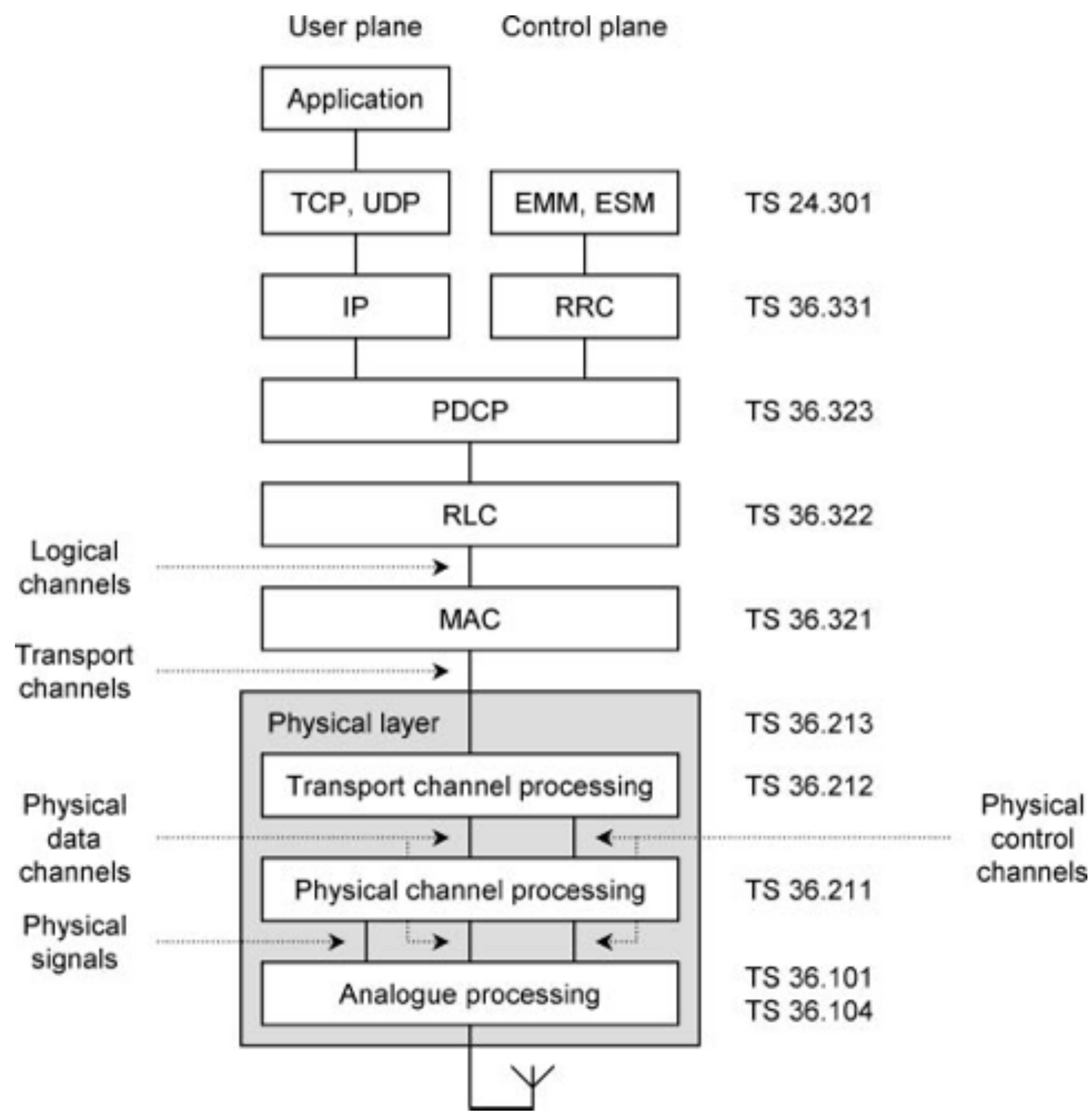
Architecture of the LTE Air Interface

- 1. Air Interface Protocol Stack
- 2. Logical, Transport and Physical Channels
- 3. The Resource Grid
- 4. Multiple Antenna Transmission
- 5. Resource Element Mapping

1. Air Interface Protocol Stack

- Figure 6.1
  - ✓ The protocols used in the <u>air interface</u>, from the viewpoint of the <u>mobile</u>



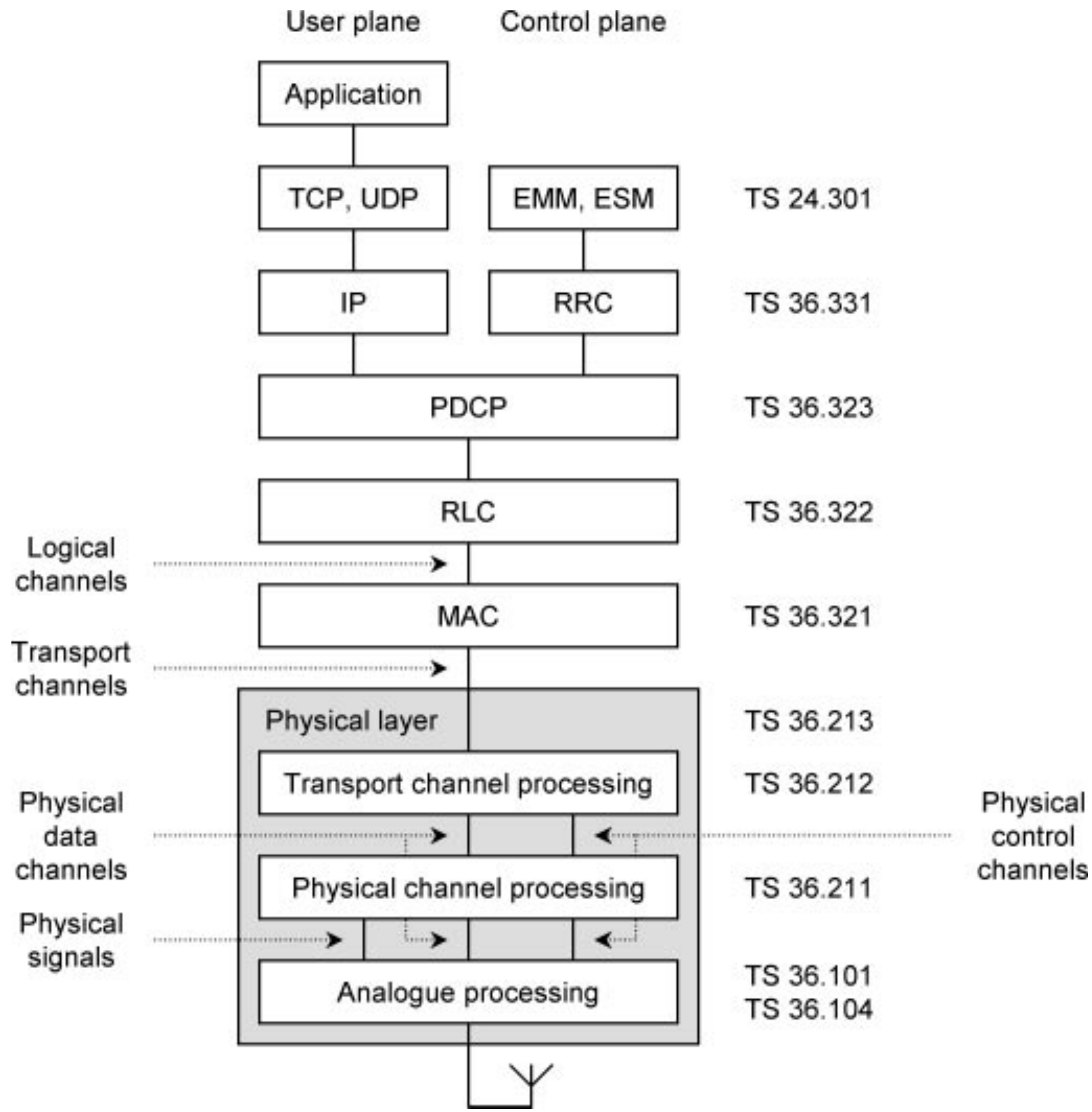
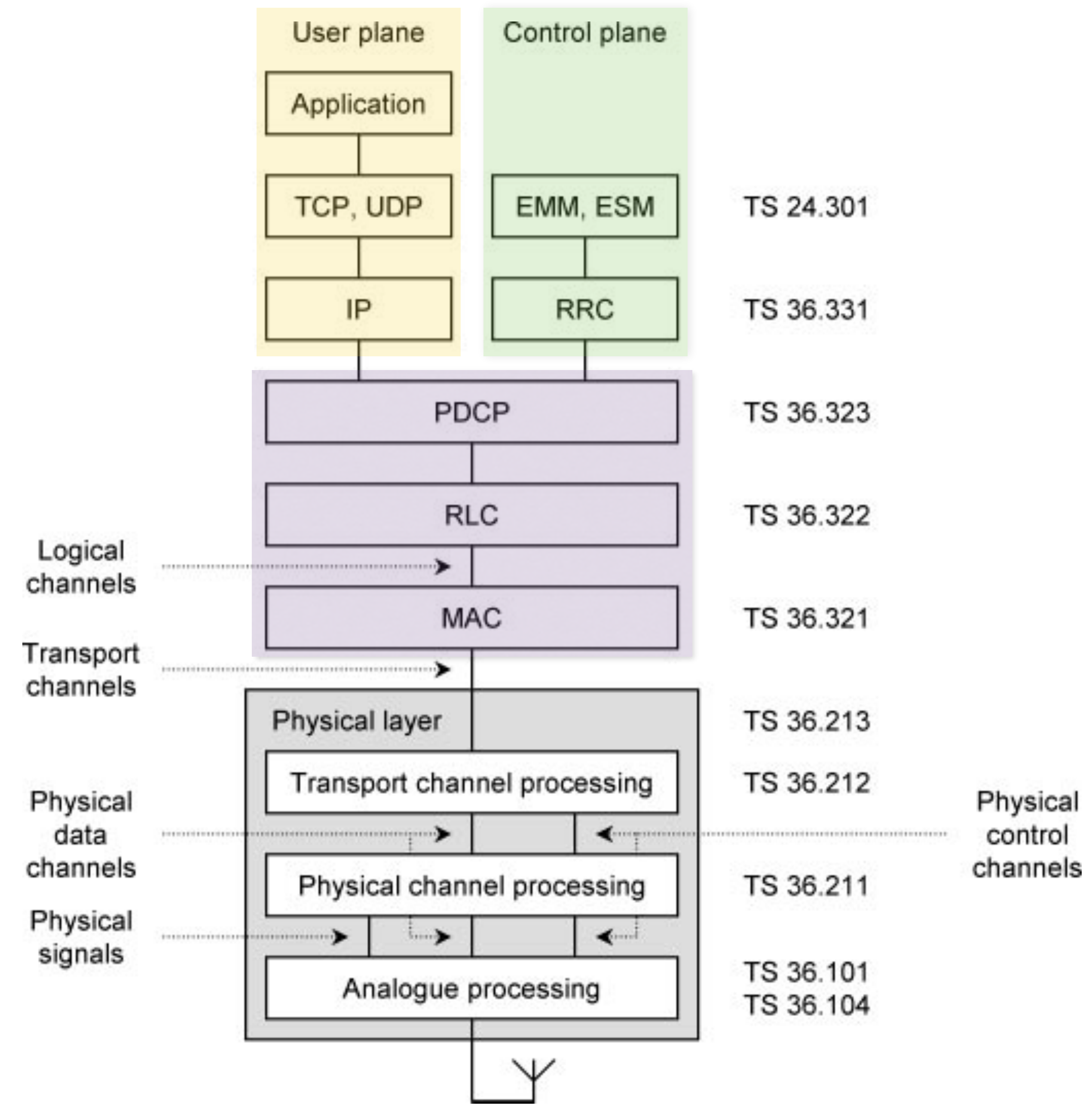
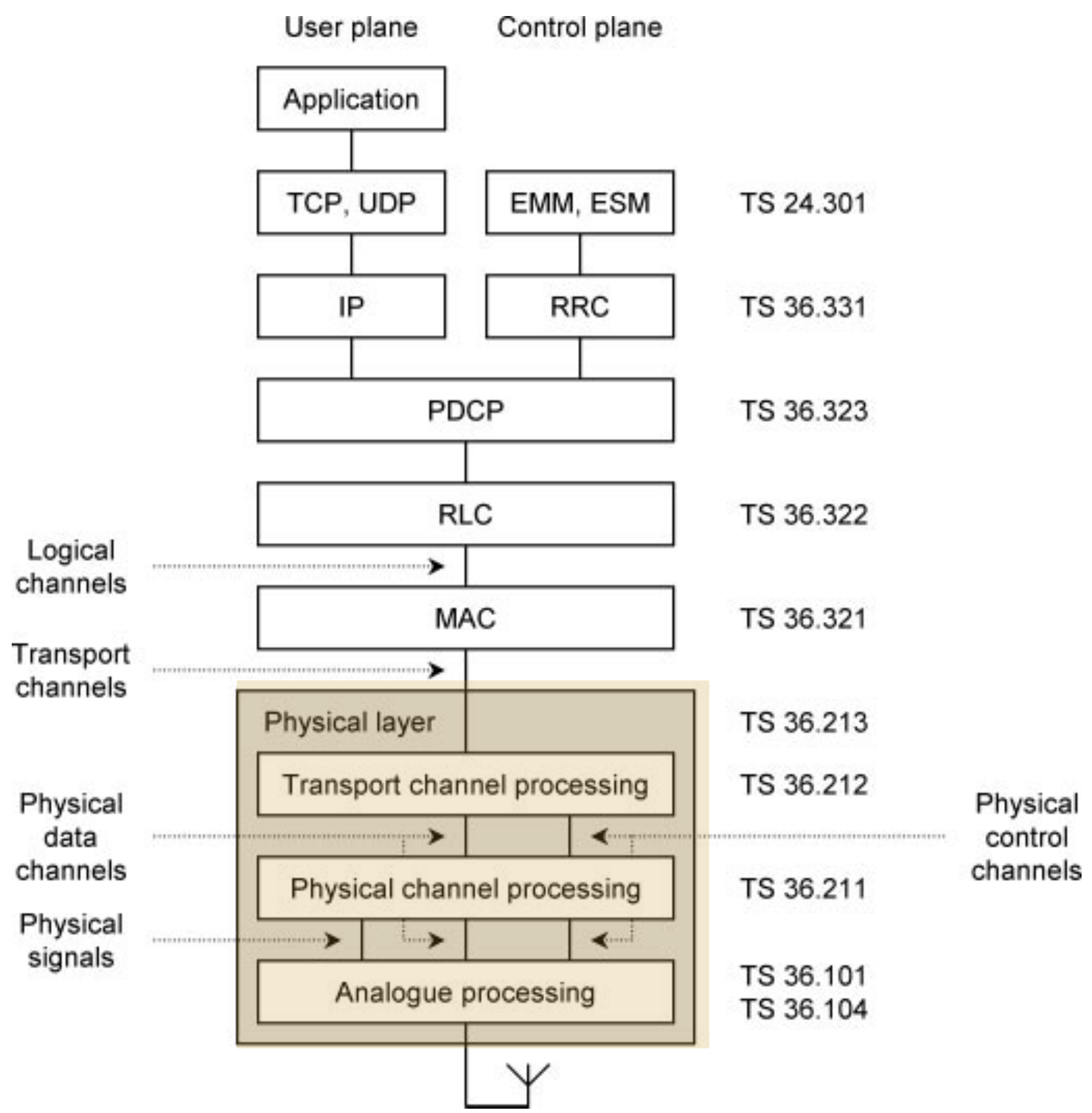


Figure 6.1 Architecture of the air interface protocol stack.

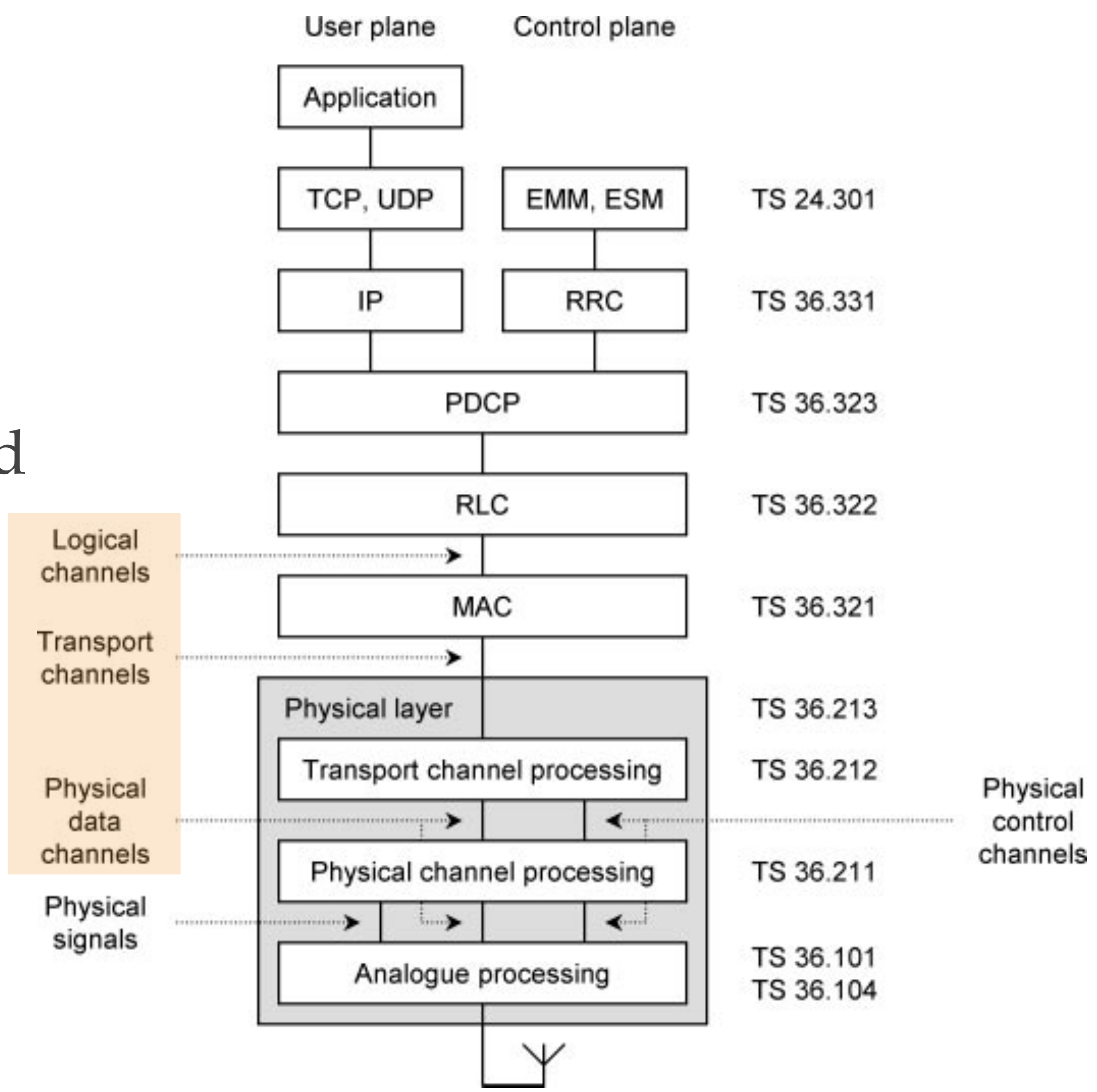
- As a transmitter
  - ✓ User plane
    - The <u>application</u> creates <u>data packets</u> that are processed by protocols such as TCP, UDP and IP
  - ✓ Control plane
    - Radio Resource Control (RRC) protocol <u>writes</u> the <u>signaling messages</u> that are <u>exchanged</u> between BS and mobile
  - ✓ In both cases, the information is processed by the following protocols before being passed to the <u>physical layer</u> for transmission
    - Packet Data Convergence Protocol (<u>PDCP</u>)
    - Radio Link Control (<u>RLC</u>) protocol
    - Medium Access Control (<u>MAC</u>) protocol



