in the downlink, a UE-specific scrambling is applied in the uplink.
- The UL-SCH is mapped to the PUSCH, which supports QPSK, 16QAM, and 64QAM modulation schemes.
- The QPSK and 16QAM modulation schemes are mandatory and support for the 64QAM modulation is optional and depends on the UE capability.
- The modulation order and the redundancy version for the channel coding of the H-ARQ protocol are contained in the 5-bit "modulation and coding scheme and redundancy version" field (I_{MCS}) in the downlink control information (DCI) carried on the PDCCH with format 0.

UPLINK SHARED CHANNELS

FREQUENCY HOPPING

- The resource mapper maps the complex-valued modulation symbols in sequence on to the physical resource blocks assigned for transmission of PUSCH.
- In LTE, only ***localized resource allocation*** is supported in the uplink due to its robustness to frequency offset compared to distributed resource allocation.
- Localized resource allocation also retains the single-carrier property in the uplink transmission.

UPLINK SHARED CHANNELS

FREQUENCY HOPPING

- As a consequence, there is ***very little frequency diversity gain***.
- On the contrary, in the downlink it is possible to allocate disjoint sets of resource blocks to a UE to extract some frequency diversity gain.
- To alleviate this issue, LTE supports frequency hopping on PUSCH, which provides additional frequency diversity gain in the uplink.
- Frequency hopping can also provide interference averaging when the system is not 100% loaded.

UPLINK SHARED CHANNELS FREQUENCY HOPPING

- In LTE both *intra-subframe* and *inter-subframe* frequency hopping are supported.
- ***Intra-subframe hopping***:
  - the UE hops to another frequency allocation from one slot to another within the same subframe
- ***Inter-subframe hopping***:
  - the frequency resource allocation changes from one subframe to another.

UPLINK SHARED CHANNELS FREQUENCY HOPPING

- Higher layers determine if the hopping is "inter-subframe" or "intra- and inter-subframe."
- In general, "intra-subframe" hopping provides higher frequency diversity gain since this gain can be extracted over a single H-ARQ transmission, which always spans only one subframe.
- In the case of "inter-subframe" hopping, multiple H-ARQ transmissions are needed in order to extract the frequency diversity gain.

UPLINK SHARED CHANNELS FREQUENCY HOPPING

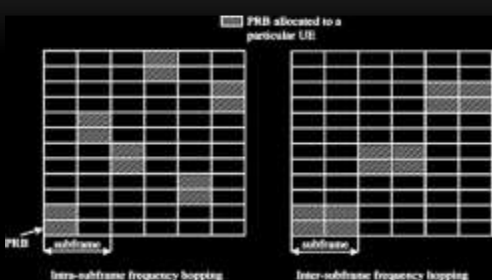


Figure : Illustrations of frequency hopping on PUSCH.

UPLINK SHARED CHANNELS FREQUENCY HOPPING

- If the single bit ***Frequency Hopping (FH)*** field in the corresponding PDCCH with DCI format 0 is set to 1, the ***UE shall perform PUSCH frequency hopping***;
  - otherwise, no PUSCH frequency hopping is performed.
- ***FH = 0* - No frequency hopping**
  - If uplink frequency hopping is disabled (*FH = 0*):
    - ➢ the set of physical resource blocks to be used for transmission is given by $n_{PRB} = n_{VRB}$,
      - where n_{VRB} is the virtual resource block index obtained from the uplink scheduling grant.

UPLINK SHARED CHANNELS FREQUENCY HOPPING

- FH = 1 - ***Frequency hopping***

If uplink frequency hopping is enabled (FH = 1), there are two frequency hopping types.

- *Type 1 hopping* uses an explicit offset in the second slot, determined by parameters in DCI format 0.
- *Type 2 hopping*, the set of physical resource blocks to be used for transmission is given by the scheduling grant together with a predefined hopping pattern.

- The UE first determines the allocated resource blocks after applying all the frequency hopping rules, and then the data is mapped onto these resources.

UPLINK SHARED CHANNELS

MULTIANTENNA TRANSMISSION

- Considering cost and complexity of the UE, LTE only supports a limited number of multi-antenna transmission schemes in the uplink:
  a) Transmit antenna selection
  b) Multiuser MIMO (MU-MIMO).

a) *Transmit Antenna Selection*

- With two or more transmit antennas at the UE, transmit antenna selection can be applied, which is able to provide *spatial diversity gain*.
- The multiantenna transmission at the UE depends on the signalling from higher layers.

UPLINK SHARED CHANNELS
MULTIANTENNA TRANSMISSION…
a) Transmit Antenna Selection…

i. No antenna selection

If transmit antenna selection is disabled or not supported by the UE, the UE shall transmit from antenna port 0.

ii. Closed-loop (CL) antenna selection

If CL UE transmit antenna selection is enabled by higher layers, the UE shall perform transmit antenna selection in response to commands received via DCI format 0 from the eNode-B.

- The DCI format 0 is scrambled with the antenna selection mask which enables the UE to determine which antenna port to select.

UPLINK SHARED CHANNELS
MULTIANTENNA TRANSMISSION
a) Transmit Antenna Selection…

Iii. Open-loop (OL) antenna selection

If OL UE transmit antenna selection is enabled by higher layers, the ***transmit antenna*** to be selected by the UE is ***not specified***.

- The UE can determine the optimum antenna based on H-ARQ ACK/NAK feedbacks.
- The UE can transmit from antenna 0 for some time instance and then switch to antenna 1 for a next time instance.
- During both of these time instances, the UE also monitors the H-ARQ ACK/NAK ratio.
  - If the ACK/NAK ratio in the time instance when antenna 0 was used is less than the ACK/NAK ratio for the time instance when antenna 1 was used, then clearly antenna 1 is a better choice and vice versa.

UPLINK SHARED CHANNELS
MULTIANTENNA TRANSMISSION

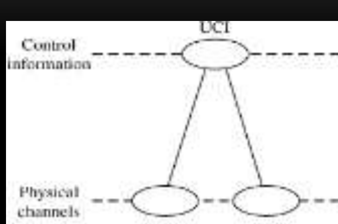
b) MU-MIMO In Uplink

- MU-MIMO is supported in the uplink, which is also referred to as "virtual" MIMO transmission.
- ***Two UEs transmit simultaneously*** on the same radio resource, forming a virtual MIMO channel, and the eNode-B separates the data streams for each UE, for example, using multiuser detection.
- This transmission mode provides a spatial multiplexing gain to increase the uplink spectrum efficiency, even with single-antenna UEs.
- The MU-MIMO mode mainly affects the operation at eNode-B, as the Channel Quality Indicator (CQI) calculation and the scheduling process will change due to the interaction between data streams for different UEs.