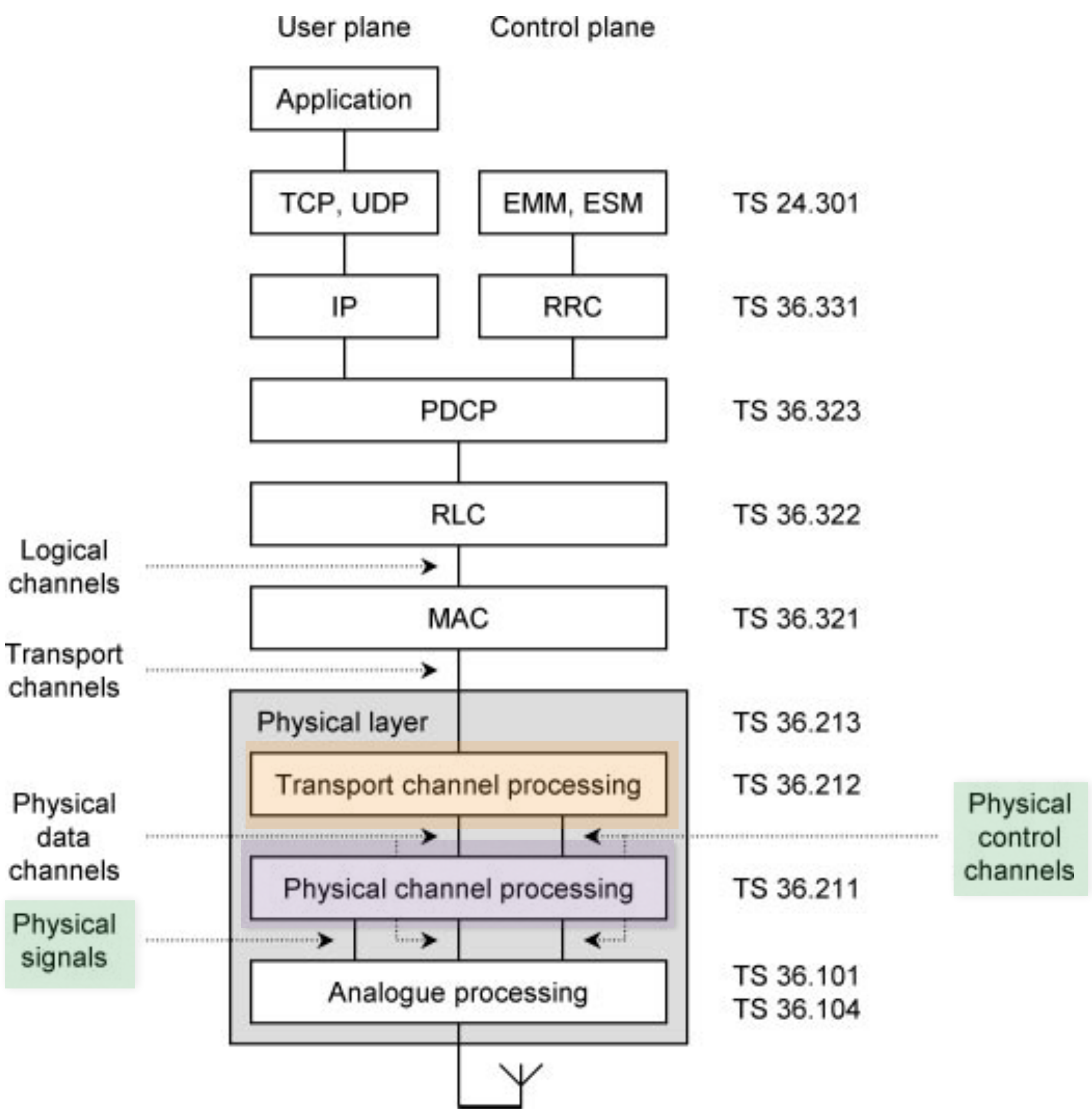
- Physical layer has three parts
  - ✓ Transport channel processor
    - Applies error management procedures
  - ✓ Physical channel processor
    - Applies the techniques of OFDMA, SC-FDMA and multiple antenna transmission
  - ✓ Analogue processor
    - Converts the information to analogue form
    - Filters it
    - Mixes it up to radio frequency for transmission



- The information flows between different protocols are known as channels and signals
- Data and signaling messages are carried on
  - ✓ Logical channels between RLC and MAC protocols
  - ✓ Transport channels between MAC and physical layer
  - ✓ Physical data channels between different levels of the physical layer
- LTE uses several different types of logical, transport and physical channel, which are distinguished by the kind of information they carry and by the way in which the information is processed



- In the transmitter
  - ✓ Transport channel processor
    - Creates control information that supports the low-level operation of physical layer
    - Sends this information to the physical channel processor in the form of physical control channels
    - The information travels as far as the transport channel processor in the receiver, but is completely invisible to higher layers
  - ✓ Physical channel processor
    - Creates physical signals, which support the lowest-level aspects of the system
    - These travel as far as the physical channel processor in the receiver, but once again are invisible to higher layers



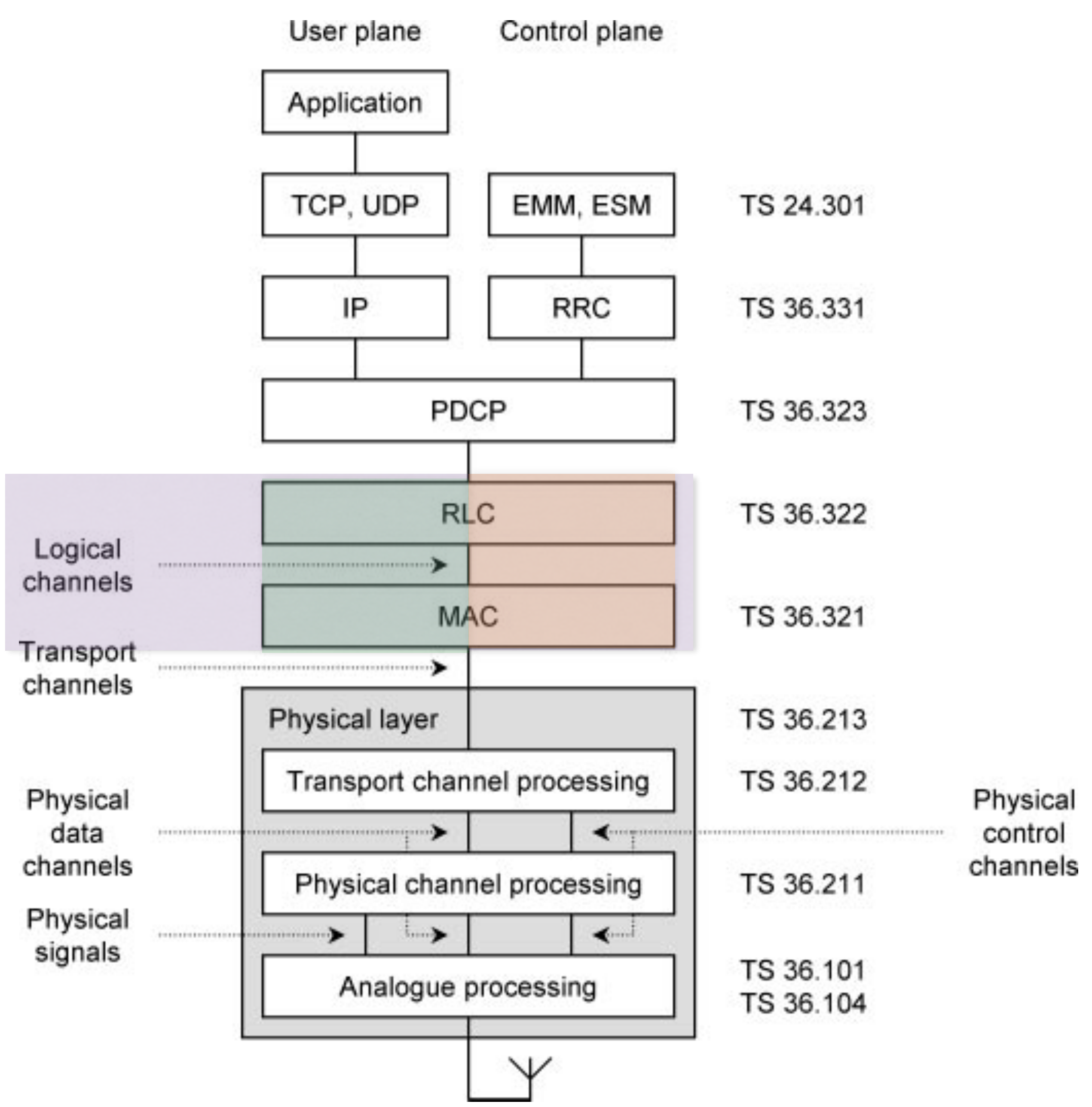
- 1. Air Interface Protocol Stack
- 2. Logical, Transport and Physical Channels
- 3. The Resource Grid
- 4. Multiple Antenna Transmission
- 5. Resource Element Mapping

2. Logical, Transport and Physical Channels

- 2.1 Logical Channels
- 2.2 Transport Channels
- 2.3 Physical Data Channels
- 2.4 Control Information
- 2.5 Physical Control Channels
- 2.6 Physical Signals
- 2.7 Information Flows

2.1 Logical Channels

- Logical channels are distinguished by the information they carry and can be classified in two ways
  - ✓ 1st
    - Logical traffic channels carry data in the user plane
    - Logical control channels carry signaling messages in the control plane
  - ✓ 2nd
    - Dedicated logical channels are allocated to a specific mobile
    - Common logical channels can be used by more than one



Channel	Release	Name	Information carried	Direction
DTCH	R8	Dedicated traffic channel	User plane data	
DCCH	R8	Dedicated control channel	Signalling on SRB 1 & 2	UL, DL
CCCH	R8	Common control channel	Signalling on SRB 0	
PCCH	R8	Paging control channel	Paging messages	
BCCH	R8	Broadcast control channel	System information	DL
MCCH	R9	Multicast control channel	MBMS signalling	
MTCH	R9	Multicast traffic channel	MBMS data	

Table 6.1 Logical channels

- Dedicated Traffic CHannel (DTCH)
  - ✓ The most important logical channels
  - ✓ Carries data to or from a single mobile
- Dedicated Control Channel (DCCH)
  - ✓ Carries the large majority of signaling messages
  - ✓ Carries all the mobile-specific signaling messages on Signaling Radio Bearers 1 and 2, for mobiles that are in RRC_CONNECTED state

Channel	Release	Name	Information carried	Direction
DTCH	R8	Dedicated traffic channel	User plane data	
DCCH	R8	Dedicated control channel	Signalling on SRB 1 & 2	UL, DL
CCCH	R8	Common control channel	Signalling on SRB 0	
PCCH	R8	Paging control channel	Paging messages	
BCCH	R8	Broadcast control channel	System information	
MCCH	R9	Multicast control channel	MBMS signalling	DL
MTCH	R9	Multicast traffic channel	MBMS data	

RRC_IDLE

- UE on standby
- No S1 or radio bearers
- No serving eNB
- Cell reselection
- Paging
  RRC connection requests

RRC_CONNECTED

- UE active
- All bearers exist
- Serving eNB allocated
- Handovers
- Any communication possible

Signalling radio bearer	Configured by	Used by
SRB 0	System information	RRC messages before establishment of SRB 1
SRB 1	RRC message on SRB 0	Subsequent RRC messages
		NAS messages before establishment of SRB 2
SRB 2	RRC message on SRB 1	Subsequent NAS messages

- Broadcast Control CHannel (BCCH)
  - ✓ Carries RRC system information messages
  - ✓ BS broadcasts BCCH message across the whole cell to tell the mobiles about how the cell is configured
- These messages are divided into two unequal groups, which are handled differently by lower layers
  - ✓ Master Information Block (MIB)
    - Carries a few important parameters such as downlink bandwidth
  - ✓ System Information Blocks (SIBs)
    - Carries the remainder

Channel	Release	Name	Information carried	Direction
DTCH	R8	Dedicated traffic channel	User plane data	UL, DL
DCCH	R8	Dedicated control channel	Signalling on SRB 1 & 2	
CCCH	R8	Common control channel	Signalling on SRB 0	
PCCH	R8	Paging control channel	Paging messages	DL
BCCH	R8	Broadcast control channel	System information	
MCCH	R9	Multicast control channel	MBMS signalling	
MTCH	R9	Multicast traffic channel	MBMS data	

- Paging Control CHannel (PCCH)
  - ✓ Carries paging messages
  - ✓ BS transmits PCCH message if it wishes to contact mobiles that are in RRC_IDLE
- Common Control CHannel (CCCH)
  - ✓ Carries messages on Signaling Radio Bearer 0, for mobiles that are moving from RRC_IDLE to RRC_CONNECTED in the procedure of RRC connection establishment

Channel	Release	Name	Information carried	Direction
DTCH	R8	Dedicated traffic channel	User plane data	
DCCH	R8	Dedicated control channel	Signalling on SRB 1 & 2	UL, DL
CCCH	R8	Common control channel	Signalling on SRB 0	
PCCH	R8	Paging control channel	Paging messages	
BCCH	R8	Broadcast control channel	System information	
MCCH	R9	Multicast control channel	MBMS signalling	DL
MTCH	R9	Multicast traffic channel	MBMS data	

- UE on standby
- No S1 or radio bearers
- No serving eNB
- Cell reselection
- Paging
  RRC connection requests

- UE active
- All bearers exist
- Serving eNB allocated
- Handovers
- Any communication possible

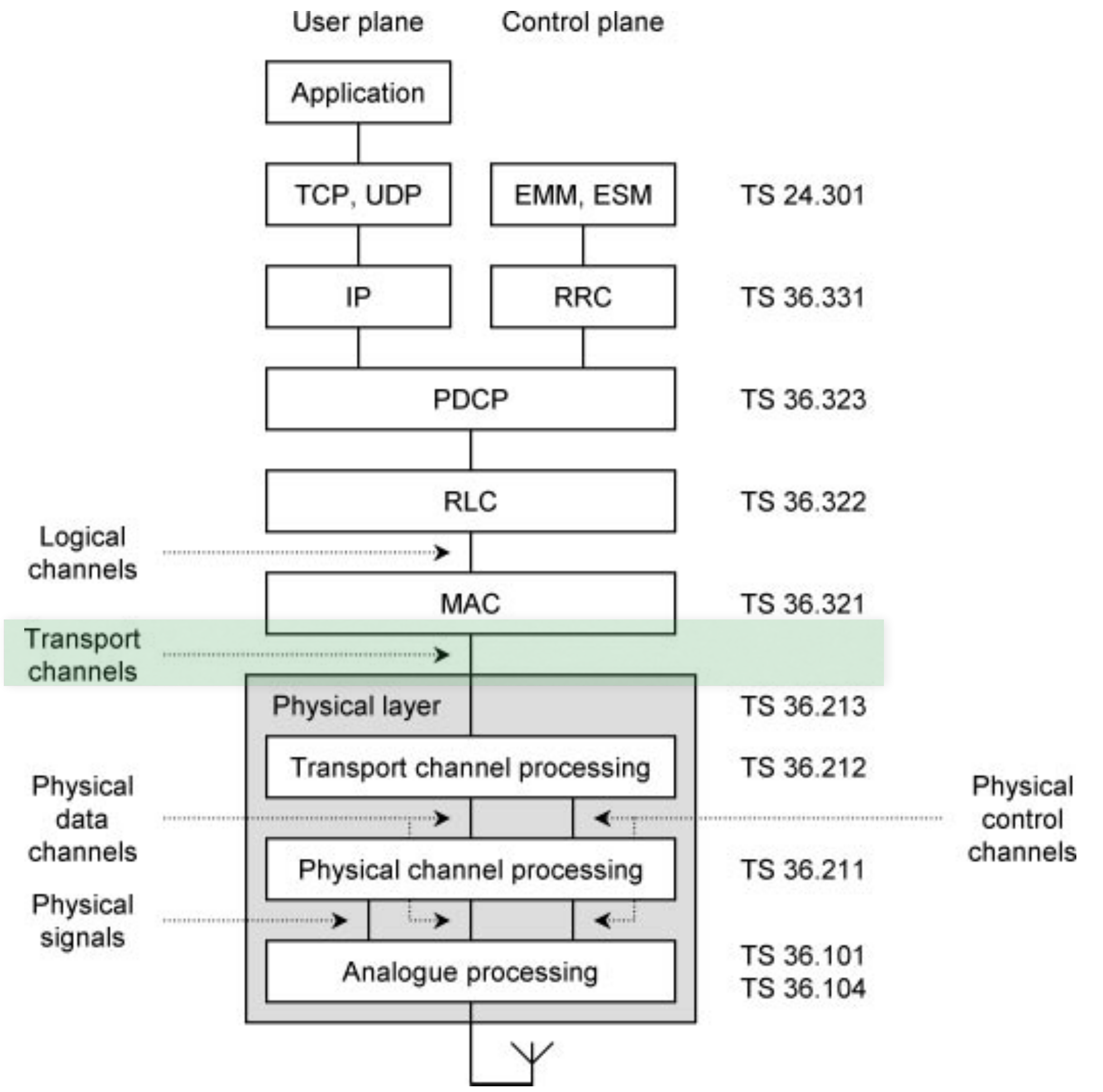
- Multicast Traffic CHannel (MTCH) and Multicast Control CHannel (MCCH)
  - ✓ Handle Multimedia Broadcast/Multicast service (MBMS) service

Channel	Release	Name	Information carried	Direction
DTCH	R8	Dedicated traffic channel	User plane data	UL, DL
DCCH	R8	Dedicated control channel	Signalling on SRB 1 & 2	UL, DL
CCCH	R8	Common control channel	Signalling on SRB 0	UL, DL
PCCH	R8	Paging control channel	Paging messages	DL
BCCH	R8	Broadcast control channel	System information	DL
MCCH	R9	Multicast control channel	MBMS signalling	DL
MTCH	R9	Multicast traffic channel	MBMS data	DL

2.2 Transport Channels

- Transport channels are distinguished by the ways in which the transport channel processor manipulates them

Channel	Release	Name	Information carried	Direction
UL-SCH	R8	Uplink shared channel	Uplink data and signalling	UL
RACH	R8	Random access channel	Random access requests	
DL-SCH	R8	Downlink shared channel	Downlink data and signalling	DL
PCH	R8	Paging channel	Paging messages	
BCH	R8	Broadcast channel	Master information block	
MCH	R8/R9	Multicast channel	MBMS	



Channel	Release	Name	Information carried	Direction
UL-SCH	R8	Uplink shared channel	Uplink data and signalling	UL
RACH	R8	Random access channel	Random access requests	
DL-SCH	R8	Downlink shared channel	Downlink data and signalling	DL
PCH	R8	Paging channel	Paging messages	
BCH	R8	Broadcast channel	Master information block	
MCH	R8/R9	Multicast channel	MBMS	

Table 6.2 Transport channels

- UpLink Shared CHannel (UL-SCH) & DownLink Shared CHannel (DL-SCH)
  - ✓ The most important transport channels
  - ✓ Carry the large majority of data and signaling messages across air interface
- Paging CHannel (PCH)
  - ✓ Carries paging messages that originated from Paging Control CHannel (PCCH)
- Broadcast CHannel (BCH)
  - ✓ Carries the broadcast control channel's Master Information Block (MIB)
  - ✓ The remaining system information messages are handled by DL-SCH, as if they were normal downlink data

Channel	Release	Name	Information carried	Direction
UL-SCH	R8	Uplink shared channel	Uplink data and signalling	UL
RACH	R8	Random access channel	Random access requests	
DL-SCH	R8	Downlink shared channel	Downlink data and signalling	DL
PCH	R8	Paging channel	Paging messages	
BCH	R8	Broadcast channel	Master information block	
MCH	R8/R9	Multicast channel	MBMS	