UCI (UPLINK CONTROL INFORMATION)

- UCI stands for Uplink Control Information. It is carried by PUCCH or PUSCH.
- It may remind you of DCI which is carried by PDCCH.
- Yes, UCI is the counter part of DCI, but the information/role of UCI is very small comparing to DCI
- The information carried by UCI is mainly following FOUR
  - SR (Scheduling Request)
  - HARQ ACK/NACK
  - CQI
  - PMI/RI (PMI stands for Pre-coding Matrix Indicator, and RI is Rank Indicator.)
- UE transmit a certain combination of these three information depending on situation. Sometimes it carries only SR, sometimes SR and HARQ ACK/NACK together etc.
- There are two channels that can carry the UCI. Sometimes PUCCH carries UCI and sometimes PUSCH carries it.

UPLINK CONTROL INFORMATION



Channel mapping for control information in the uplink.

UPLINK CONTROL INFORMATION

- The Uplink Control Information (UCI) is to assist physical layer procedures by providing the following types of physical layer control information:

1. • *Downlink CQI*, which is used to assist the adaptive modulation and coding and the channel-dependent scheduling of the downlink transmission.
   - The CQI indicates the highest modulation and coding rate that can be supported in the downlink with a 10% block error rate on the first H-ARQ transmission.
2. • *H-ARQ acknowledgment (H-ARQ-ACK)* associated with the downlink H-ARQ process.

UPLINK CONTROL INFORMATION

3. • ***Scheduling Request (SR)*** to request radio resources for the uplink transmission.

4. • ***Precoding Matrix Indicator (PMI) and Rank Indication (RI)*** for downlink MIMO transmission.
   - ***RI*** indicates the maximum number of layers that can be used for ***spatial multiplexing*** in the downlink
   - ***PMI*** indicates the ***preferred precoding matrix***.

UPLINK CONTROL INFORMATION

- Unlike the downlink, which has three different physical control channels, there is only one physical control channel defined for the UCI—the PUCCH.
- The UCI can also be mapped onto PUSCH when the UE has been assigned uplink radio resources.
- When this happens, the ***UCI is frequency-multiplexed with the UL-SCH data on the PUSCH*** unless the PUSCH carries a random access response grant or a retransmission as part of the ***contention-based random access procedure***.
- When the UE does not have uplink allocation on the PUSCH, the UCI is transmitted on the PUCCH in the specifically assigned radio resource.

CHANNEL CODING FOR UPLINK CONTROL INFORMATION

- the UCI can be transmitted on ***PUCCH, or on PUSCH*** if there is uplink assignment.
- The channel coding for UCI therefore depends on whether it is carried on the PUCCH or PUSCH.
- In addition, ***different types of control information are encoded differently***, which ***allows individual adjustments of transmission energy*** using different coding rates.

UCI ON PUCCH

- When the UCI is transmitted on the PUCCH, three channel coding scenarios are considered:
  - 1) the UCI contains CQI/PMI but not H-ARQ-ACK,
  - 2) the UCI contains H-ARQ-ACK and/or SR but not CQI/PMI, and
  - 3) the UCI contains both CQI/PMI and H-ARQ-ACK.

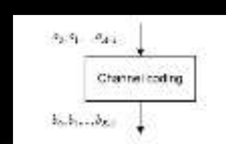
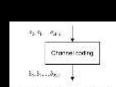


Figure 5.2.3-1. Processing for UCI

UCI ON PUCCH

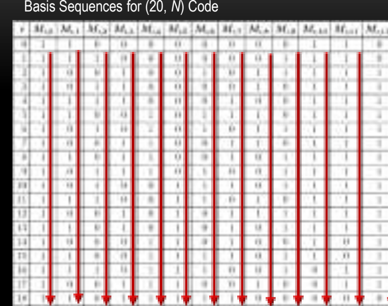
- • ***Encoding CQI/PMI*** The CQI/PMI is encoded using a (20, N_{CQI}) code, with codewords being a linear combination of the 13 basis sequences that are defined in Table and N_{CQI} is the number of CQI and PMI bits.
- Denote a_i, $i = 1, \dots, N_{CQI}$ as the input channel quality bits, and the encoding is performed as:

$$b_i = \sum_{n=0}^{N_{CQI}-1} (a_n \cdot M_{i,n}) \bmod 2,\ i = 0, 1, \dots, 19.$$



UCI ON PUCCH...

Basis Sequences for (20, *N*) Code



UCI ON PUCCH

Encoding H-ARQ-ACK and SR

- The H-ARQ-ACK bits and SR indication are received from higher layers.
- Each ***positive*** acknowledgement (ACK) is encoded as a ***binary '1'*** while each ***negative*** acknowledgment (NAK) is encoded as a ***binary '0'***.
- There is one H-ARQ-ACK bit for single-codeword transmission and two H-ARQ-ACK bits for two-codeword transmission (spatial multiplexing).

UCI ON PUCCH….

Encoding CQI/PMI + H-ARQ-ACK

- When CQI/PMI and H-ARQ-ACK are transmitted in the same subframe, the following coding scheme is used:
  - – With the normal CP, the CQI/PMI is encoded using the (20, N_{CQI}) code, and then the H-ARQ-ACK bits are added at the end of the resulting codeword.
  - – With the extended CP, the CQI/PMI and H-ARQ-ACK are ***jointly encoded*** using the same (20, N) code as that for encoding CQI/PMI alone, with N as the sum of CQI/PMI bits and H-ARQ-ACK bits.

UCI ON PUCCH….

PUCCH FORMATS

- Based on different types of control information carried on the PUCCH, there are six different PUCCH formats defined in LTE, as shown in Table.
- The ***parameter*** M_{bit} is the number of encoded bits for each PUCCH format, which can be easily inferred from the channel coding scheme.
  - *For example*, if the UCI carries CQI/PMI only, or carries CQI/PMI and H-ARQ-ACK with the extended CP, the (20, N_{CQI}) encoder is applied, so there are 20 coded bits, corresponding to PUCCH format 2.
- The SR is carried by the presence/absence of transmission of PUCCH from the UE, so there are no extra bits.

UCI ON PUCCH….

PUCCH FORMATS

PUCCH Format	Contents	M_{bit}
1	Scheduling Request (SR)	N/A
1a	H-ARQ-ACK, H-ARQ-ACK+SR	1
1b	H-ARQ-ACK, H-ARQ-ACK+SR	2
2	CQI/PMI or RI, (CQI/PMI or RI)+H-ARQ-ACK (extended CP)	20
2a	(CQI/PMI or RI)+H-ARQ-ACK (normal CP)	21
2b	(CQI/PMI or RI)+H-ARQ-ACK (normal CP)	22

Table 8.4 Supported PUCCH Formats

UCI ON PUSCH WITH UL-SCH DATA

- If there is uplink radio resource assigned to the UE, the UCI can be multiplexed with the UL-SCH data on the PUSCH channel and there is no need to send SR.
- In this case, the channel coding for H-ARQ-ACK, RI, and CQI/PMI is done independently.
- Different coding rates can be achieved by allocating different numbers of coded symbols, depending on the amount of allocated radio resource.

UCI ON PUSCH WITH UL-SCH DATA

Coding for H-ARQ-ACK

- For the ***FDD mode***, there is ***one or two H-ARQ-ACK bits***.
- For the TDD mode, two ACK/NAK feedback modes are supported, with different information bits:
  - ➢ • ACK/NAK bundling, which consists of one or two bits of information
  - ➢ • ACK/NAK multiplexing, which consists of between one and four bits of information

UCI ON PUSCH WITH UL-SCH DATA

Coding for RI (rank indicator)

- The mapping between the RI bits and the channel rank is shown in Table.
- Denote N_{RI} as the number of RI bits.
- Similar to H-ARQ-ACK, the N_{RI}-bit RI is first encoded into an $N_{RI}Q_m$ codeword, and then multiple encoded RI blocks are concatenated to form a bit sequence.

RI Bits	Channel Rank
0	1
1	2
0, 0	1
0, 1	2
1, 0	3
1, 1	4

Table 8.5 RI Mapping

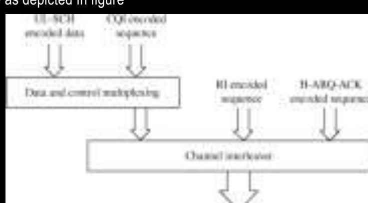
CODING FOR CQI/PMI

The coding scheme for CQI/PMI ***depends on the total number of CQI and PMI bits***.

- • If the payload size N_{CQI} is less than or equal to 11 bits, the CQI/PMI bits are first encoded using a (32, N_{CQI}) block code, with the codewords as a linear combination of 11, length-32 basis sequences.
- The 11 basis sequences allow encoding a maximum of 11 CQI/PMI bits.
- The encoded CQI/PMI block is b_0, b_1, ..., b_{31}, and then the output bit sequence q_0, q_1, ..., q_Q is obtained by circular repetition of the encoded block as $q_i = b_{(i \bmod 32)}$, where i = 1, 2, ..., Q.
- The length of the output sequence (Q) depends on the assigned radio resource for PUSCH.
  - • If N_{CQI} > 11, first a CRC is added, and then the tail-biting convolutional code with rate 1/3 is used as the coding scheme.

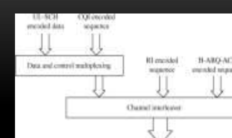
CODING FOR CQI/PMI

- After channel encoding, the CQI encoded sequence is multiplexed with the UL-SCH data, the output of which is interleaved with the RI and H-ARQ-ACK encoded sequence as depicted in figure



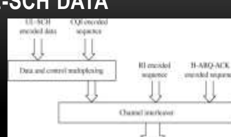
Multiplexing of data and control information on the PUSCH channel.

CODING FOR CQI/PMI



- The multiplexing ensures that control and data information bits are mapped to different modulation symbols.
- The channel interleaving, together with resource mapping, is to ensure that
  - ➢ H-ARQ-ACK information is present on both slots in a subframe and
  - ➢ is mapped to the radio resource around the uplink demodulation reference signals.

UCI ON PUSCH WITHOUT UL-SCH DATA



- It is done in this way since the ***H-ARQ ACK/NAK bits are not transmitted with much protection*** and
  - placing them close to the reference signal ensures that they are decoded properly at the eNode-B.
- For this case, the channel coding for CQI, RI, and H-ARQ-ACK information is performed in the same manner as if the UCI is transmitted with UL-SCH data, and then the coded sequences are interleaved.
- The same interleaver is applied without the UL-SCH data.

MODULATION OF PUCCH

- When the UCI is transmitted on the PUSCH, the modulation scheme is determined by the scheduler in the MAC layer.
- The modulation scheme and the number of bits per subframe for different PUCCH formats are specified in Table
- All PUCCH formats use a cyclic shift of a based sequence to transmit in each SC-FDMA symbol, so UCI from multiple UEs can be transmitted on the same radio resource through code division multiplexing (CDM).

PUCCH Format	Modulation Scheme	M_{bit}
1	N/A	N/A
1a	BPSK	[illegible]
1b	QPSK	2
2	QPSK	20
2a	QPSK+BPSK	21
2b	QPSK+QPSK	22

Table 8.6 Modulation for Different PUCCH Formats

RESOURCE MAPPING

- PUCCH is never transmitted simultaneously with the PUSCH from the same UE, that is, the PUCCH is time-division multiplexed with the PUSCH from the same UE.
- This is done in order to retain the single-carrier property of SC-FDMA.
- ***However, the PUCCH can be frequency-division multiplexed with the PUSCH from other UEs in the same subframe.***
- For frame structure type 2 (the TDD mode), the PUCCH is not transmitted in the UpPTS field, which is only for the transmission of uplink sounding reference signals or random access.
- If the UE has not been assigned any uplink resource for the UL-SCH transmission, a certain set of uplink resources are assigned for the transmission of the PUCCH.
- The PUCCH uses one resource block in each of the two slots in a subframe.

MODULATION OF PUCCH

- The physical resource blocks to be used for PUCCH transmission in slot n_s are given by:

$$n_{PRB} = \begin{cases} \left\lfloor \frac{m}{2} \right\rfloor & \text{if } (m + n_s \bmod 2) \bmod 2 = 0 \\ N_{RB}^{UL} - 1 - \left\lfloor \frac{m}{2} \right\rfloor & \text{if } (m + n_s \bmod 2) \bmod 2 = 1 \end{cases}$$

  - where the parameter *m* depends on the PUCCH format.
- According to this rule, the mapping of PUCCH to physical resource blocks in one subframe is shown in Figure 8.7 for different values of *m*.
- We see that the ***PUCCH is transmitted at the bandwidth edge***, which is to provide the contiguous bandwidth in the middle for data transmission as only localized resource allocation is allowed in the uplink.
- In addition, the frequency hopping between different slots provides frequency diversity.
- The PUCCH symbols are mapped to resource elements not used for reference signal transmission.