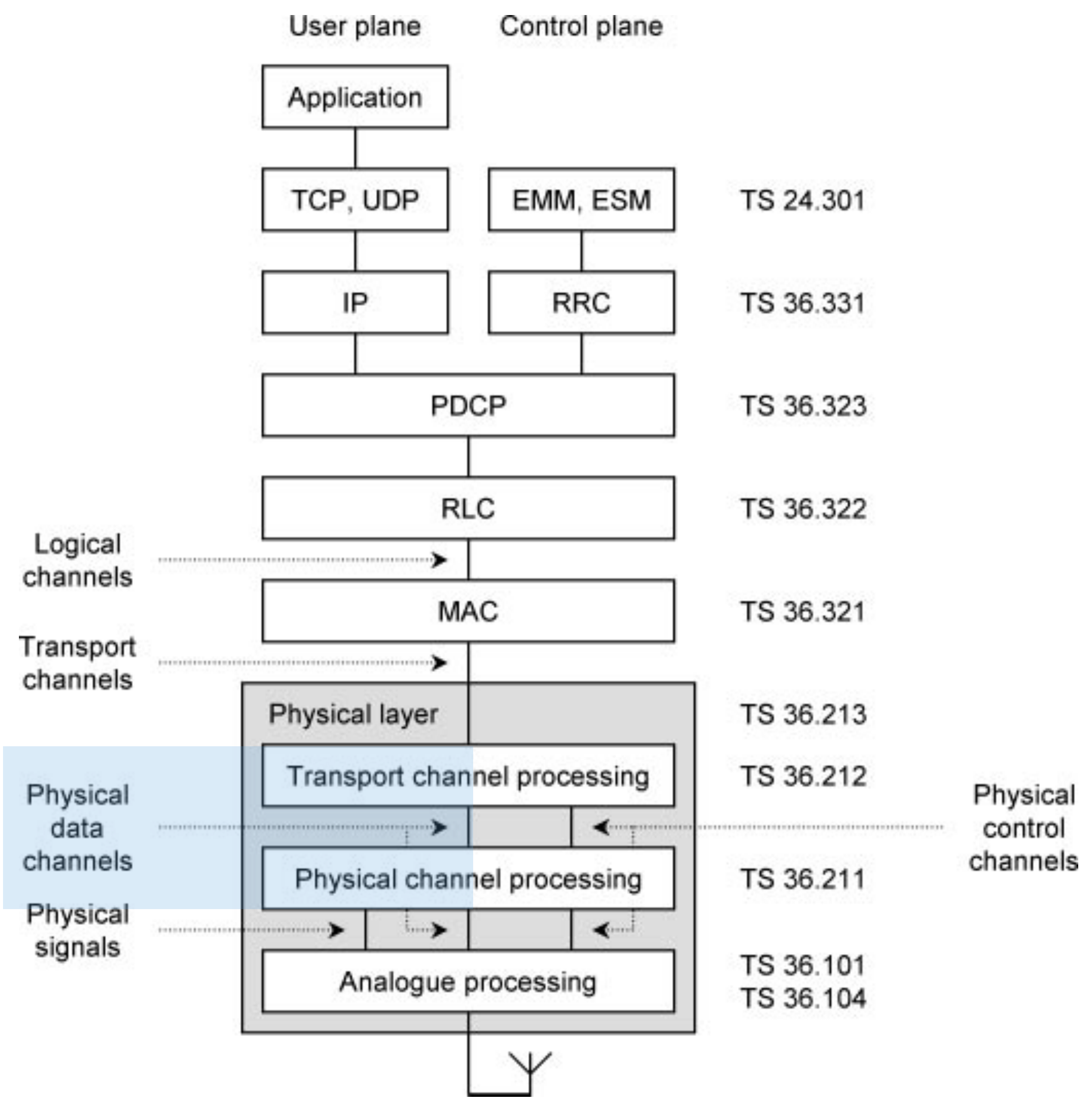
- Multicast CHannel (MCH)
  - ✓ Carry data from multimedia broadcast/multicast service
  - ✓ The BS usually schedules the transmissions that a mobile makes, by granting it resources for downlink transmission at specific times and on specific sub-carriers
- Random Access CHannel (RACH)
  - ✓ A special channel through which the mobile can contact the network without any prior scheduling
  - ✓ Random access transmissions are composed by mobile's MAC protocol and travel as far as the MAC protocol in the BS, but are completely invisible to higher layers.

Channel	Release	Name	Information carried	Direction
UL-SCH	R8	Uplink shared channel	Uplink data and signalling	UL
RACH	R8	Random access channel	Random access requests	
DL-SCH	R8	Downlink shared channel	Downlink data and signalling	DL
PCH	R8	Paging channel	Paging messages	
BCH	R8	Broadcast channel	Master information block	
MCH	R8/R9	Multicast channel	MBMS	

- Main differences between transport channels lie in their approaches to error management
  - ✓ UL-SCH & DL-SCH
    - The only transport channels that use ARQ and hybrid ARQ
    - The only channels that can adapt their coding rate to changes in the received SINR
  - ✓ The other transport channels use FEC alone and have a fixed coding rate

2.3 Physical Data Channels

- Physical data channels are distinguished by
  - ✓ The ways in which the physical channel processor manipulates them, and
  - ✓ The ways in which they are mapped onto the <u>symbols</u> and <u>sub-carriers</u> used by OFDMA



Channel	Release	Name	Information carried	Direction
PUSCH	R8	Physical uplink shared channel	UL-SCH and/or UCI	UL
PRACH	R8	Physical random access channel	RACH	
PDSCH	R8	Physical downlink shared channel	DL-SCH and PCH	
PBCH	R8	Physical broadcast channel	BCH	DL
PMCH	R8/R9	Physical multicast channel	MCH	

Table 6.3 Physical data channels

- Physical Downlink Shared CHannel (PDSCH) & Physical Uplink Shared CHannel (PUSCH)
  - ✓ The most important physical channels
- PDSCH
  - ✓ Carries data and signaling messages from DL-SCH
  - ✓ Carries paging messages from PCH
- PUSCH
  - ✓ Carries data and signaling messages from UL-SCH
  - ✓ Sometimes carries uplink control information

Channel	Release	Name	Information carried	Direction
PUSCH	R8	Physical uplink shared channel	UL-SCH and/or UCI	UL
PRACH	R8	Physical random access channel	RACH	
PDSCH	R8	Physical downlink shared channel	DL-SCH and PCH	DL
PBCH	R8	Physical broadcast channel	BCH	
PMCH	R8/R9	Physical multicast channel	MCH	

- Physical Broadcast CHannel (PBCH)
  - ✓ Carries the MIB (Master Information Block) from broadcast channel
- Physical Random Access CHannel (PRACH)
  - ✓ Carries random access transmissions from random access channel
- Physical Multicast CHannel (PMCH)
  - ✓ Carries data from multicast channel

Channel	Release	Name	Information carried	Direction
PUSCH	R8	Physical uplink shared channel	UL-SCH and/or UCI	UL
PRACH	R8	Physical random access channel	RACH	
PDSCH	R8	Physical downlink shared channel	DL-SCH and PCH	DL
PBCH	R8	Physical broadcast channel	BCH	
PMCH	R8/R9	Physical multicast channel	MCH	

- PDSCH and PUSCH
  - ✓ The only physical channels that can adapt their modulation schemes in response to changes in the received SINR
- The other physical channels all use a fixed modulation scheme, usually QPSK

UCI: Uplink Control Information (UCI)

Channel	Release	Name	Information carried	Direction
PUSCH	R8	Physical uplink shared channel	UL-SCH and/or UCI	UL
PRACH	R8	Physical random access channel	RACH	
PDSCH	R8	Physical downlink shared channel	DL-SCH and PCH	DL
PBCH	R8	Physical broadcast channel	BCH	
PMCH	R8/R9	Physical multicast channel	MCH	

2.4 Control Information

- Transport channel processor composes several types of control information to support the low-level operation of physical layer

Field	Release	Name	Information carried	Direction
UCI	R8	Uplink control information	Hybrid ARQ acknowledgements Channel quality indicators (CQI) Pre-coding matrix indicators (PMI) Rank indications (RI) Scheduling requests (SR)	UL
DCI	R8	Downlink control information	Downlink scheduling commands Uplink scheduling grants Uplink power control commands	DL
CFI	R8	Control format indicator	Size of downlink control region	DL
HI	R8	Hybrid ARQ indicator	Hybrid ARQ acknowledgements	DL

Field	Release	Name	Information carried	Direction
UCI	R8	Uplink control information	Hybrid ARQ acknowledgements Channel quality indicators (CQI) Pre-coding matrix indicators (PMI) Rank indications (RI) Scheduling requests (SR)	UL
DCI	R8	Downlink control information	Downlink scheduling commands Uplink scheduling grants Uplink power control commands	DL
CFI	R8	Control format indicator	Size of downlink control region	DL
HI	R8	Hybrid ARQ indicator	Hybrid ARQ acknowledgements	

Table 6.4 Control information

- Uplink Control Information (UCI) contains several fields
  - ✓ Hybrid ARQ acknowledgements
    - The mobile's acknowledgements of the BS's transmissions on the DL-SCH (DownLink Shared CHannel)
  - ✓ Channel Quality Indicator (CQI)
    - Describes the received SINR as a function of frequency in support of frequency-dependent scheduling
  - ✓ Precoding Matrix Indicator (PMI) and Rank Indication (RI)
    - Support the use of spatial multiplexing
  - ✓ Collectively, CQI, PMI and RI are sometimes known as Channel State Information (CSI)
  - ✓ Scheduling Request (SR)
    - Sent by the mobile, if it wishes to transmit uplink data on the PUSCH, but does not have the resources to do so

Field	Release	Name	Information carried	Direction
UCI	R8	Uplink control information	Hybrid ARQ acknowledgements Channel quality indicators (CQI) Pre-coding matrix indicators (PMI) Rank indications (RI) Scheduling requests (SR)	UL
DCI	R8	Downlink control information	Downlink scheduling commands Uplink scheduling grants Uplink power control commands	DL
CFI	R8	Control format indicator	Size of downlink control region	DL
HI	R8	Hybrid ARQ indicator	Hybrid ARQ acknowledgements	

- Downlink Control Information (DCI) contains most of the downlink control fields
  - ✓ Using scheduling commands and scheduling grants, the BS can
    - Alert the mobile to forthcoming transmissions on the downlink shared channel and
    - Grant it resources for transmissions on the uplink shared channel
  - ✓ It can also adjust the power with which the mobiles are transmitting using power control commands

Field	Release	Name	Information carried	Direction
UCI	R8	Uplink control information	Hybrid ARQ acknowledgements Channel quality indicators (CQI) Pre-coding matrix indicators (PMI) Rank indications (RI) Scheduling requests (SR)	UL
DCI	R8	Downlink control information	Downlink scheduling commands Uplink scheduling grants Uplink power control commands	DL
CFI HI	R8 R8	Control format indicator Hybrid ARQ indicator	Size of downlink control region Hybrid ARQ acknowledgements	DL

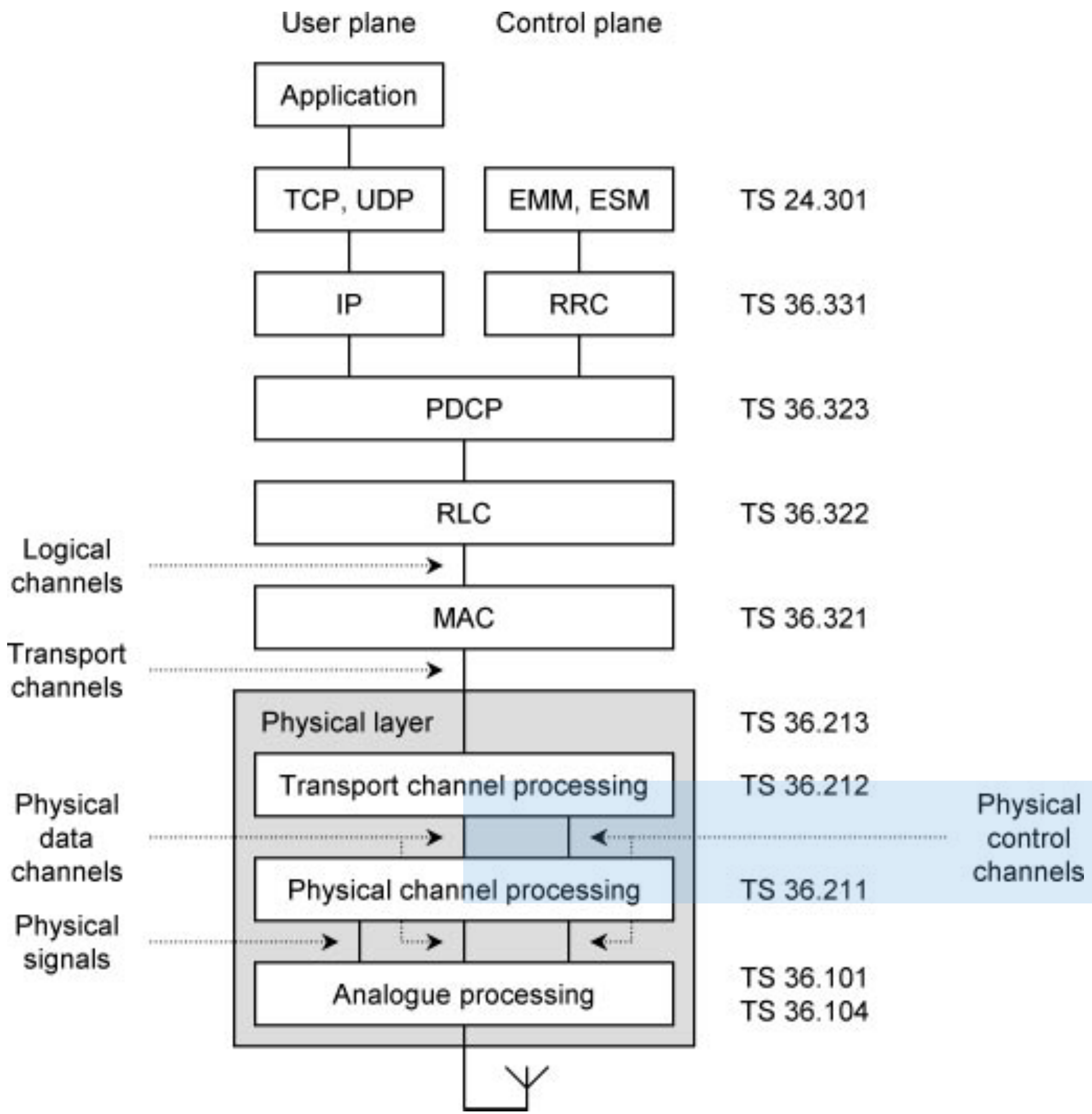
- Control Format Indicators (CFIs)
  - ✓ Tell the mobiles about the organization of data and control information on the downlink
- Hybrid ARQ Indicators (HIs)
  - ✓ The BS's acknowledgements of the mobiles' uplink transmissions on the UL-SCH

Field	Release	Name	Information carried	Direction
UCI	R8	Uplink control information	Hybrid ARQ acknowledgements Channel quality indicators (CQI) Pre-coding matrix indicators (PMI) Rank indications (RI) Scheduling requests (SR)	UL
DCI	R8	Downlink control information	Downlink scheduling commands Uplink scheduling grants Uplink power control commands	DL
CFI	R8	Control format indicator	Size of downlink control region	DL
HI	R8	Hybrid ARQ indicator	Hybrid ARQ acknowledgements	DL

2.5 Physical Control Channels

- In the downlink, there is a one-to-one mapping between physical control channels and control information listed above
- Physical Control Format Indicator CHannel (PCFICH)
  - ✓ Carry control format indicators (CFI)
- ARQ Indicator Channel (PHICH)
  - ✓ Carry hybrid ARQ indicators (HI)
- Downlink Control CHannel (PDCCH)
  - ✓ Carry downlink control information (DCI)
- Relay Physical Downlink Control CHannel (R-PDCCH)
  - ✓ Supports the use of relaying

Channel	Release	Name	Information carried	Direction
PUCCH	R8	Physical uplink control channel	UCI	UL
PCFICH	R8	Physical control format indicator channel	CFI	DL
PHICH	R8	Physical hybrid ARQ indicator channel	HI	
PDCCH	R8	Physical downlink control channel	DCI	
R-PDCCH	R10	Relay physical downlink control channel	DCI	


User plane
Control plane
Application
TCP, UDP
EMM, ESM
TS 24.301
IP
RRC
TS 36.331
PDCP
TS 36.323
RLC
TS 36.322
Logical channels
MAC
TS 36.321
Transport channels
Physical layer
TS 36.213
Transport channel processing
TS 36.212
Physical data channels
Physical control channels
Physical channel processing
TS 36.211
Physical signals
Analogue processing
TS 36.101
TS 36.104

Channel	Release	Name	Information carried	Direction
PUCCH	R8	Physical uplink control channel	UCI	UL
PCFICH	R8	Physical control format indicator channel	CFI	DL
PHICH	R8	Physical hybrid ARQ indicator channel	HI	
PDCCH	R8	Physical downlink control channel	DCI	
R-PDCCH	R10	Relay physical downlink control channel	DCI	

Table 6.5 Physical control channels

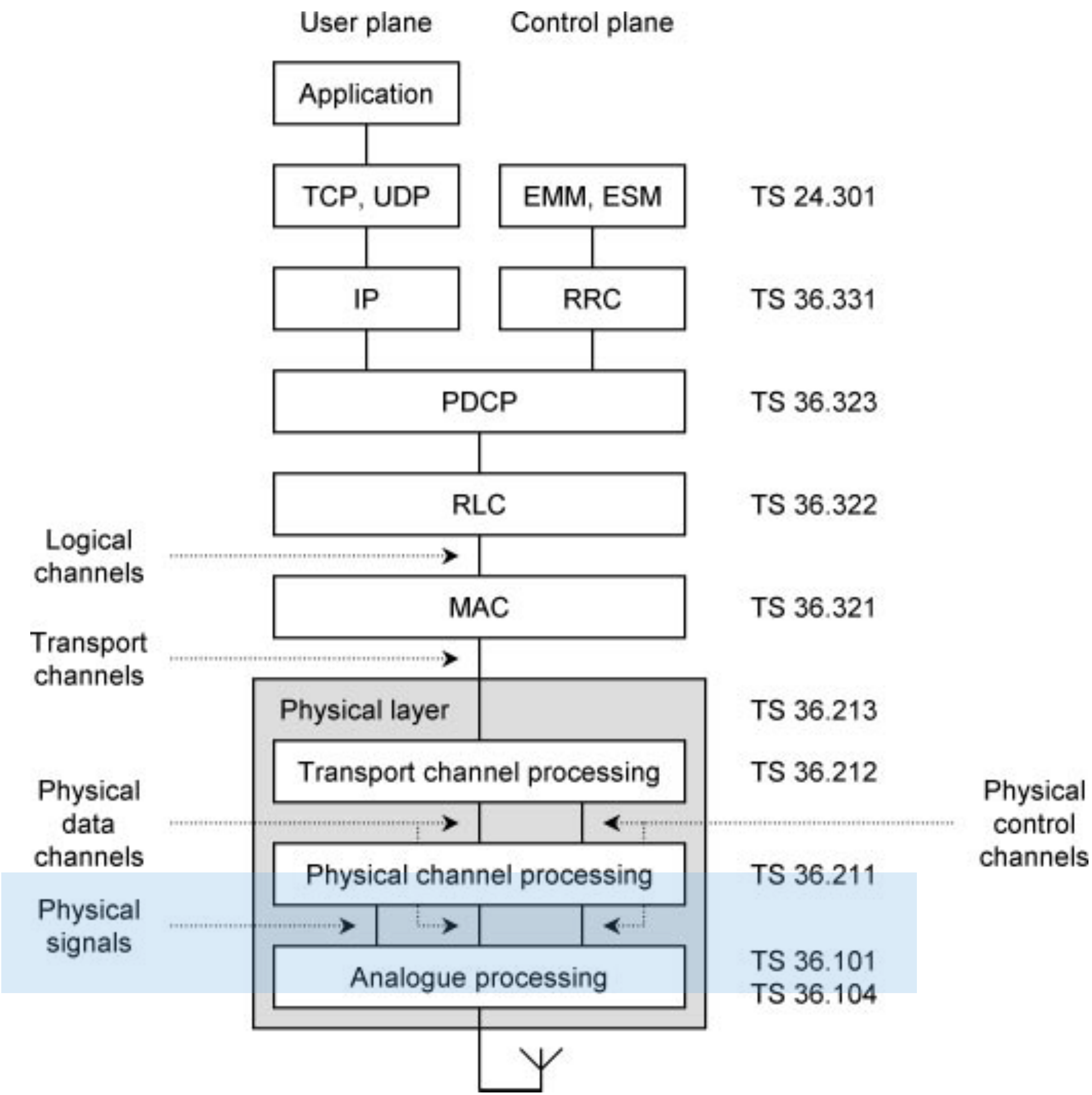
- The uplink control information is sent
  - ✓ On the Physical Uplink Shared CHannel (PUSCH) if the mobile is transmitting uplink data at the same time
  - ✓ On the Physical Uplink Control CHannel (PUCCH) otherwise