MODULATION OF PUCCH

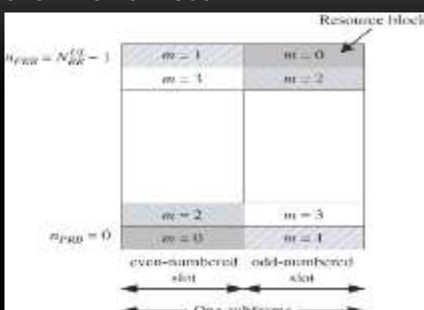
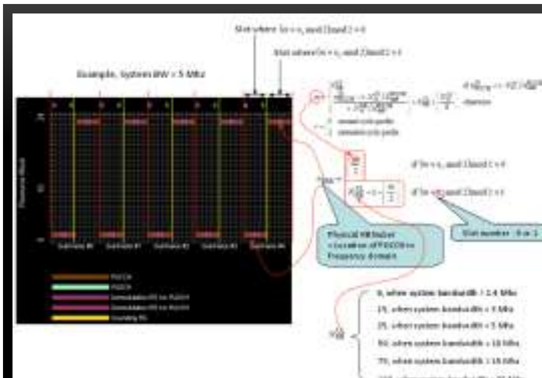
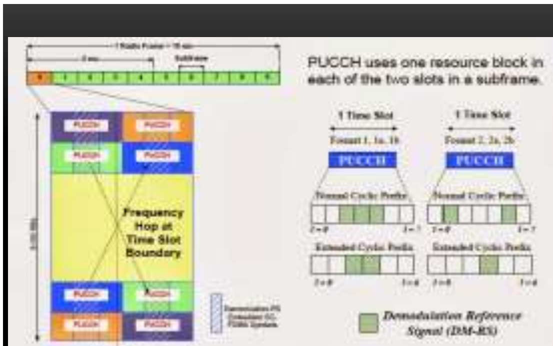


Figure 8.7 Mapping to physical resource blocks for PUCCH.





UPLINK REFERENCE SIGNALS

- In LTE there are two types of reference signals defined in the uplink:

1. **Demodulation reference signals**, which are transmitted on uplink resources assigned to the UE, are for coherent demodulation of data and control information at the eNode-B.
   - As PUCCH cannot be transmitted simultaneously with PUSCH
     - there are demodulation reference signals defined for each of them
       - that is, there are demodulation reference signals for PUSCH and demodulation reference signals for PUCCH.
2. **Sounding reference signals** are wideband reference signals for the eNode-B to measure uplink channel quality information for uplink resource allocation.
   - They are not associated with the transmission of PUSCH or PUCCH.

UPLINK REFERENCE SIGNALS...

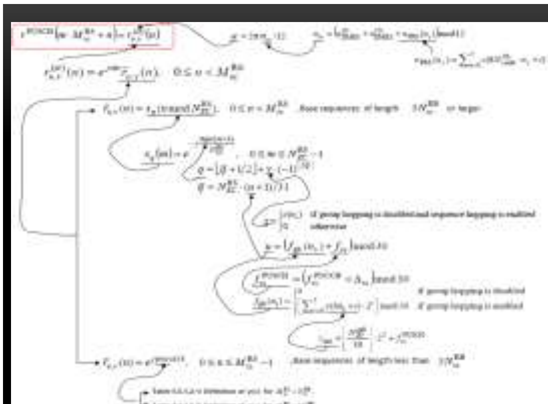
The *reason for having two types of reference signals* in the uplink:

- Unlike the downlink, the demodulation reference signals in uplink are only transmitted on subcarriers assigned to the UE and therefore *cannot provide sufficient wideband channel quality information* for resource allocation, particularly over the resource blocks that are not allocated to the UE.
- Unlike the downlink, the reference signal in the uplink cannot be transmitted at the same time as user data.
- Instead, the uplink reference signals are time-division multiplexed with the uplink data on the assigned subcarriers.
- In this way, the *power level of the reference signal can be different from that of the data symbol* as they are transmitted over different SC-FDMA symbols, so the PAPR is minimized over each SC-FDMA symbol.

REFERENCE SIGNAL SEQUENCE

- Both the *demodulation reference signal* and the *sounding reference signal* are *defined by a cyclic shift of the same base sequence*.
- The generation of the base sequence depends on the reference signal sequence length which is $M_{sc}^{RS} = mN_{sc}^{RB}$ with $1 \le m \le N_{RB}^{max,UL}$, where *m* is the size of the resource blocks assigned to the UE.
  - • If $m \geq 3$ (the UE is assigned three resource blocks or more), the base sequence is based on prime-length Zadoff-Chu sequences that are cyclically extended to the desired length.
  - • For $m = 1$ or $m = 2$, the base sequence is of the form $e^{j\varphi(n)\pi/4}$
- Multiple reference signals can then be created by different shifts of the same base sequence.

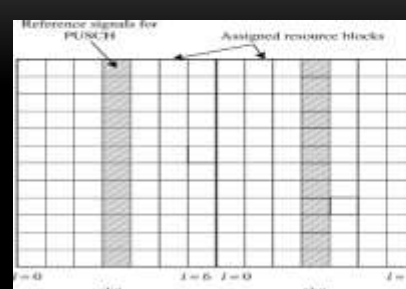
- Generating the DMRS is not that simple. Big picture is simple since PUSCH DMRS is also a kind of Zadoff - Chu Sequence.
- But there are so many parameters being used to create a specific Zadoff-Chu sequence for a specific case
- It would be hard to grasp the meaning of each parameters unless you implement this algorithm on your own, but just taking a brief look-at of these equations would give you the idea on what kind of factors are involved in this sequence generation.



RESOURCE MAPPING OF DEMODULATION REFERENCE SIGNALS

- The resource mapping of the demodulation reference signal is different for PUSCH and PUCCH channels.
- In addition, different from the downlink, *the reference signals are inserted in the time domain, which is to preserve the low PAPR property of SC-FDMA.*
- For PUSCH, the demodulation reference signal sequence is mapped to resource elements (*k, l*) with *l* = 3 for normal CP and *l* = 2 for extended CP, with increasing order first in *k* and then in the slot number.
- An example of demodulation reference signal mapping for PUSCH is shown in Figure 8.8, with the normal CP.

RESOURCE MAPPING OF DEMODULATION REFERENCE SIGNALS

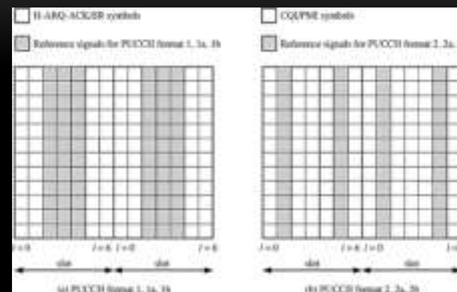


- Resource mapping of demodulation reference signals for PUSCH with the normal CP.

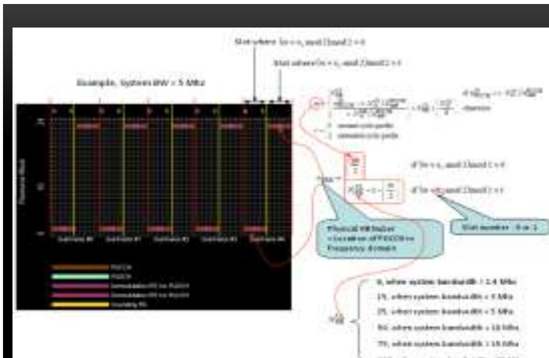
RESOURCE MAPPING OF SOUNDING REFERENCE SIGNALS

- For the ***FDD mode***, the ***sounding reference signal is transmitted in the last SC-FDMA symbol*** in the specified subframe.
- For the ***TDD mode***, the ***sounding reference signal is transmitted only in configured uplink subframes*** or ***the UpPTS field in the special subframe***.
- The subframes in which the sounding reference signals are transmitted are indicated by the ***broadcast signalling***, and there are 15 different configurations.
- In the frequency domain, the mapping starts from the position k_0, which is determined by system parameters, and fills every other subcarrier.
- The bandwidth of sounding reference signals is configured by higher layers and also depends on the system bandwidth.