Channel	Release	Name	Information carried	Direction
PUCCH	R8	Physical uplink control channel	UCI	UL
PCFICH	R8	Physical control format indicator channel	CFI	DL
PHICH	R8	Physical hybrid ARQ indicator channel	HI	
PDCCH	R8	Physical downlink control channel	DCI	
R-PDCCH	R10	Relay physical downlink control channel	DCI	

2.6 Physical Signals

- Physical signals support the lowest-level operation of the physical layer

Signal	Release	Name	Use	Direction
DRS	R8	Demodulation reference signal	Channel estimation	UL
SRS	R8	Sounding reference signal	Scheduling	
PSS	R8	Primary synchronization signal	Acquisition	DL
SSS	R8	Secondary synchronization signal	Acquisition	
	R8	Cell specific reference signal	Channel estimation and scheduling	
	R8	UE specific reference signal	Channel estimation	
RS	R8/R9	MBMS reference signal	Channel estimation	DL
	R9	Positioning reference signal	Location services	
	R10	CSI reference signal	Scheduling	


User plane
Control plane
Application
TCP, UDP
EMM, ESM
TS 24.301
IP
RRC
TS 36.331
PDCP
TS 36.323
RLC
TS 36.322
Logical channels
MAC
TS 36.321
Transport channels
Physical layer
TS 36.213
Transport channel processing
TS 36.212
Physical data channels
Physical control channels
Physical channel processing
TS 36.211
Physical signals
Analogue processing
TS 36.101
TS 36.104

Signal	Release	Name	Use	Direction
DRS	R8	Demodulation reference signal	Channel estimation	UL
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RS	R8/R9	MBMS reference signal	Channel estimation	DL
	R9	Positioning reference signal	Location services	
	R10	CSI reference signal	Scheduling	

Table 6.6 Physical signals

- In the uplink, the mobile
  - ✓ Transmits the Demodulation Reference Signal (DRS) at the same time as the PUSCH and PUCCH, as a phase reference for use in channel estimation
  - ✓ Transmit the Sounding Reference Signal (SRS) at times configured by the BS, as a power reference in support of frequency-dependent scheduling

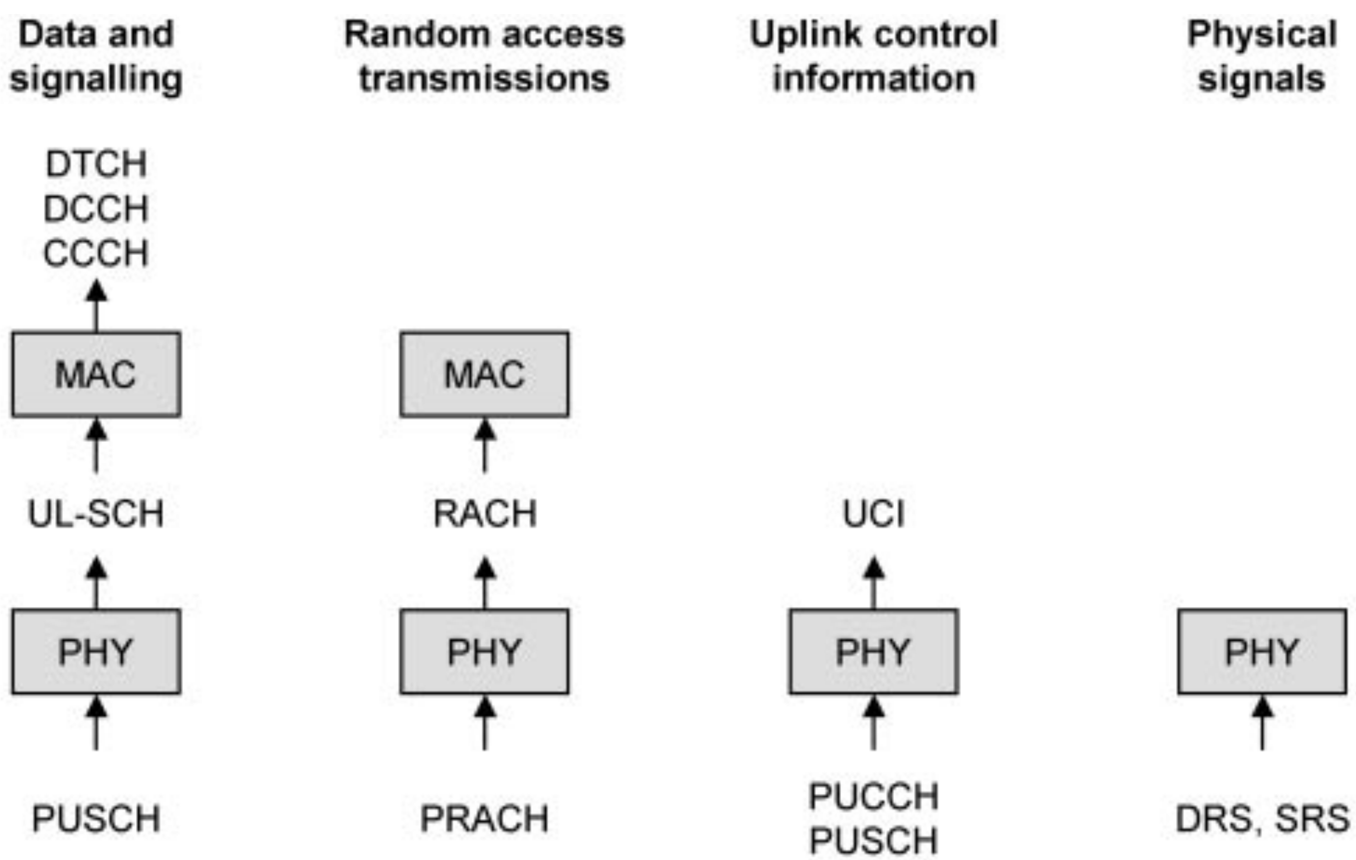
Signal	Release	Name	Use	Direction
DRS	R8	Demodulation reference signal	Channel estimation	UL
SRS	R8	Sounding reference signal	Scheduling	
PSS	R8	Primary synchronization signal	Acquisition	DL
SSS	R8	Secondary synchronization signal	Acquisition	
	R8	Cell specific reference signal	Channel estimation and scheduling	
	R8	UE specific reference signal	Channel estimation	
RS	R8/R9	MBMS reference signal	Channel estimation	DL
	R9	Positioning reference signal	Location services	
	R10	CSI reference signal	Scheduling	

- The downlink
  - ✓ Usually combines DRS and SRS in the form of cell specific Reference Signal (RS)
  - ✓ UE specific reference signals are less important and are sent to mobiles that are using beamforming in support of channel estimation
- BS also transmits two other physical signals, which help the mobile acquire the BS after it first switches on
  - ✓ Primary Synchronization Signal (PSS)
  - ✓ Secondary Synchronization Signal (SSS)

Signal	Release	Name	Use	Direction
DRS	R8	Demodulation reference signal	Channel estimation	UL
SRS	R8	Sounding reference signal	Scheduling	
PSS	R8	Primary synchronization signal	Acquisition	DL
SSS	R8	Secondary synchronization signal	Acquisition	
	R8	Cell specific reference signal	Channel estimation and scheduling	
	R8	UE specific reference signal	Channel estimation	
RS	R8/R9	MBMS reference signal	Channel estimation	DL
	R9	Positioning reference signal	Location services	
	R10	CSI reference signal	Scheduling	

2.7 Information Flows

- Tables 6.1 to 6.6 contain a large number of channels, but LTE uses them in just a few types of information flow
- Figure 6.2 shows the information flows that are used in the uplink, with the arrows drawn from the viewpoint of the BS, so that uplink channels have arrows pointing upwards, and vice versa
- Figure 6.3 shows the corresponding situation in the downlink



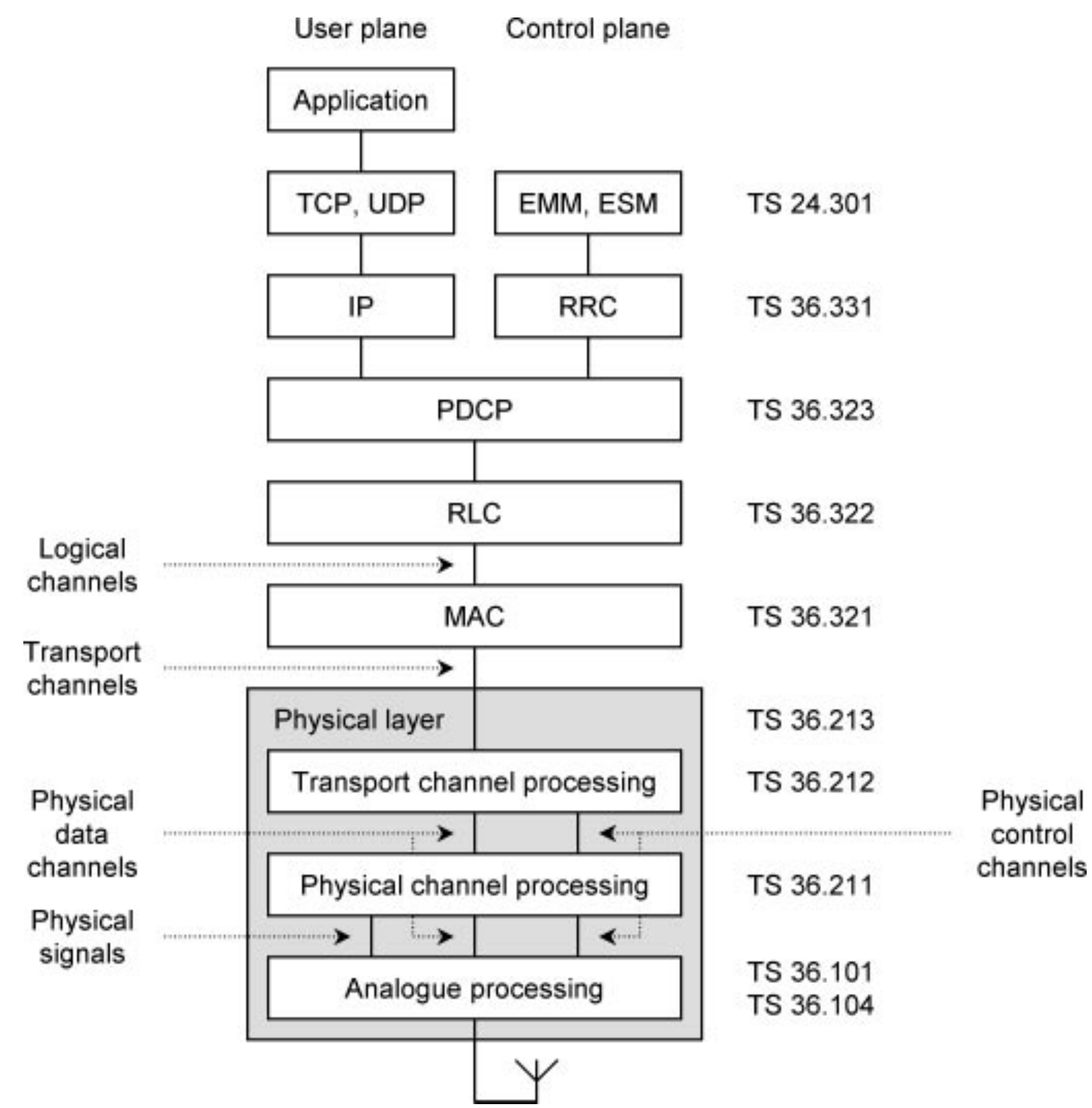
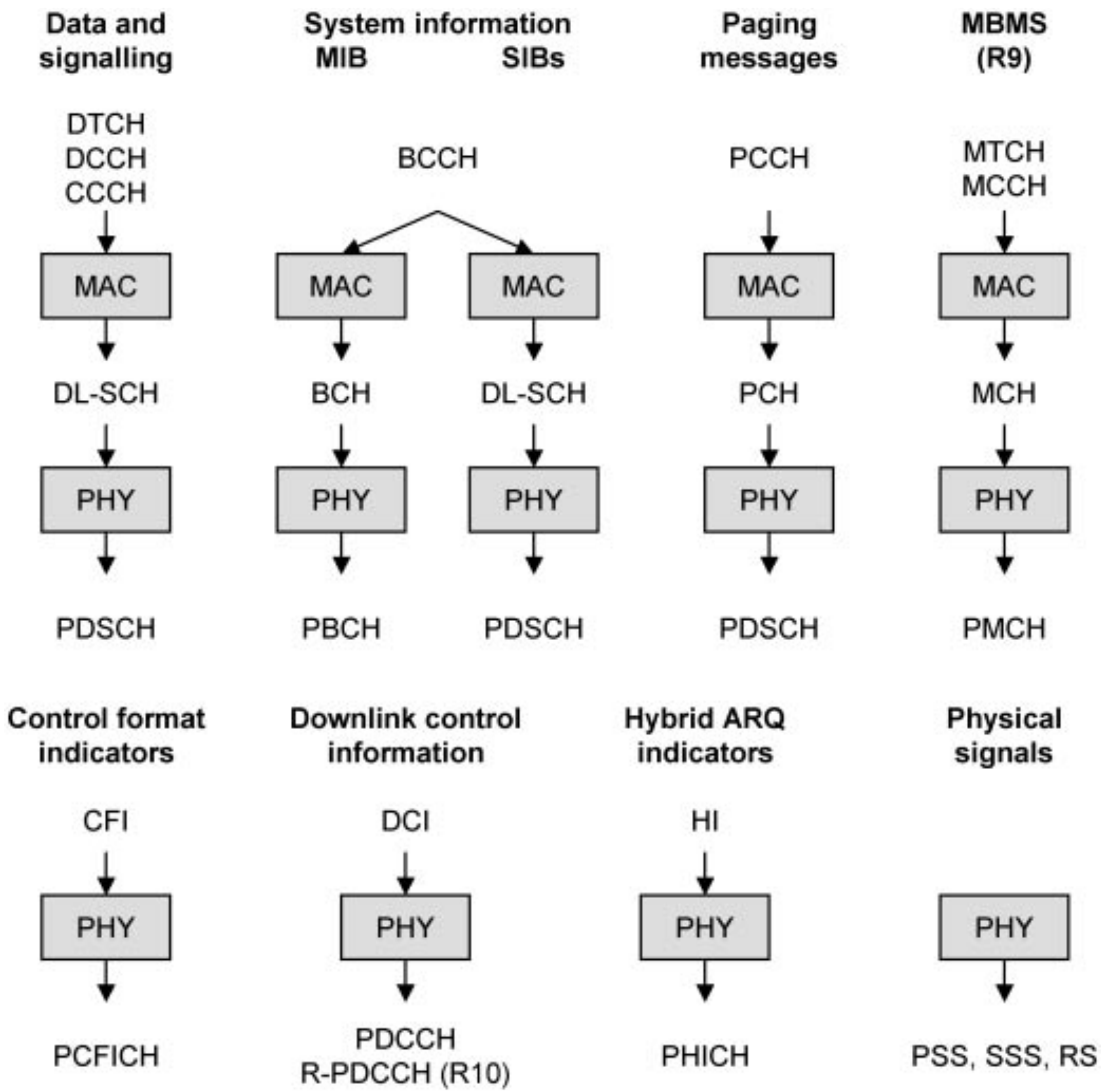


Figure 6.2 Uplink information flows used by LTE.



MBMS : Broadcast/ Multicast service
MIB : Master Information Block
SIB : System Information Block

Figure 6.3 Downlink information flows used by LTE.

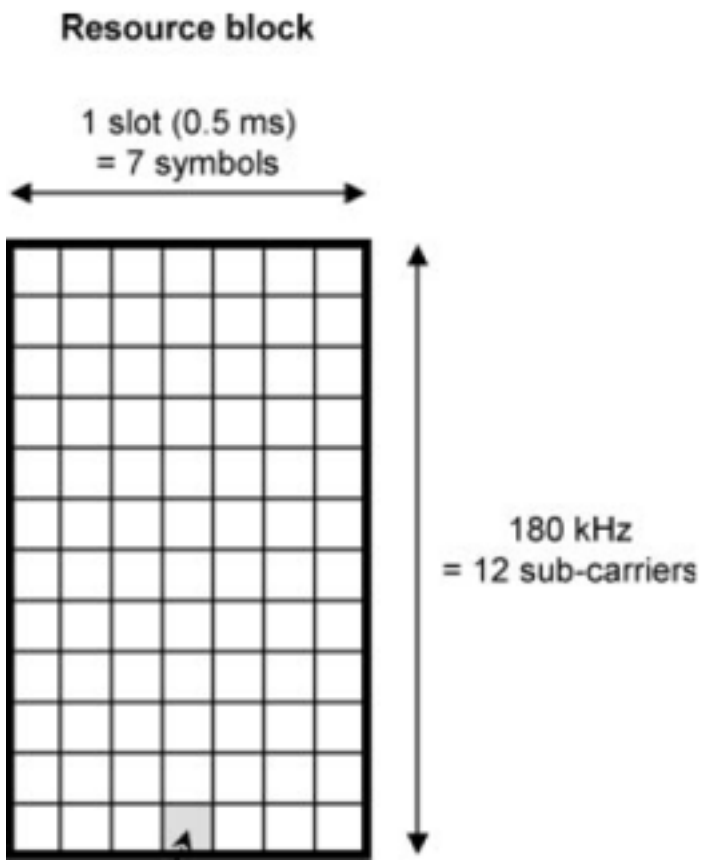
- 1. Air Interface Protocol Stack
- 2. Logical, Transport and Physical Channels
- 3. The Resource Grid
- 4. Multiple Antenna Transmission
- 5. Resource Element Mapping

3. The Resource Grid

- 3.1 Slot Structure
- 3.2 Frame Structure
- 3.3 Uplink Timing Advance
- 3.4 Resource Grid Structure
- 3.5 Bandwidth Options

3.1 Slot Structure

- LTE maps physical channels and physical signals onto OFDMA symbols and subcarriers
- How LTE organizes its symbols and sub-carriers in the time and frequency domains