RESOURCE MAPPING OF SOUNDING REFERENCE SIGNALS



- **Figure** An example of resource mapping of sounding reference signals, with the normal CP.



RESOURCE MAPPING OF SOUNDING REFERENCE SIGNALS

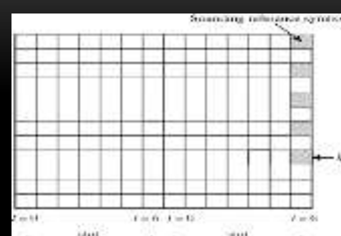


Figure: Resource mapping of demodulation reference signals for PUCCH with the normal CP.

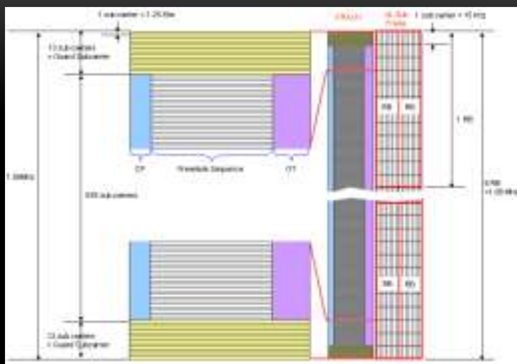
- By allocating every other subcarrier to a UE for the sounding reference signal, the system allows two UEs to use the same resource for sounding.
- The second UE uses the subcarriers not used by the first UE.

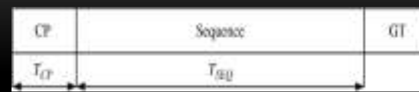
RACH

- RACH stands for Random Access Channel.
- This is the first message from UE to eNB when you power it on.
- Even though they use a little bit different name, in all cellular technology (CDMA, GSM, WCDMA, LTE) there is a specific signal that perform the same function.

RANDOM ACCESS CHANNELS

- The uplink random access procedure is used during initial access or to re-establish uplink synchronization.
- the random access preamble consists of a CP of length T_{CP} and a sequence part of length T_{SEQ}.
- As uplink synchronization may not be established prior to the random access procedure, a Guard Time (GT) is also needed to account for the round trip propagation delay between the UE and the eNode-B.
- The values of T_{CP} and T_{SEQ} depend on the cell size and base station implementation. There are five different preamble formats defined in LTE, specified in Table, where T_s = 1/(15000 × 2048) sec.
- Format 0 is for normal cells; format 1, also known as the extended format, is used for large cells; format 2 and format 3 use repeated preamble sequences to compensate for increased path loss, and are used for small cells and large cells, respectively; format 4 is defined for frame structure type 2 only.





- **Figure 8.11** The random access preamble format.
- **Table 8.10** Random Access Preamble Parameters

Preamble Format	T_{CP}	T_{SEQ}
0	$3168 \cdot T_s$	$24576 \cdot T_s$
1	$21024 \cdot T_s$	$24576 \cdot T_s$
2	$6240 \cdot T_s$	$2 \cdot 24576 \cdot T_s$
3	$21024 \cdot T_s$	$2 \cdot 24576 \cdot T_s$
4	$448 \cdot T_s$	$4096 \cdot T_s$

RANDOM ACCESS PREAMBLES

- The random access preambles are generated from ***Zadoff-Chu sequences***, which are similar to reference signals.
- The network configures the set of preamble sequences that the UE is allowed to use.
- In each cell, there are 64 available preambles, which are generated from one or several root Zadoff-Chu sequences.
- Due to the zero cross-correlation between different cyclic shifts of the same Zadoff-Chu sequence, there is no intra-cell interference from multiple random access attempts using different preambles in the same cell.

PHYSICAL RANDOM ACCESS CHANNEL (PRACH)

- The transmission of a random access preamble is restricted to certain time and frequency resources.
- The Physical Random Access Channel (PRACH) resources within a radio frame are indicated by a PRACH configuration index, which is given by higher layers.
- For frame structure type 1 with preamble format 0–3, there is at most one random access resource per subframe;
- for frame structure type 2 with preamble format 0–4, there might be multiple random access resources in an uplink subframe depending on the uplink/downlink configuration.

PHYSICAL RANDOM ACCESS CHANNEL (PRACH)

- In the frequency domain, the random access burst occupies a bandwidth corresponding to six consecutive resource blocks (72 subcarriers) in a subframe or a set of consecutive subframes.
- The PRACH uses a different subcarrier spacing (Δf_{RA}) than other physical channels, which is listed in Table 8.11 together with the preamble sequence length N_{ZC}.
- Note that the data symbol subcarrier spacing Δf= 15kHz is an integer multiple of the PRACH subcarrier spacing Δf_{RA}.
- This is to minimize the orthogonality loss in the frequency domain and can also reuse the IFFT/FFT component.

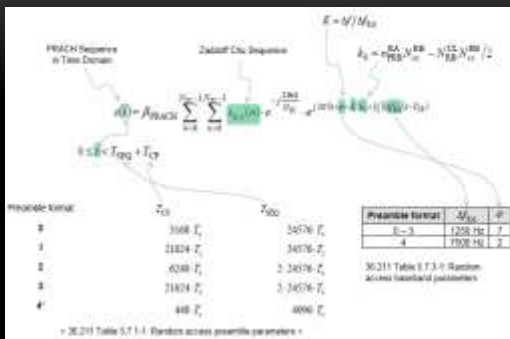
PHYSICAL RANDOM ACCESS CHANNEL (PRACH)

- **Table 8.11** Parameters for Random Access Preamble

Preamble Format	Δf_{RA}	N_{ZC}	φ
0–3	1.25 kHz	839	7
4	7.5 kHz	139	2

- The baseband signal generation for the PRACH is different from other uplink physical channels, and no DFT-based precoding is applied, as the DFT of a Zadoff-Chu sequence is also a Zadoff-Chu sequence.
- The continuous-time random access signal is defined by:

$$s(t) = \beta \sum_{k=0}^{N_{ZC}-1} \sum_{n=0}^{N_{ZC}-1} x_{u,v}(n) \cdot e^{-j\frac{2\pi nk}{N_{ZC}}} \cdot e^{j2\pi(k+\varphi+K(k_0+1/2))\Delta f_{RA}(t-T_{CP})}$$



- where $0 \le t \le (T_{SEQ} + T_{CP})$ and:
- • β is an amplitude scaling factor for power control;
- • $x_{u,v}(n)$ is the uth root Zadoff-Chu sequence with cyclic shift v;
- • φ is a fixed offset determining the frequency-domain location of the random preamble within the physical resource blocks, given in Table 8.11;
- • $K = \Delta f/\Delta f_{RA}$ accounts for the difference in subcarrier spacing between the random access preamble and uplink data transmission;
- • controls the random access preamble location in the frequency domain, with as the physical resource block number configured by higher layers.