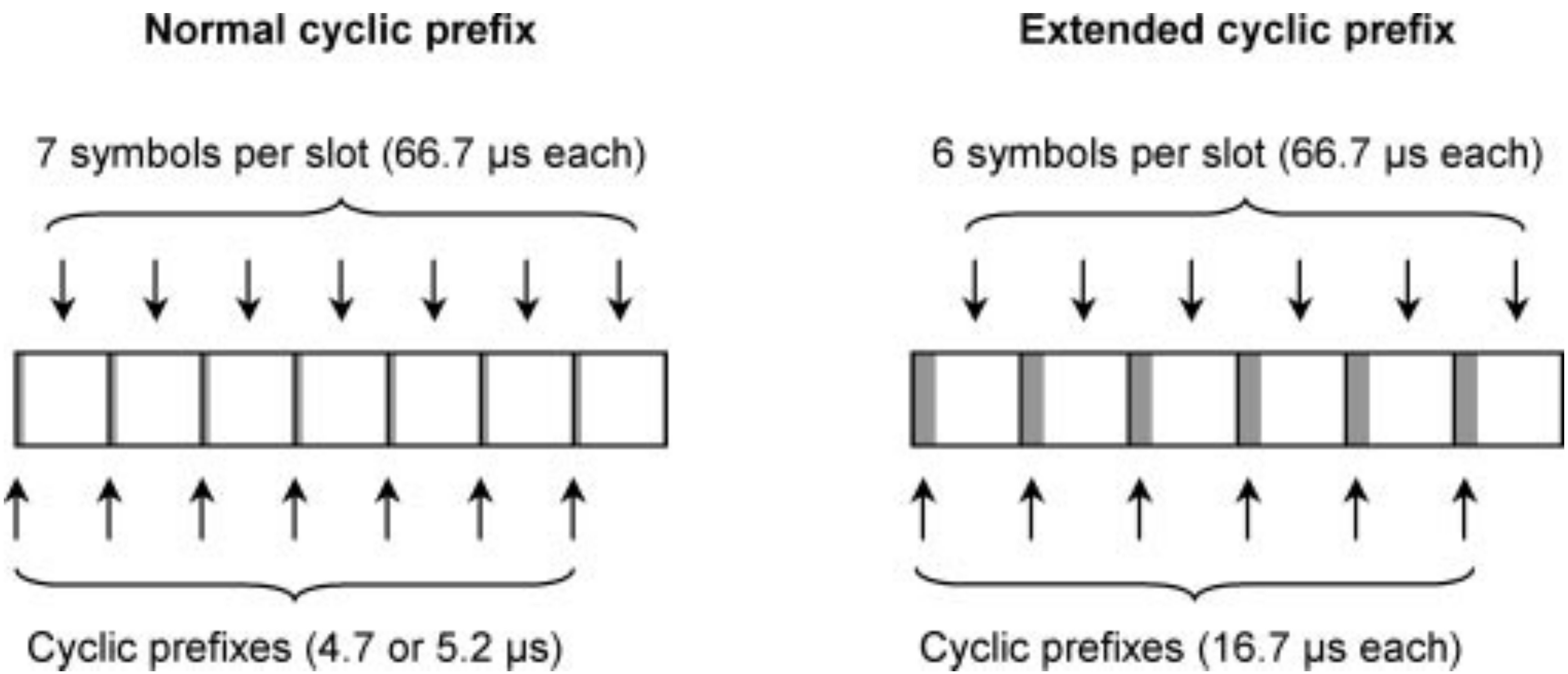


- Consider the time domain
  - ✓ The timing of the LTE transmissions is based on a time unit T_s

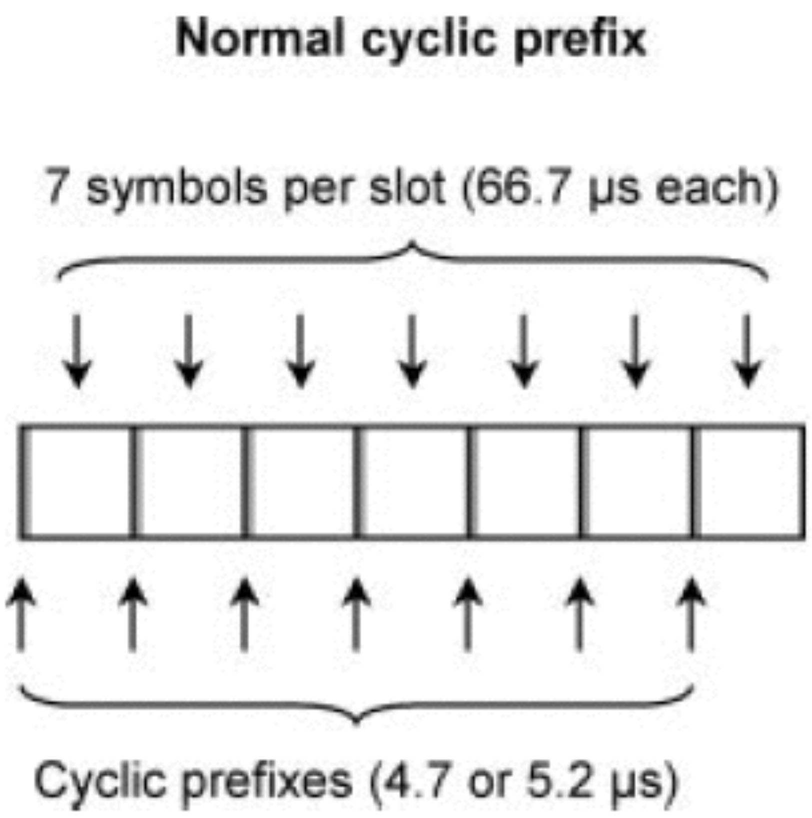
$$T_s = \frac{1}{2048 \times 15000} \text{ sec} \approx 32.6\ ns$$

    - T_s is the shortest time interval that is of interest to the physical channel processor
    - (To be exact, T_s is the sampling interval if the system uses a fast Fourier transform that contains 2048 points)
  - ✓ The 66.7 μs symbol duration is then equal to 2048 T_s (66.7 μs = 2048 × 32.6 ns)

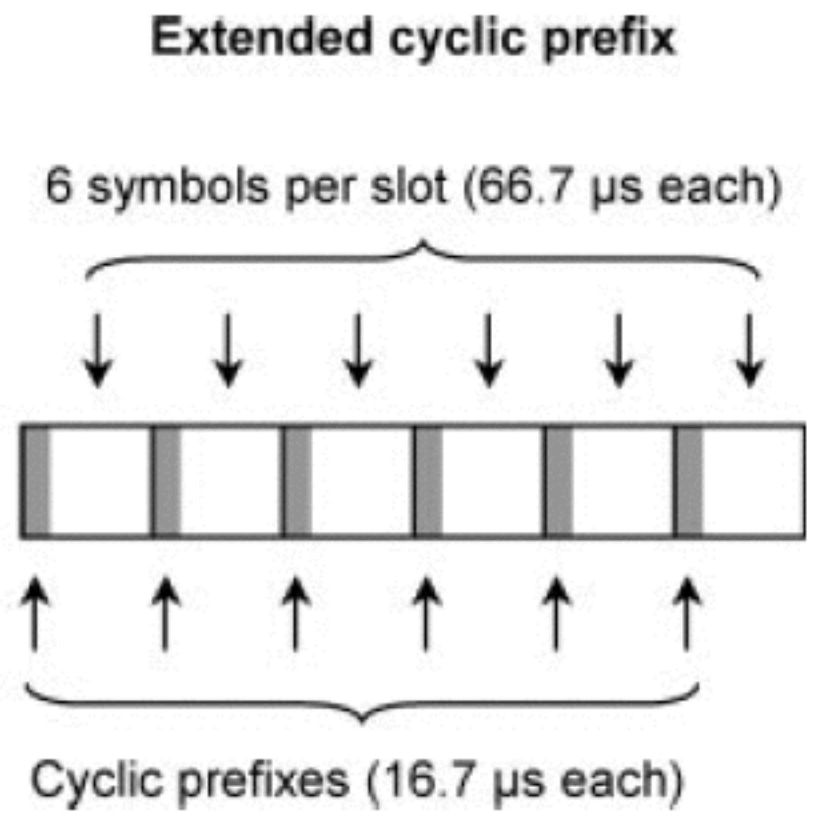
- The symbols are grouped into slots, whose duration is 0.5ms (= 15,360T_s), this can be done in two ways
  - ✓ Normal cyclic prefix
  - ✓ Extended cyclic prefix



- Normal cyclic prefix
  - ✓ Each symbol is preceded by a cyclic prefix that is usually 144 T_s (4.7 μs) long
  - ✓ The first cyclic prefix has a longer duration of 160 T_s (5.2 μs), to tidy up the unevenness that results from fitting seven symbols into a slot
  - ✓ The receiver can remove inter-symbol interference with a delay spread of 4.7 μs, corresponding to a path difference of 1.4 km between the lengths of the longest and shortest rays
  - ✓ This is normally plenty, but may not be enough if the cell is unusually large or cluttered
  - ✓ To deal with this possibility, LTE also supports an extended cyclic prefix

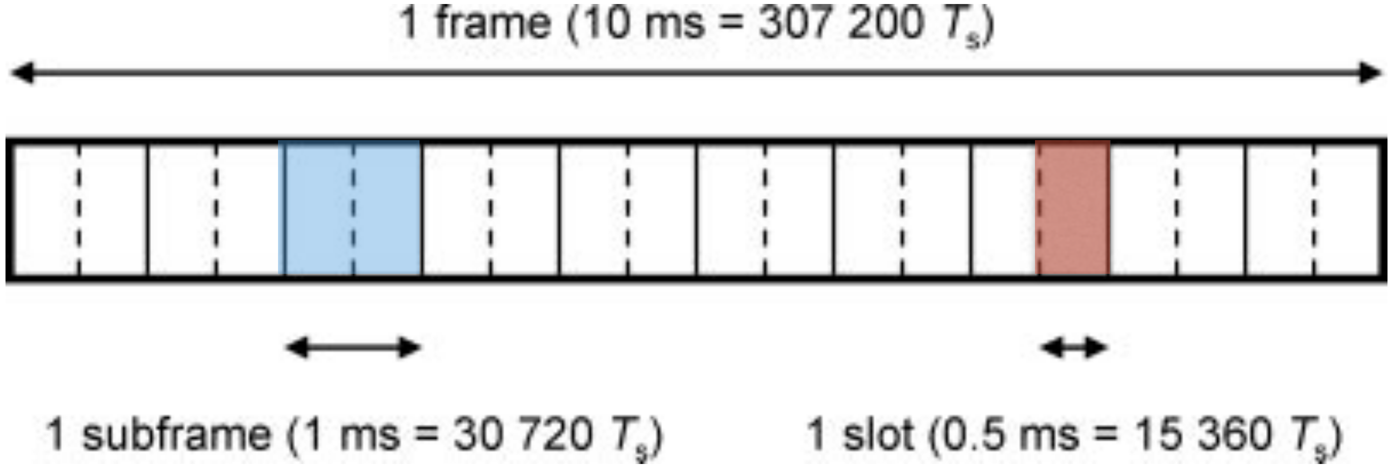


- Extended cyclic prefix
  - ✓ The number of symbols per slot is reduced to six
  - ✓ This allows cyclic prefix to be extended to 512 Ts (16.7 μs), to support a max path difference of 5 km
- The normal cyclic prefix is far more common



3.2 Frame Structure

- At a higher level, the slots are grouped into subframes and frames
- In FDD mode, this is done using frame structure type 1
- Two slots make one subframe, which is *1ms* long (30,720 T_s)



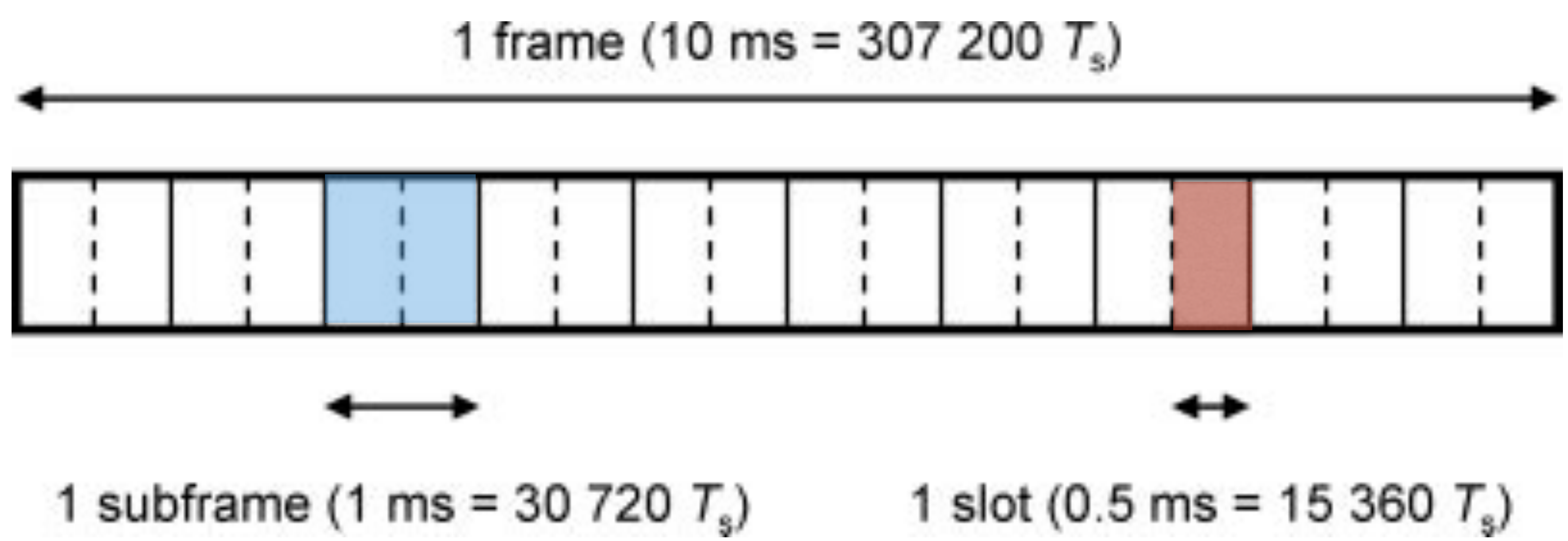
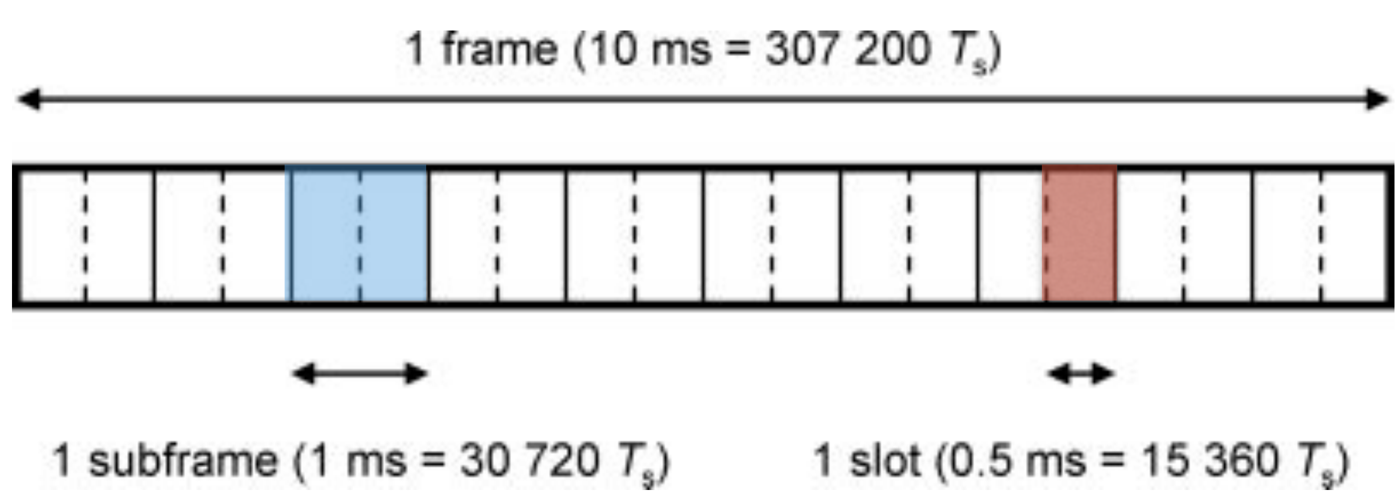
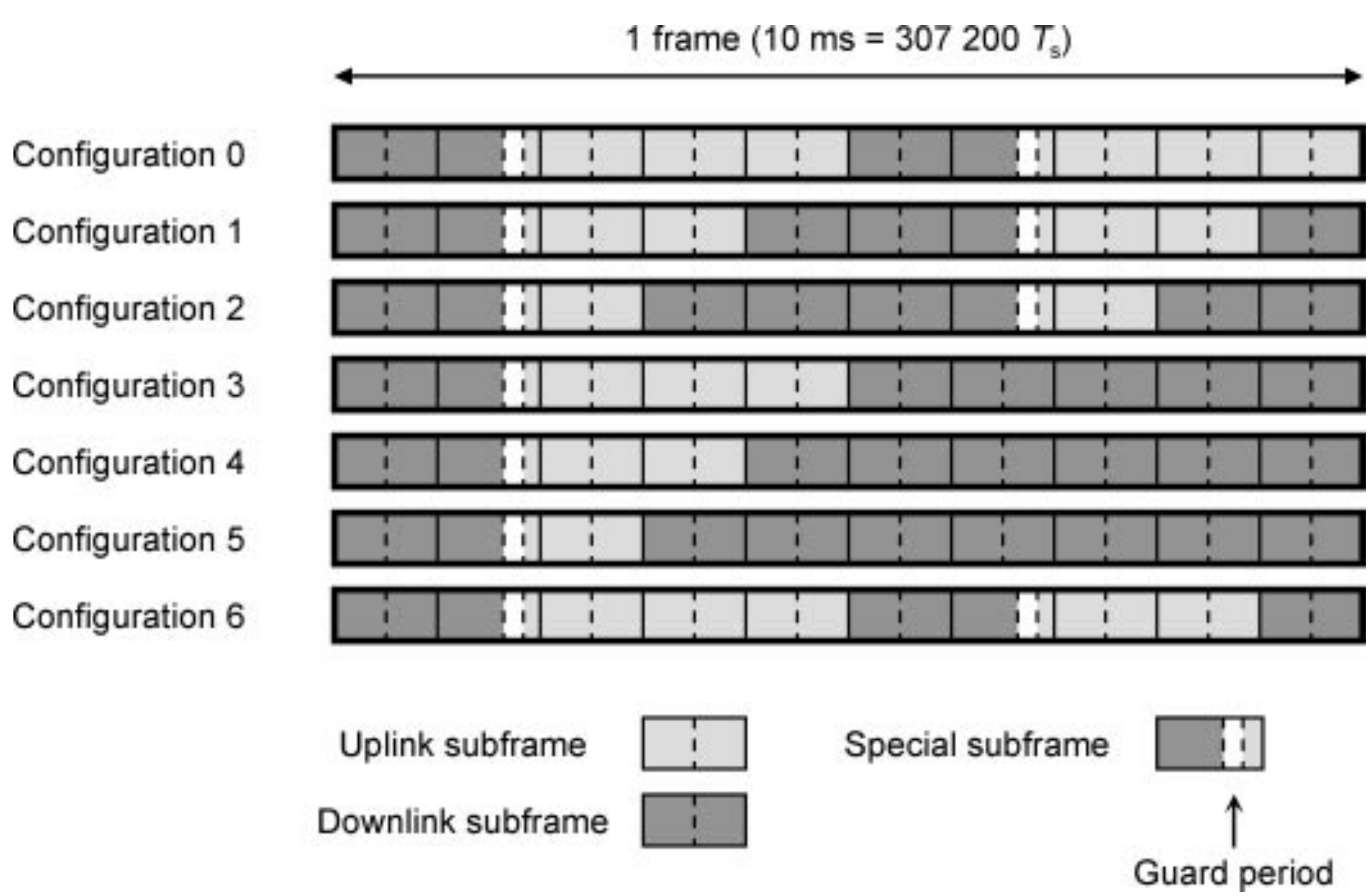


Figure 6.5 Frame structure type 1, used in FDD mode.