DIFFERENCE BETWEEN ARQ AND HARQ

- ARQ:
  - Works at RLC layer
  - If the received data has an error (as detected by ARQ) then it is discarded, and a new re-transmission is requested from the sender
- HARQ:
  - Works at PHY layer but controlled by MAC layer
  - If the received data has an error then the Receiver buffers the data and requests a re-transmission from the sender.
  - When the receiver receives the re-transmitted data, it then combines it with buffered data prior to channel decoding and error detection. This helps the performance of the re-transmissions.

HARQ

- Two Types of HARQ
  - Synchronous for UL
  - Asynchronous for DL

H-ARQ IN THE UPLINK

- The H-ARQ retransmission protocol is also used in the LTE uplink, so the ***eNode-B has the capability to request retransmissions*** of incorrectly received data packets.
- For the uplink H-ARQ process, the corresponding ACK/NAK information is carried on the ***PHICH*** (Physical channel H-ARQ Indicator Channel).
- LTE uplink applies the ***synchronous H-ARQ protocol***, that is,
  - ➢ The retransmissions are scheduled on a ***periodic interval*** unlike downlink where the scheduler determines the timing of retransmissions.

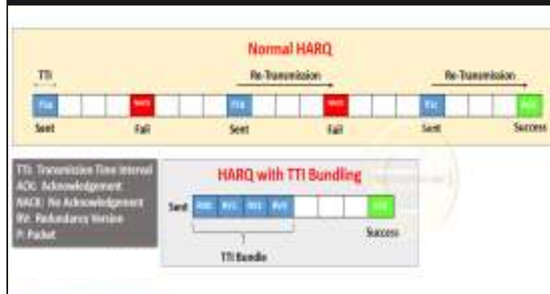
H-ARQ IN THE UPLINK

- Synchronous retransmission is preferred in the uplink because
  - ➢ ***it does not require to explicitly signal the H-ARQ process number*** so there is **less protocol overhead**.
- The number of H-ARQ processes and the time interval between the transmission and retransmission ***depend on the duplexing mode*** and the H-ARQ operation type

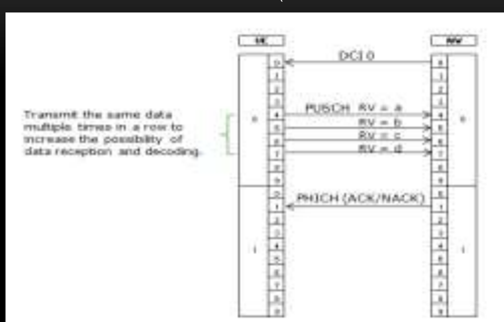
H-ARQ IN THE UPLINK…

- There are *two types of H-ARQ operation in the uplink*:
  1. The *non-subframe bundling* operation (***normal H-ARQ operation***), and
  2. The *subframe bundling* operation (***also called TTI bundling***), in which four redundancy versions are transmitted over four consecutive uplink subframes.
     - Same as *sending four H-ARQ retransmissions back to back* without waiting for the H-ARQ ACK/NAK feedback.
     - When TTI bundling is used, the eNode-B waits for four TTIs to receive and decode the four redundancy versions jointly before sending an H-ARQ ACK/NAK over the PHICH in the downlink.
- Similar to the downlink, the N-channel Stop-and-Wait protocol is used in the uplink.

H-ARQ IN THE UPLINK…

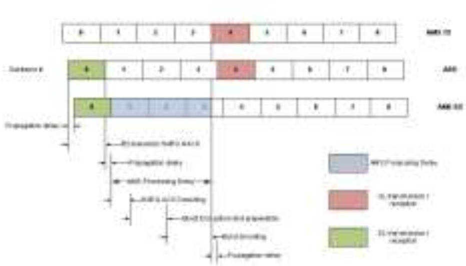


H-ARQ IN THE UPLINK…
SUBFRAME BUNDLING OPERATION (ALSO CALLED *TTI BUNDLING*)



- HARQ is a process where receiver combines the new transmission every time with previous erroneous data.
- There is one drawback however, that it can result in delay and too much control overhead in case of poor radio conditions if the sender has to attempt many transmissions.
- For services like VoIP this means bad end user experience.
- Well, there is another way- Instead of re-transmitting the erroneous data with new set of coded bits, why not send few versions (redundancy versions) of the same set of bits in consecutive TTI and eNB sends back Ack when it successfully decodes the bits

FDD UL HARQ Retransmission



THE TDD MODE

- For the TDD mode, the number of H-ARQ processes is determined by the DL/UL configuration
- For TDD UL/DL configurations 1–6 and the normal H-ARQ operation, upon detection of an NAK in subframe *n*, the UE retransmits in subframe *n* + *k*, with *k* given in Table
- For TDD UL/DL configuration 0 and the normal H-ARQ operation, upon detection of an NAK in subframe *n*, the UE will retransmit in subframe *n* + 7 or *n* + *k* with *k* given in Table 8.13, which depends on the UL index field in DCI and the value of *n*.
- TABLE: Number of Synchronous UL H-ARQ Processes for TDD

TDD UL/DL Configuration	Number of H-ARQ Processes for Normal H-ARQ Operation	Number of H-ARQ Processes for Subframe Bundling Operation
0	7	3
1	4	2
2	2	N/A
3	3	N/A
4	2	N/A
5	1	N/A
6	6	3

THE TDD MODE

- For TDD UL/DL configurations 1 and 6 with subframe bundling, upon detection of an NAK in subframe $n - l$ with l given in Table 8.14, the UE retransmits the corresponding first PUSCH transmission in the bundle in subframe $n + k$, with k given in Table 8.13.
- For TDD UL/DL configuration 0 and the subframe bundling operation, upon detection of an NAK in subframe $n - l$ with l given in Table 8.14, the UE retransmits in subframe $n + 7$ or $n + k$ with k given in Table 8.13, depending on the UL index field in DCI and the value of n.
- **Table** The Value of k for TDD Configurations 0–6

TDD UL/DL Configuration	DL Subframe Number n									
	0	1	2	3	4	5	6	7	8	9
0	4	6				4	6			
1		6			4		6			4
2				4					4	
3	4								4	4
4									4	4
5									4	
6	7	7				7	7			5

- **Table** The Value of l for TDD Configurations 0, 1, and 6

TDD UL/DL Configuration	DL Subframe Number n									
	0	1	2	3	4	5	6	7	8	9
0	9	6				9	6			
1		2			3		2			3
6	5	5				6	6			8

Physical Layer Procedures and Scheduling

MODULE 4, PART 2 OF 2

HYBRID-ARQ FEEDBACK

- ***H-ARQ protocol*** is applied to ***improve the transmission reliability*** over the wireless channel.
- The LTE ***downlink*** employs the ***asynchronous adaptive H-ARQ protocol***
  - ➢ Retransmissions are scheduled in a similar fashion to the first transmission,
  - ✓ i.e., the ***TTI and resource allocation*** for the retransmission is ***dynamically determined by the scheduler***.