- Subframes are used for scheduling
  - ✓ When a BS transmits to a mobile on the downlink, it
    - Schedules its Physical Downlink Shared Channel (PDSCH) transmissions one subframe at a time, and
    - Maps each block of data onto a set of sub-carriers within that subframe
  - ✓ A similar process happens on the uplink
- 10 subframes make one frame, which is 10 ms long (307,200 T_s)
- Each frame is numbered using a system frame number (SFN), which runs repeatedly from 0 to 1023
- Frames help to schedule a number of slowly changing processes, such as the transmission of system information and reference signals



- TDD mode uses frame structure type 2
  - ✓ The slots, subframes and frames have the same duration as before
  - ✓ But each subframe can be allocated to either uplink or downlink using one of the TDD configurations shown in the figure



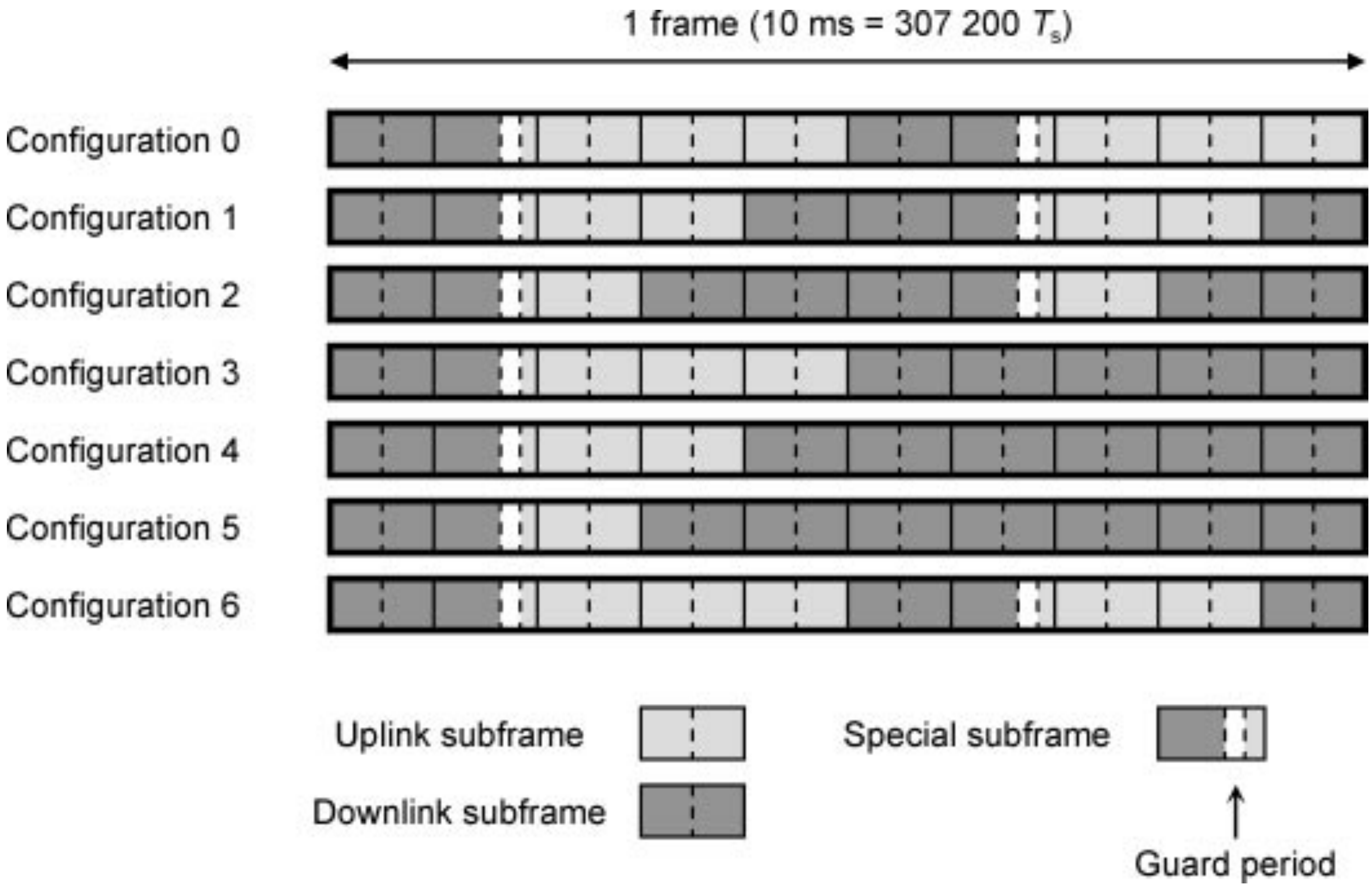
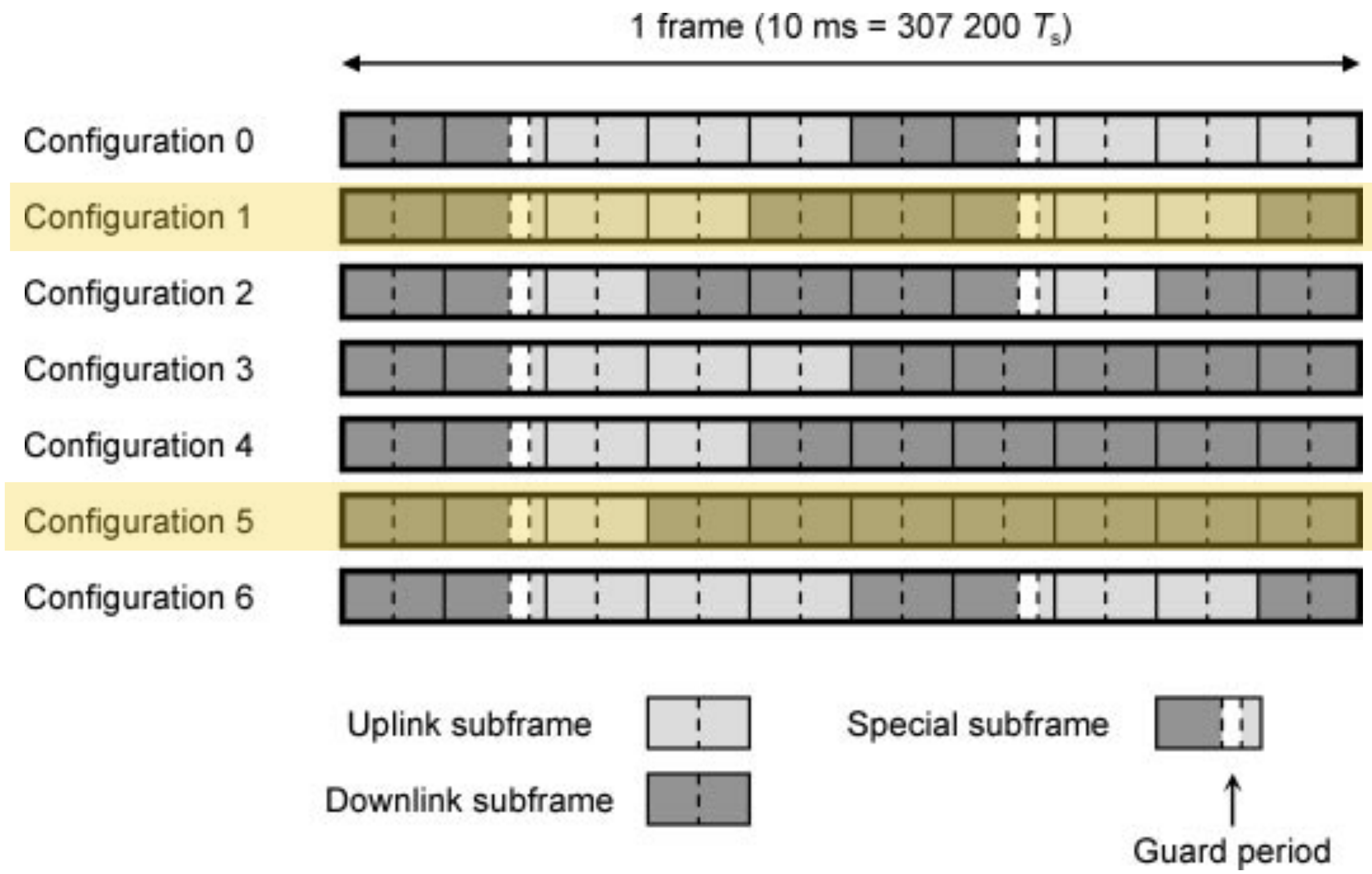


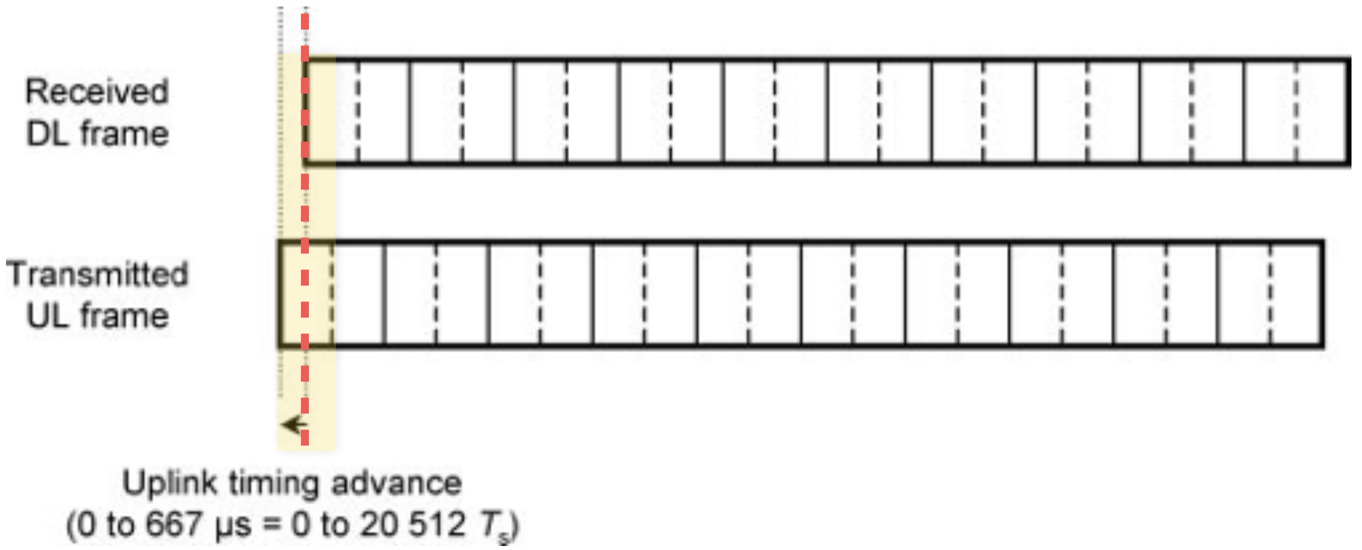
Figure 6.6 TDD configurations using frame structure type 2.

- Different cells can have different TDD configurations, which are advertised as part of the cells' system information
  - ✓ Configuration 1
    - Might be suitable if the data rates are similar on the uplink and downlink
  - ✓ Configuration 5
    - Might be used in cells that are dominated by downlink transmissions
- Nearby cells should generally use the same TDD configuration, to minimize the interference between uplink and downlink



3.3 Uplink Timing Advance

- In LTE, a mobile starts transmitting its uplink frames at a time TA (Timing Advance) before the arrival of the corresponding frames on the downlink
- TA is used for the following reason
  - ✓ Even traveling at the speed of light, a mobile's transmissions take time (typically a few microseconds) to reach the BS
  - ✓ However, the signals from different mobiles have to reach the BS at roughly the same time, with a delay spread less than the cyclic prefix duration, to prevent any risk of inter-symbol interference between them
  - ✓ To enforce this requirement, distant mobiles have to start transmitting slightly earlier than they otherwise would



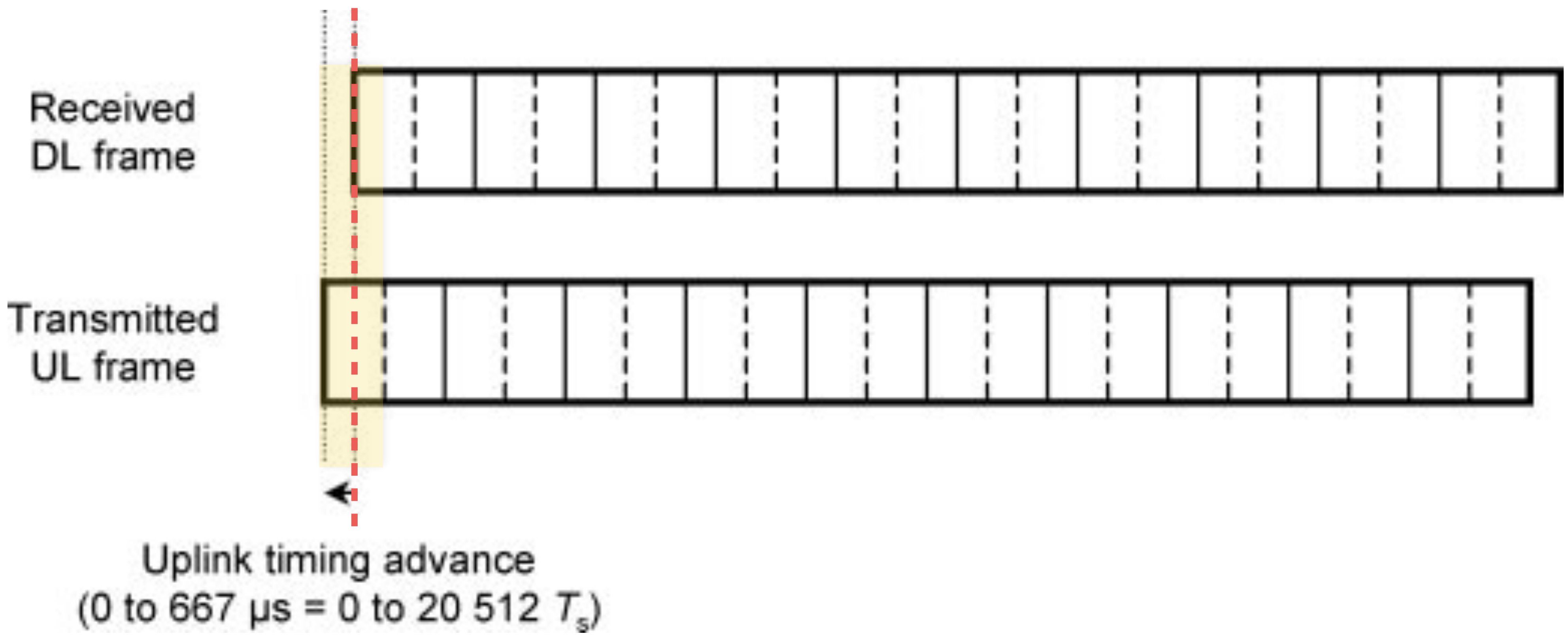


Figure 6.7 Timing relationship between the uplink and downlink in FDD mode.

- Because the uplink transmission time is based on the downlink arrival time, the TA has to compensate for the round-trip travel time between BS and mobile

$$\text{TA} \approx \frac{2L}{c}$$

  - ✓ L : the distance between mobile and BS
  - ✓ c : the speed of light
- The TA does not have to be completely accurate, as the cyclic prefix can handle any remaining errors

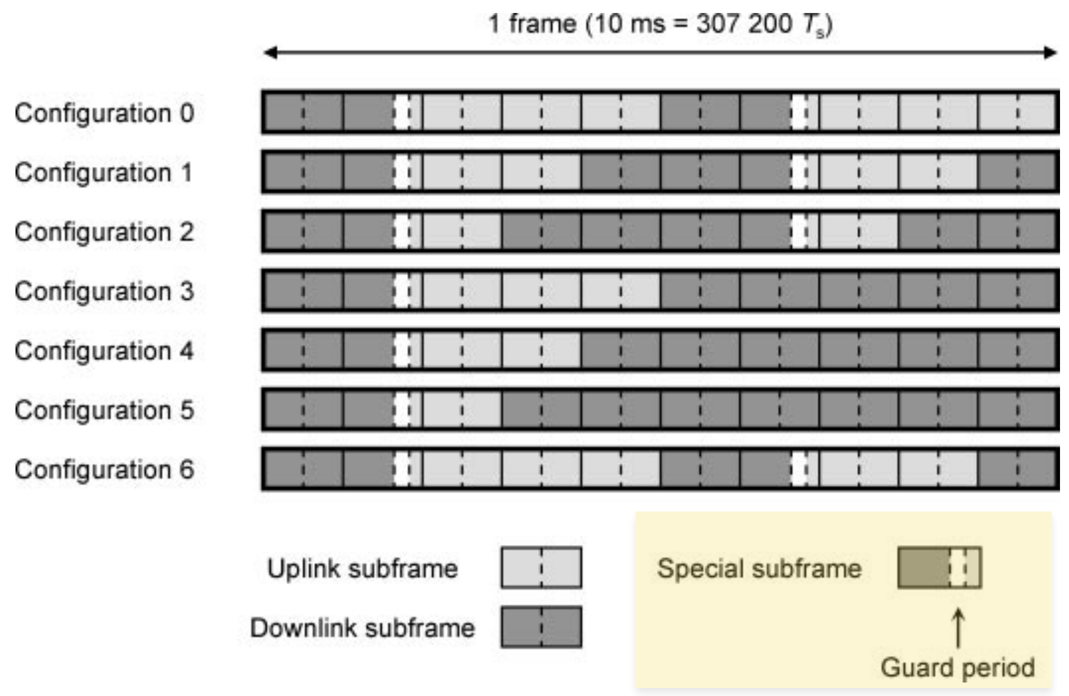
- The specifications define the TA as follows:

$$TA = (N_{TA} + N_{TAoffset})\,T_s$$

  - ✓ N_{TA}
    - Lies between 0 and 20,512
    - This gives a max TA of about 667 μs (two-thirds of a subframe), which supports a max cell size of 100 km
    - N_{TA} is initialized by random access procedure, and updated by timing advance procedure

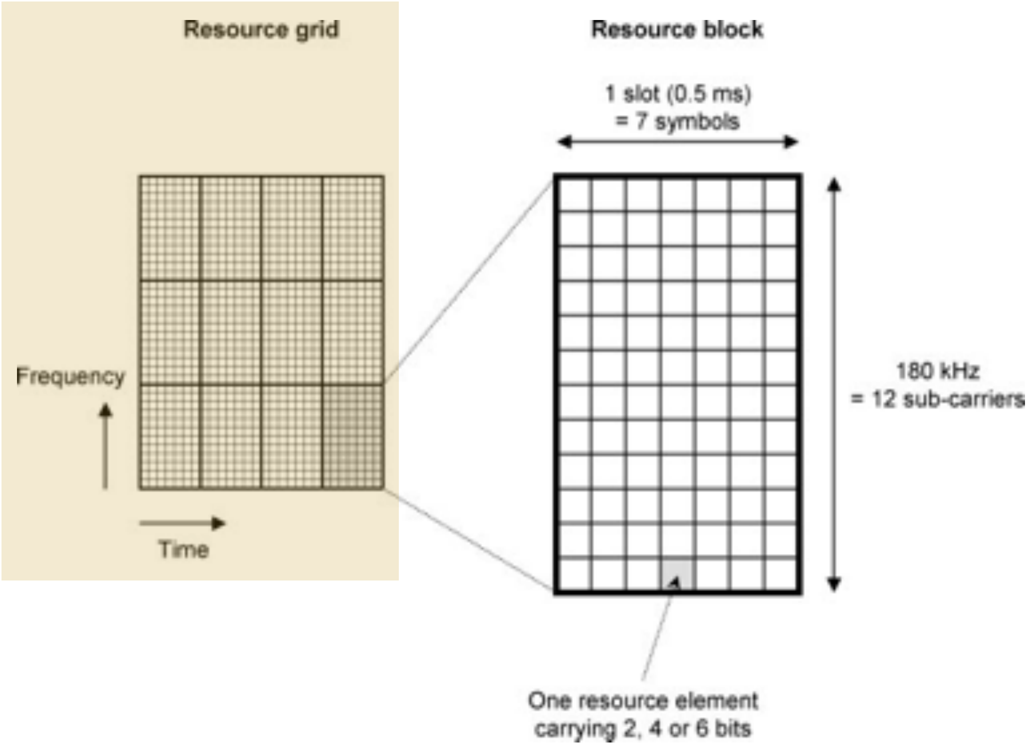
- $N_{TAoffset}$
  - $N_{TAoffset}$ is zero in FDD mode, but 624 in TDD mode
  - This creates a small gap at the transition from uplink to downlink transmissions, which gives BS time to switch from one to the other

- The guard period in each special subframe creates a longer gap at the transition from downlink to uplink, which allows the mobile to advance its uplink frames without them colliding with the frames received on the downlink



3.4 Resource Grid Structure

- In LTE, information is organized as a function of frequency as well as time, using a resource grid
- The figure shows the resource grid for the case of a normal cyclic prefix
- There is a similar grid for the extended cyclic prefix, which uses six symbols per slot rather than seven



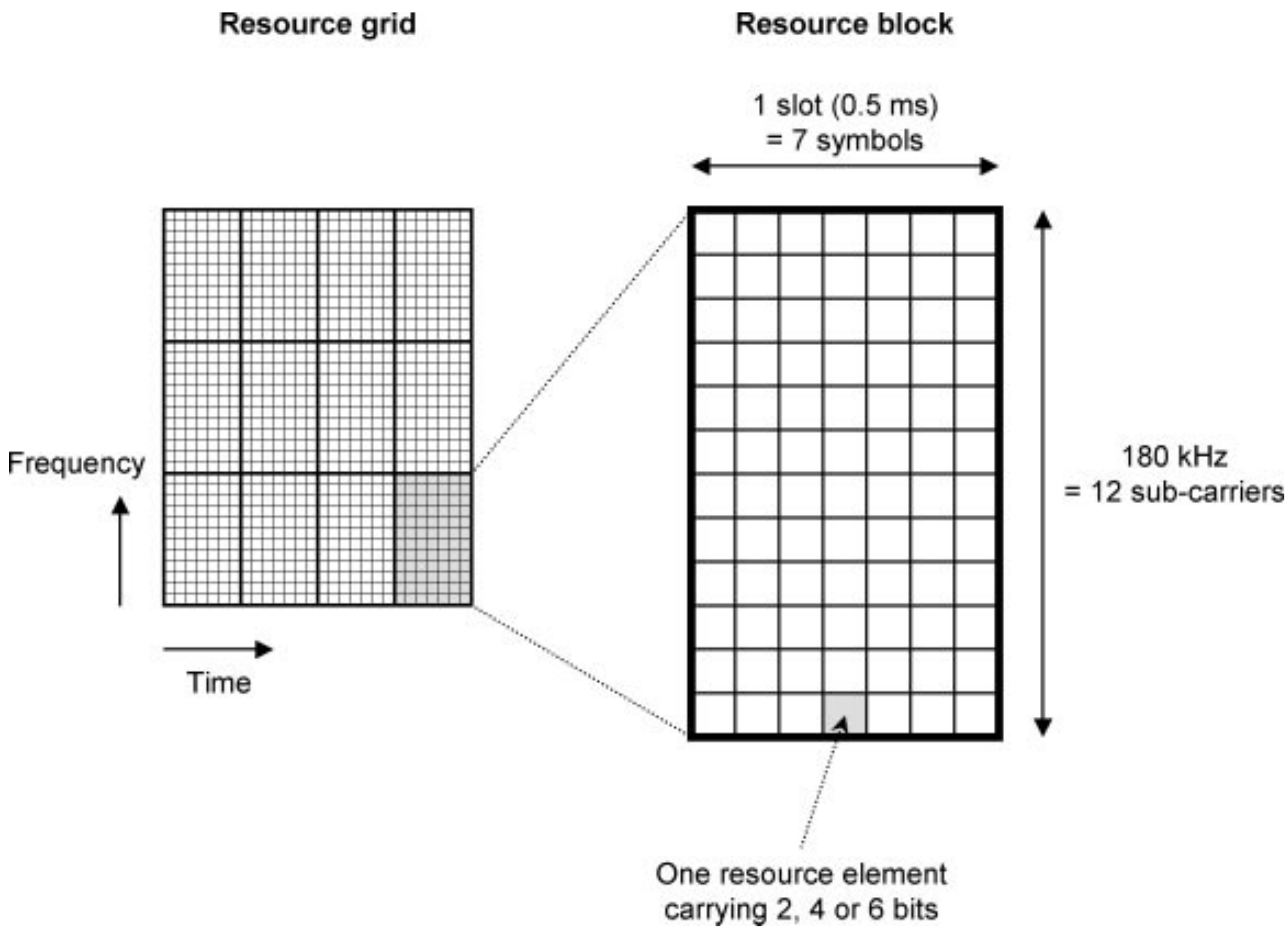
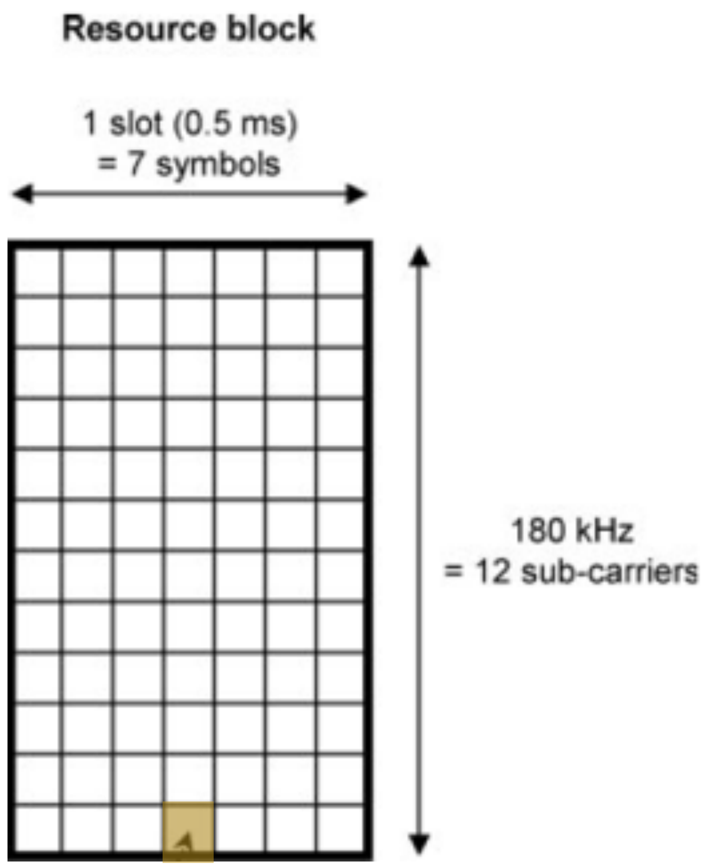


Figure 6.8 Structure of the LTE resource grid in the time and frequency domains, using a <u>normal cyclic prefix</u>.

- Resource element (RE)
  - ✓ The basic unit of resource grid
  - ✓ Each RE spans one symbol by one subcarrier
  - ✓ Each RE usually carries two, four or six physical channel bits, depending on whether the modulation scheme is QPSK (2 bits), 16-QAM (4 bits) or 64-QAM (6 bits)
- Resource block (RB)
  - ✓ REs are grouped into resource blocks (RBs)
  - ✓ Each RB spans 0.5 ms (one slot) by 180 kHz (twelve sub-carriers)
  - ✓ BS uses RBs for frequency dependent scheduling, by allocating the symbols and sub-carriers within each subframe in units of RBs



3.5 Bandwidth Options

- A cell can be configured with several different bandwidths as shown in the table
- In a 5MHz band, for example, BS transmits using 25 RBs (equal to 12 x 25 = 300 sub-carriers), giving a transmission bandwidth of 4.5MHz (= 25 x 0.18MHz)
- This arrangement leaves room for guard bands at the upper and lower edges of the frequency band (5MHz - 4.5MHz = 0.5MHz = 2 x 0.25MHz), which minimize the amount of interference with the next band along
- The two guard bands are usually the same width, but the network operator can adjust them if necessary by shifting the centre frequency in units of 100kHz

Total bandwidth	Number of resource blocks	Number of sub-carriers	Occupied bandwidth	Usual guard bands
1.4 MHz	6	72	1.08 MHz	2×0.16 MHz
3 MHz	15	180	2.7 MHz	2×0.15 MHz
5 MHz	25	300	4.5 MHz	2×0.25 MHz
10 MHz	50	600	9 MHz	2×0.5 MHz
15 MHz	75	900	13.5 MHz	2×0.75 MHz
20 MHz	100	1200	18 MHz	2×1 MHz

- The existence of all these bandwidth options makes it easy for network operators to deploy LTE in a variety of spectrum management regimes, e.g.
  - ✓ 1.4MHz is close to the bandwidths previously used by cdma2000 and TD-SCDMA
  - ✓ 5MHz is the same bandwidth used by WCDMA
  - ✓ 20MHz allows an LTE BS to operate at its highest possible data rate
- In FDD mode, the uplink and downlink bandwidths are usually the same

Total bandwidth	Number of resource blocks	Number of sub-carriers	Occupied bandwidth	Usual guard bands
1.4 MHz	6	72	1.08 MHz	2×0.16 MHz
3 MHz	15	180	2.7 MHz	2×0.15 MHz
5 MHz	25	300	4.5 MHz	2×0.25 MHz
10 MHz	50	600	9 MHz	2×0.5 MHz
15 MHz	75	900	13.5 MHz	2×0.75 MHz
20 MHz	100	1200	18 MHz	2×1 MHz

Total bandwidth	Number of resource blocks	Number of sub-carriers	Occupied bandwidth	Usual guard bands
1.4 MHz	6	72	1.08 MHz	2 × 0.16 MHz
3 MHz	15	180	2.7 MHz	2 × 0.15 MHz
5 MHz	25	300	4.5 MHz	2 × 0.25 MHz
10 MHz	50	600	9 MHz	2 × 0.5 MHz
15 MHz	75	900	13.5 MHz	2 × 0.75 MHz
20 MHz	100	1200	18 MHz	2 × 1 MHz

Table 6.7 Cell bandwidths supported by LTE

- 1. Air Interface Protocol Stack
- 2. Logical, Transport and Physical Channels
- 3. The Resource Grid
- 4. Multiple Antenna Transmission
- 5. Resource Element Mapping

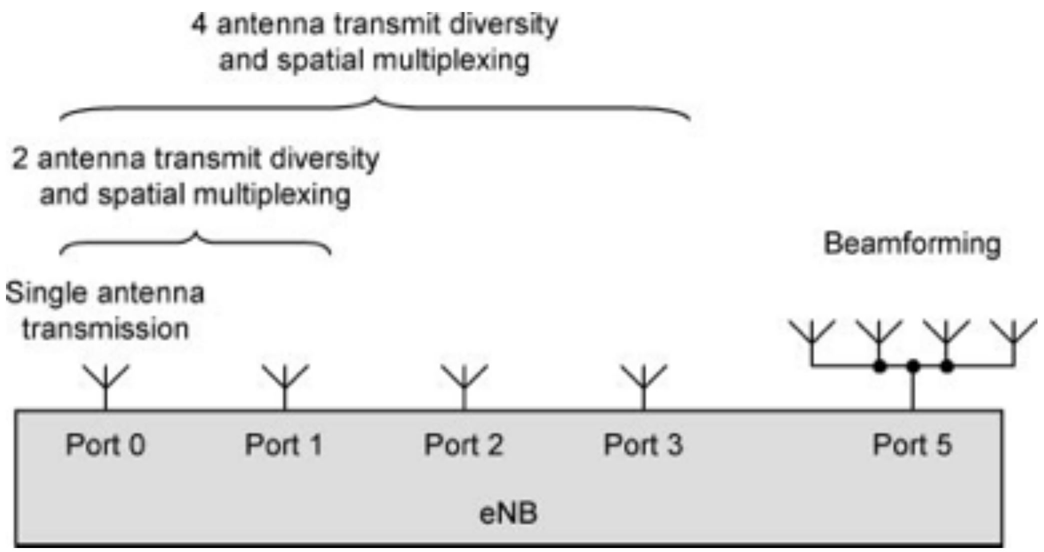
4. Multiple Antenna Transmission

- 4.1 Downlink Antenna Ports
- 4.2 Downlink Transmission Modes

4.1 Downlink Antenna Ports

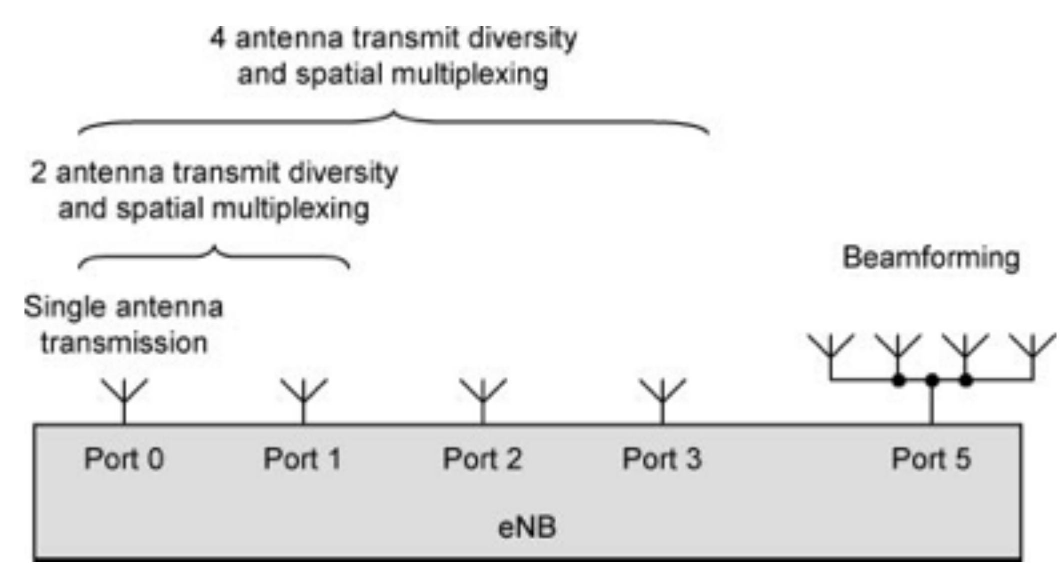
- In the downlink, multiple antenna transmissions are organized using antenna ports, each of which has its own copy of the resource grid
- The following table lists the BS antenna ports that LTE uses

Antenna port	Release	Application
0	R8	Single antenna transmission 2 and 4 antenna transmit diversity and spatial multiplexing
1	R8	2 and 4 antenna transmit diversity and spatial multiplexing
2	R8	4 antenna transmit diversity and spatial multiplexing
3	R8	4 antenna transmit diversity and spatial multiplexing
4	R8/R9	MBMS
5	R8	Beamforming
6	R9	Positioning reference signals
7–8	R9	Dual layer beamforming 8 antenna spatial multiplexing
9–14	R10	8 antenna spatial multiplexing
15–22	R10	CSI reference signals



- Ports 0 to 3 are used for single antenna transmission, transmit diversity and spatial multiplexing
- Port 5 is reserved for beamforming (or spatial filtering)
  - ✓ Beamforming is a signal processing technique used in sensor arrays for directional signal transmission or reception
  - ✓ A sensor array is a group of sensors deployed in a certain geometry pattern. The advantage of using a sensor array over using a single sensor lies in the factor that an array can increase the antenna gain in the direction of the signal while decreasing the gain in the directions of noise and interferences
  - ✓ Beamforming is achieved by changing the directionality of the array when transmitting, a beamformer controls the phase and relative amplitude of the signal at each transmitter, in order to create a pattern of constructive and destructive interference in the wavefront
  - ✓ When receiving, information from different sensors is combined in a way where the expected pattern of radiation is preferentially observed
- The remaining antenna ports are introduced in Releases 9 and 10

Antenna port	Release	Application
0	R8	Single antenna transmission 2 and 4 antenna transmit diversity and spatial multiplexing
1	R8	2 and 4 antenna transmit diversity and spatial multiplexing
2	R8	4 antenna transmit diversity and spatial multiplexing
3	R8	4 antenna transmit diversity and spatial multiplexing
4	R8/R9	MBMS
5	R8	Beamforming
6	R9	Positioning reference signals
7–8	R9	Dual layer beamforming 8 antenna spatial multiplexing
9–14	R10	8 antenna spatial multiplexing
15–22	R10	CSI reference signals



Antenna port	Release	Application
0	R8	Single antenna transmission 2 and 4 antenna transmit diversity and spatial multiplexing
1	R8	2 and 4 antenna transmit diversity and spatial multiplexing
2	R8	4 antenna transmit diversity and spatial multiplexing
3	R8	4 antenna transmit diversity and spatial multiplexing
4	R8/R9	MBMS
5	R8	Beamforming
6	R9	Positioning reference signals
7–8	R9	Dual layer beamforming 8 antenna spatial multiplexing
9–14	R10	8 antenna spatial multiplexing
15–22	R10	CSI reference signals

Table 6.8 Antenna ports used by the LTE downlink

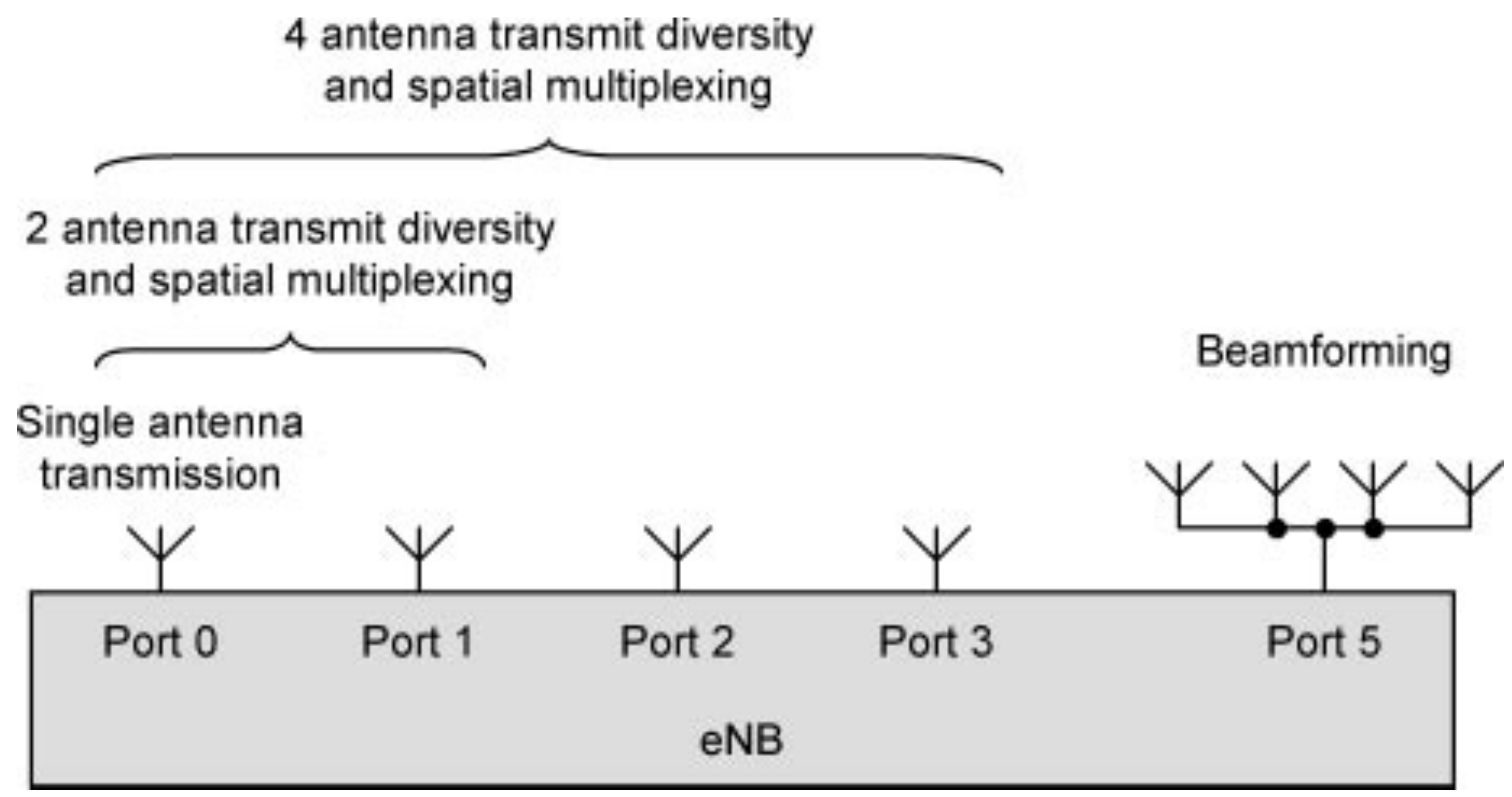


Figure 6.9 Antenna ports used by a Release 8 base station

4.2 Downlink Transmission Modes

- To support the use of <u>multiple antennas</u>, the BS can optionally configure the <u>mobile</u> into one of the following downlink transmission modes