HYBRID-ARQ FEEDBACK

- In the ***uplink***, ***synchronous adaptive H-ARQ protocol*** is used,
  - ➢ for which the retransmissions are automatically scheduled after a certain time window and the UE does not need to send the H-ARQ process number.
- This reduces the amount of signalling overhead in the uplink.
- With different frame structures, the H-ARQ feedback is different for FDD and TDD modes.

H-ARQ FEEDBACK FOR DOWNLINK (DL) TRANSMISSION

- ***UEs need to feed back*** the associated ACK/NAK information on PUCCH or PUSCH for ***H-ARQ transmissions in the downlink***.
- One ACK/NAK bit is transmitted in case of single-codeword downlink transmission, while two ACK/NAK bits are transmitted in case of two-codeword downlink transmission.
- For ***two-codeword transmission***, ***codeword swap is enabled by a 1-bit transport block to codeword swap flag***
  - which allows both codewords to experience similar channel conditions after H-ARQ retransmission when the channel is static or experiences little or no variation between subsequent H-ARQ transmissions.

CHANNEL QUALITY INDICATOR (CQI) FEEDBACK

- The Channel Quality Indicator (*CQI*) *contains information* sent from a UE to the eNode-B *to indicate a suitable downlink transmission data rate*,
  - i.e., a Modulation and Coding Scheme (MCS) value.
- CQI is a 4-bit integer and is based on the observed signal-to-interference-plus-noise ratio (SINR) at the UE.
- The *CQI estimation process takes into account the UE capability* such as the number of antennas and the type of receiver used for detection.

WIDEBAND AND SUBBAND CQI REPORTING

- *A wideband CQI value is a single 4-bit integer* that *represents an effective SINR* as observed by the UE over the entire channel bandwidth.
  - With wideband CQI, the variation in the SINR across the channel due to *frequency selective nature of the channel is masked out*.
- Therefore, *frequency selective scheduling* where a UE is placed only in resource blocks with high SINR is *not possible with wideband CQI reporting*.
- To support *frequency selective scheduling*, each UE needs to report the CQI with a fine frequency granularity, which is possible with *subband CQI reporting*.

WIDEBAND AND SUBBAND CQI REPORTING

- A *subband CQI report consists of a vector of CQI values* where each CQI value is representative of the SINR observed by the UE over a subband.
- A *subband* is a *collection of n-adjacent Physical Resource Blocks* (PRBs)
  - where the value of *n* can be 2, 3, 4, 6, or 8 depending on the channel bandwidth and the CQI feedback mode.

CQI FEEDBACK MODES

- CQI is reported with other uplink control information including Precoder Matrix Indicator (PMI) and Rank Indicator (RI) on PUSCH or PUCCH.
- The reporting of CQI, PMI, and RI in the time domain can be categorized into two classes:

1. *Periodic reporting*: The UE reports CQI, PMI, and RI with reporting periods configured by the higher layer on the PUCCH.
   - If the UE is scheduled in the uplink, the periodic reporting is carried on PUSCH.
2. *Aperiodic reporting*: The UE reports CQI, PMI, and RI using the PUSCH upon receiving either a DCI format 0 or a random access response grant.
   - Feedback via PUSCH can be used to provide large and more detailed reporting in a single reporting instance compared to the periodic feedback.

APERIODIC REPORTING

- In LTE there are two distinct reporting mechanisms for subband CQI feedback when the aperiodic reporting mode is used:
- *Higher Layer Configured Subband Report:* In this case, the UE reports the subband CQI for each band in a single feedback report.
  - The size of a band is specified by a higher layer message and is contingent on the system bandwidth.
- *UE Selected Subband Report*: In this case, the UE reports the subband CQI for the 'M' bands with the highest CQI values.
  - The CQI for the rest of the bands is not reported.
  - In this case, the value of *M* and the size of a band is given by a higher layer message and is also contingent on the system bandwidth.

UPLINK CHANNEL SOUNDING

- Channel sounding is *mainly used for uplink channel quality measurement* at the eNode-B.
- The *Sounding Reference Symbol (SRS)* is transmitted by the UE in the uplink for the eNode-B *to estimate the channel state information*, which includes the MIMO channel of the desired signal, SINR, noise, interference level, etc.
- The SRS can also be used for *uplink timing estimation* and *uplink power control*.
- The SRS transmission is always in the last SC-FDMA symbol in the configured subframe, on which PUSCH data transmission is not allowed.
- The eNode-B can either request an individual SRS transmission from a UE or configure a UE to periodically transmit SRS.
- The periodicity may take any value of 2, 5, 10, 20, 40, 80, 160, and 320 ms.

THE UE-SPECIFIC SRS PARAMETERS

- The UE-specific SRS parameters include:
  - i. *The **starting** physical resource block **assignment***
  - ii. *Duration of SRS transmission*
  - iii. *SRS periodicity and SRS subframe offset*
  - iv. *SRS bandwidth, frequency hopping bandwidth*
  - v. *Cyclic shift.*
- These parameters are ***semi-statically configured*** by higher layers.

THE UE-SPECIFIC SRS PARAMETERS

- A UE ***shall not transmit*** SRS in the following ***scenarios***:
  - • If ***SRS*** and ***PUCCH format 2/2a/2b*** transmissions happen to ***coincide in the same subframe***
  - • Whenever ***SRS*** and ***ACK/NAK*** and/or ***positive SR transmissions*** happen to ***coincide in the same subframe*** unless the parameter *Simultaneous-AN-and-SRS* is TRUE
- If the UE is equipped with ***two transmit antennas***, then ***it alternates between two-antennas*** every time the SRS is transmitted.
- This allows the eNode-B to select the transmit antenna if the closed-loop antenna selection is enabled.

BUFFER STATUS REPORTING IN UPLINK

- A ***Buffer Status Report (BSR)*** is sent from the UE to the serving eNode-B ***to provide information about the amount of pending data*** in the **uplink buffer** of the UE.
- The buffer status, along with other information, such as priorities allocated to different logical channels, is useful for
  - ➢ the uplink scheduling process to ***determine which UEs*** or ***logical channels*** should be ***granted radio resources*** at a ***given time***.

BUFFER STATUS REPORTING IN UPLINK

A **BSR** is ***triggered*** if any of the following events occurs:

1. Uplink data for a logical channel becomes available for transmission, and
   - Either the data belongs to a logical channel with higher priority than the priorities of the logical channels for which data is already available for transmission,
   - or there is no data available for transmission for any of the logical channels.
   - ➢ In this case, the **BSR** is referred to as "***regular BSR***."
2. Uplink resources are allocated and the number of padding bits is equal to or larger than the size of the BSR MAC control element, in which case the **BSR** is referred to as "***padding BSR***."

BUFFER STATUS REPORTING IN UPLINK…

3. • A serving cell change occurs, in which case the **BSR** is referred to as "**regular BSR**."
4. • The retransmission **BSR** timer expires and the UE has data available for transmission, in which case the **BSR** is referred to as "**regular BSR**."
5. • The periodic BSR timer expires, in which case the **BSR** is referred to as "***periodic BSR***."

SCHEDULING AND RESOURCE ALLOCATION

- The main purpose of scheduling and resource allocation is to efficiently allocate the available radio resources to UEs to
  - ➢ optimize a certain performance metric with QoS requirement constraints

Scheduling algorithms for LTE can be divided into two categories:

1. • ***Channel-dependent scheduling***: The allocation of resource blocks to a UE is based on the channel condition, *e.g., proportional fairness scheduler, max CI (Carrier to Interference) scheduler, etc.*
2. • ***Channel-independent scheduling***: The allocation of resource blocks to a UE is random and not based on channel condition, *e.g., round-robin scheduler*

CHANNEL-DEPENDENT SCHEDULING

- In a multicarrier system such as LTE, ***channel-dependent scheduling*** can be further ***divided into two categories***:

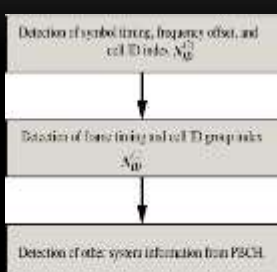
I. ***Frequency diverse scheduling:*** The UE selection is based on wideband CQI.
- However, the PRB allocation in the frequency domain is random.
- It can exploit time selectivity and frequency diversity of the channel.

II. ***Frequency selective scheduling:*** The UE selection is based on both wideband and subband CQI, and the PRB allocation is based on the subband CQI.
- This can exploit both time and frequency selectivity of the channel.

CELL SEARCH

- When a ***UE powers on***,
  - it needs to ***acquire time and frequency synchronization*** with a cell and
  - ***detect the physical-layer cell ID*** of that cell through the cell search procedure or synchronization procedure.
- Such synchronization is especially important for LTE,
  - as the performance of LTE systems relies on the orthogonal intra-cell transmission in both uplink and downlink.
- During cell search, different types of information need to be identified by the UE, including:
  - symbol and frame timing, frequency, cell identification,
  - transmission bandwidth, antenna configuration
  - the cyclic prefix length.

CELL SEARCH



CELL SEARCH

- After the cell search, the UE can detect the broadcast channel to obtain other physical layer information,
  - e.g., system bandwidth, number of transmit antennas, and system frame number.
- The system information is divided into ***Master Information Block (MIB) transmitted on the PBCH*** and ***System Information Blocks (SIB) transmitted on the PDSCH***.
- At this stage, the UE detects MIB from the PBCH.

TIMING ADVANCE PROCEDURE

- To maintain the uplink intra-cell orthogonality:
  - ***uplink transmissions from different UEs should arrive*** at the eNode-B ***within a cyclic prefix***.
- This is achieved through the *timing advance* procedure.
- The timing advance is obtained from the uplink received timing and sent by the eNode-B to the UE.
- The ***UE advances or delays its timing of transmissions*** to ***compensate for propagation delay*** and thus time-aligns its transmissions with other UEs.
- The timing advance command is on a per-need basis with a ***granularity in the step size of 0.52μs (16 × T_s)***.

RANDOM ACCESS PROCEDURES

In LTE, there are two random access mechanisms:

1. • ***Non-synchronized random access***: Non-synchronized random access is used when the UE uplink has not been time synchronized, or when the UE uplink loses synchronization.
   - Its main purpose is
     - to obtain synchronization of the uplink
     - notify the eNode-B that the UE has data to transmit, or
     - transmit a small amount of control information and data packets.
2. • ***Synchronized random access***: Synchronized random access is used when uplink synchronization is present.
   - Its main purpose is to request resources for uplink data transmission from the eNode-B scheduler.

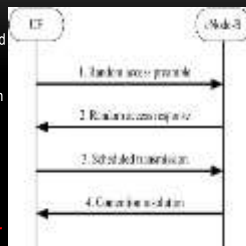
NON-SYNCHRONIZED RANDOM ACCESS PROCEDURE

1. First, multiple ***UEs transmit*** randomly selected ***random access code***.

2. Second, eNode-B conducts a multiuser detection process and ***allocates resources*** to the detected UEs.

3. Third, each ***UE transmits detailed information*** using allocated resources.

4. Fourth, the ***eNode-B transmits the contention-resolution*** message on the DL-SCH. .



When the previous steps are finished successfully, eNode-B and each UE initiate data communication

POWER CONTROL IN UPLINK

- With SC-FDMA-based transmission in the LTE uplink, orthogonality between intra-cell transmission from multiple UEs is achieved, which removes
  - the ***intra-cell interference*** and
  - the ***near-far issue*** typical of CDMA-based systems such as W-CDMA/HSPA.
- This leaves ***inter-cell interference*** as the major cause of interference and performance degradation, especially for the ***cell-edge UEs***.
- In LTE, the ***power control*** in the uplink ***is to control the interference caused by UEs*** to ***neighbouring cells*** while ***maintaining the required SINR at the serving cell***.

POWER CONTROL IN UPLINK

- ***Conventional power control*** in the uplink is ***to achieve the same SINR*** for different UEs at the base station, also known as ***full compensation***
  - But it suffers low spectral efficiency as the common SINR is limited by the cell-edge UEs.
- LTE specifies ***Fractional Power Control (FPC)*** as the open-loop power control scheme, which allows for full or partial compensation of path loss and shadowing.
- FPC allows the ***UEs with higher path loss***, i.e., cell-edge UEs,
  - to operate with lower SINR requirements so that they generate less interference to other cells,
  - while having a minor impact on the cell-interior UEs so that they are able to transmit at higher data rates.

POWER CONTROL IN UPLINK

- Besides open-loop power control, there is also a closed-loop power control component
  - which is to further adjust the UE transmission power to optimize the system performance.
- the FPC scheme, based on which the UE adjusts the transmission power according to:

$$P = \min\{P_{max}, 10\log M + P_0 + \alpha \cdot PL\} \text{ [dBm]},$$

END OF MODULE 4