			Uplink feedback required		
Mode	Release	Purpose	CQI	RI	PMI
1	R8	Single antenna transmission	✓		
2	R8	Open loop transmit diversity	✓		
3	R8	Open loop spatial multiplexing	✓	✓	
4	R8	Closed loop spatial multiplexing	✓	✓	✓
5	R8	Multiple user MIMO	✓		✓
6	R8	Closed loop transmit diversity	✓		✓
7	R8	Beamforming	✓		
8	R9	Dual layer beamforming	✓	Configurable	
9	R10	Eight layer spatial multiplexing	✓	Configurable	

CQI : Channel Quality Indicator
RI : Rank Indication
PMI : Precoding Matrix Indicator

			Uplink feedback required		
Mode	Release	Purpose	CQI	RI	PMI
1	R8	Single antenna transmission	✓		
2	R8	Open loop transmit diversity	✓		
3	R8	Open loop spatial multiplexing	✓	✓	
4	R8	Closed loop spatial multiplexing	✓	✓	✓
5	R8	Multiple user MIMO	✓		✓
6	R8	Closed loop transmit diversity	✓		✓
7	R8	Beamforming	✓		
8	R9	Dual layer beamforming	✓	Configurable	
9	R10	Eight layer spatial multiplexing	✓	Configurable	

Table 6.9 Downlink transmission modes

- The transmission mode defines
  - ✓ Type of multiple antenna processing that the BS will use for its transmissions on PDSCH (Physical Downlink Shared CHannel)
  - ✓ Type of processing that the mobile should use for PDSCH reception
  - ✓ It also defines the feedback that the BS will expect from the mobile

Mode	Release	Purpose	Uplink feedback required		
			CQI	RI	PMI
1	R8	Single antenna transmission	✓		
2	R8	Open loop transmit diversity	✓		
3	R8	Open loop spatial multiplexing	✓	✓	
4	R8	Closed loop spatial multiplexing	✓	✓	✓
5	R8	Multiple user MIMO	✓		✓
6	R8	Closed loop transmit diversity	✓		✓
7	R8	Beamforming	✓		
8	R9	Dual layer beamforming	✓	Configurable	
9	R10	Eight layer spatial multiplexing	✓	Configurable	

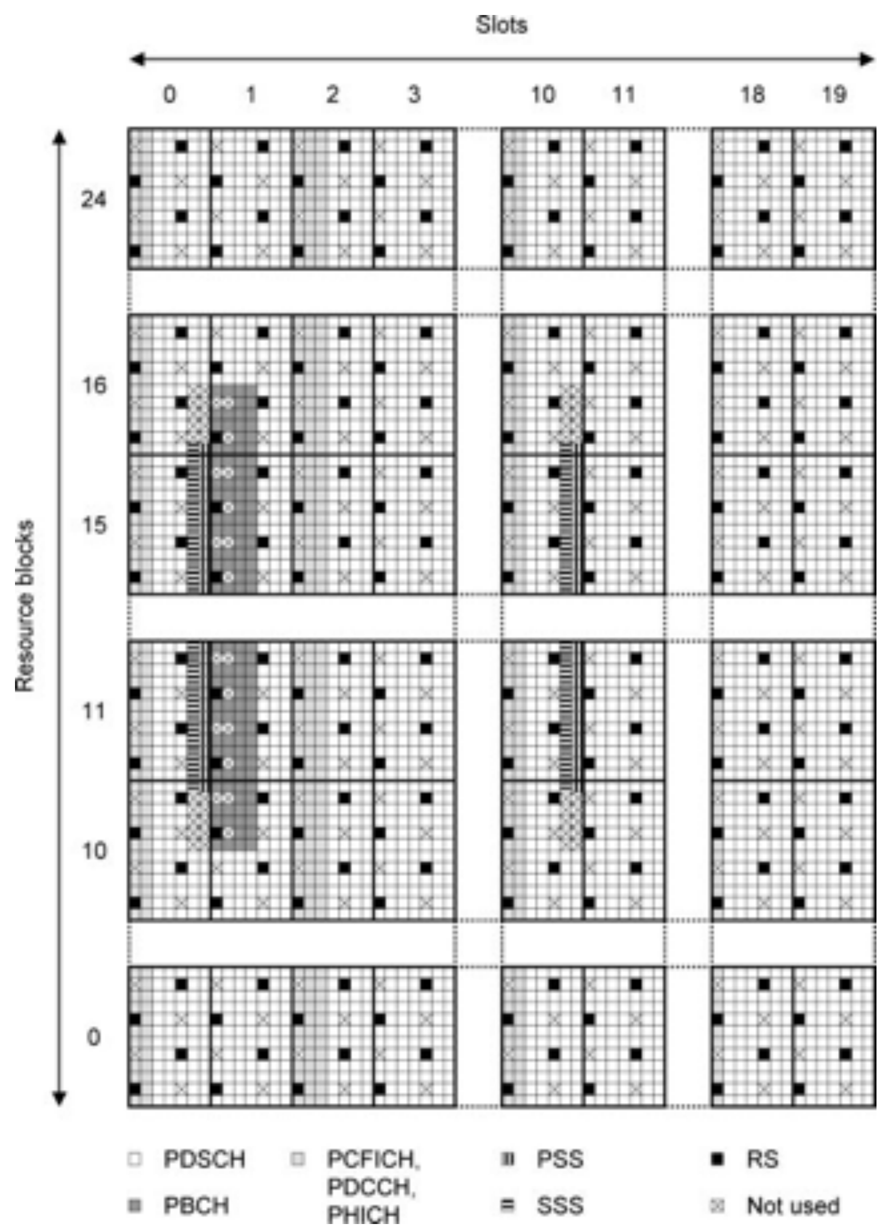
- 1. Air Interface Protocol Stack
- 2. Logical, Transport and Physical Channels
- 3. The Resource Grid
- 4. Multiple Antenna Transmission
- 5. Resource Element Mapping

5. Resource Element Mapping

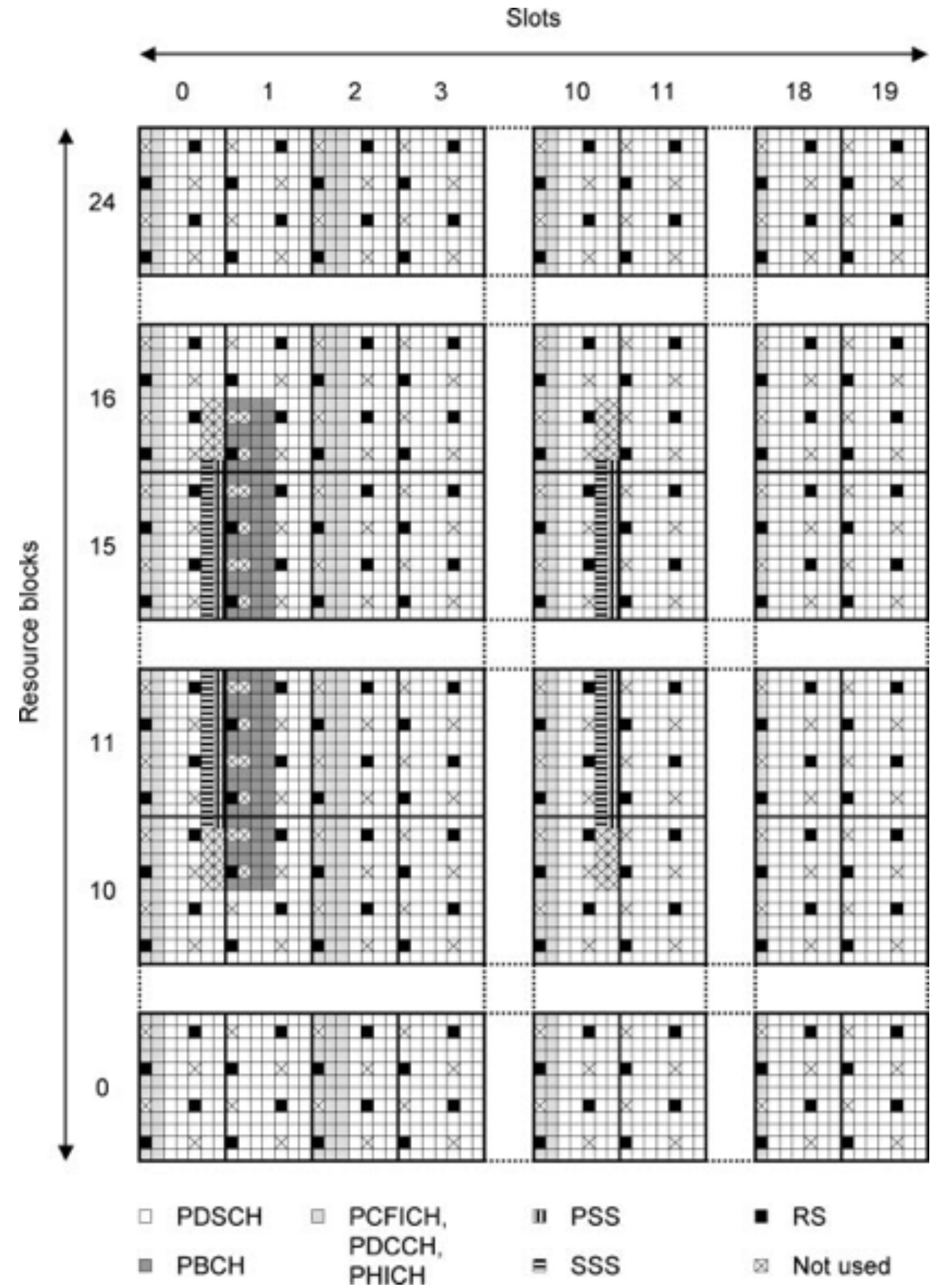
- 5.1 Downlink Resource Element Mapping
- 5.2 Uplink Resource Element Mapping

5.1 Downlink Resource Element Mapping

- LTE physical layer transmits the <u>physical channels</u> and <u>physical signals</u> by mapping them onto <u>resource elements</u>
- The exact mapping depends on the exact configuration of the BS and mobile
- Some example mappings for the uplink and downlink, for a typical system configuration



- The figure shows an example <u>resource element</u> mapping for <u>downlink</u>
  - ✓ Assumes use of <u>FDD mode</u>, <u>normal cyclic prefix</u> and a <u>bandwidth of 5MHz</u>
  - ✓ Time
    - Plotted horizontally and spans the <u>20 slots</u> that make up <u>one frame</u>
  - ✓ Frequency
    - Plotted vertically and spans the <u>25 RBs</u> that make up transmission band



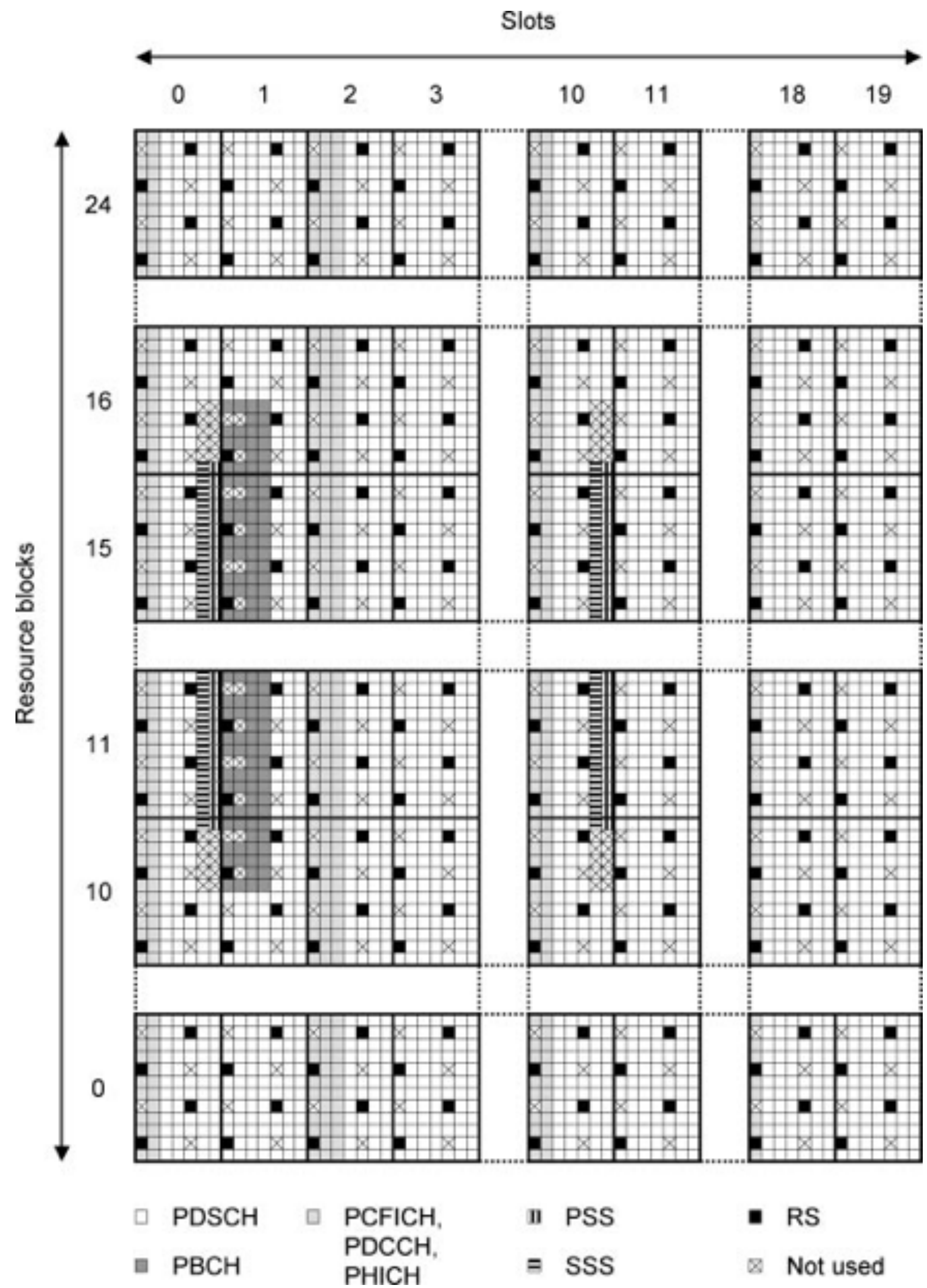


Figure 6.10 Example mapping of physical channels to resource elements in the downlink, using FDD mode, a normal cyclic prefix, a 5MHz bandwidth, the first antenna port of two and a physical cell ID of 1

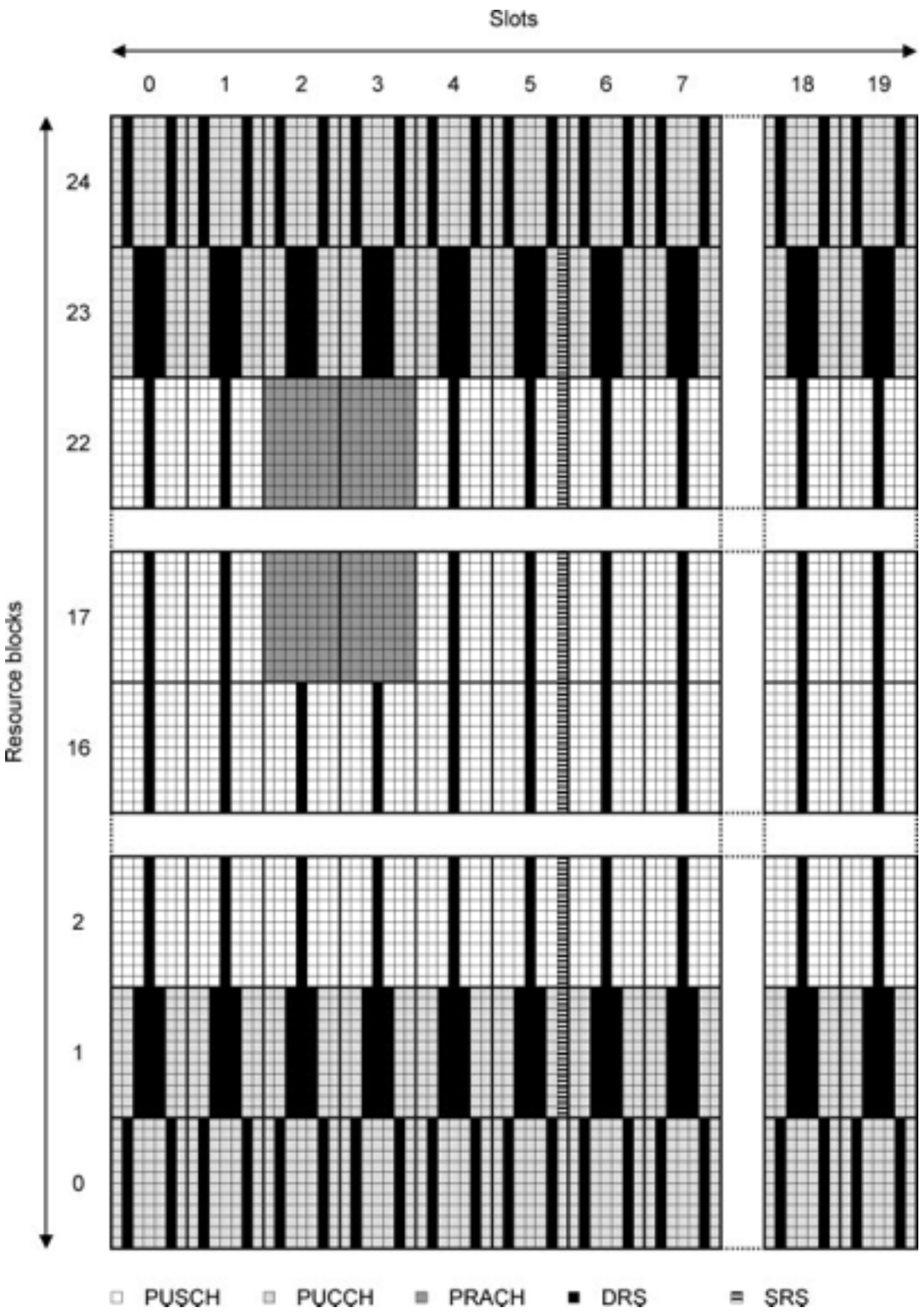
- The cell specific reference signals are scattered across time and frequency domains
  - ✓ While one antenna port is sending a reference signal, the others keep quiet, so that the mobile can measure the received reference signal from one antenna port at a time
- Within each frame, certain resource elements are
  - ✓ Reserved for
    - The primary and secondary synchronization signals
    - The physical broadcast channel
  - ✓ Read during the acquisition procedure

- At the start of each subframe
  - ✓ A few symbols are reserved for the control information that the BS transmits on PCFICH, PDCCH and PHICH
  - ✓ The rest of the subframe is
    - Reserved for data transmissions on the PDSCH
    - Allocated to individual mobiles in units of RBs within each subframe

Channel	Release	Name	Information carried	Direction
PUCCH	R8	Physical uplink control channel	UCI	UL
PCFICH	R8	Physical control format indicator channel	CFI	DL
PHICH	R8	Physical hybrid ARQ indicator channel	HI	
PDCCH	R8	Physical downlink control channel	DCI	
R-PDCCH	R10	Relay physical downlink control channel	DCI	

5.2 Uplink Resource Element Mapping

- The figure shows the mapping of physical channels to resource elements in the uplink
  - ✓ Assume the use of FDD mode, a normal cyclic prefix, a 5MHz bandwidth



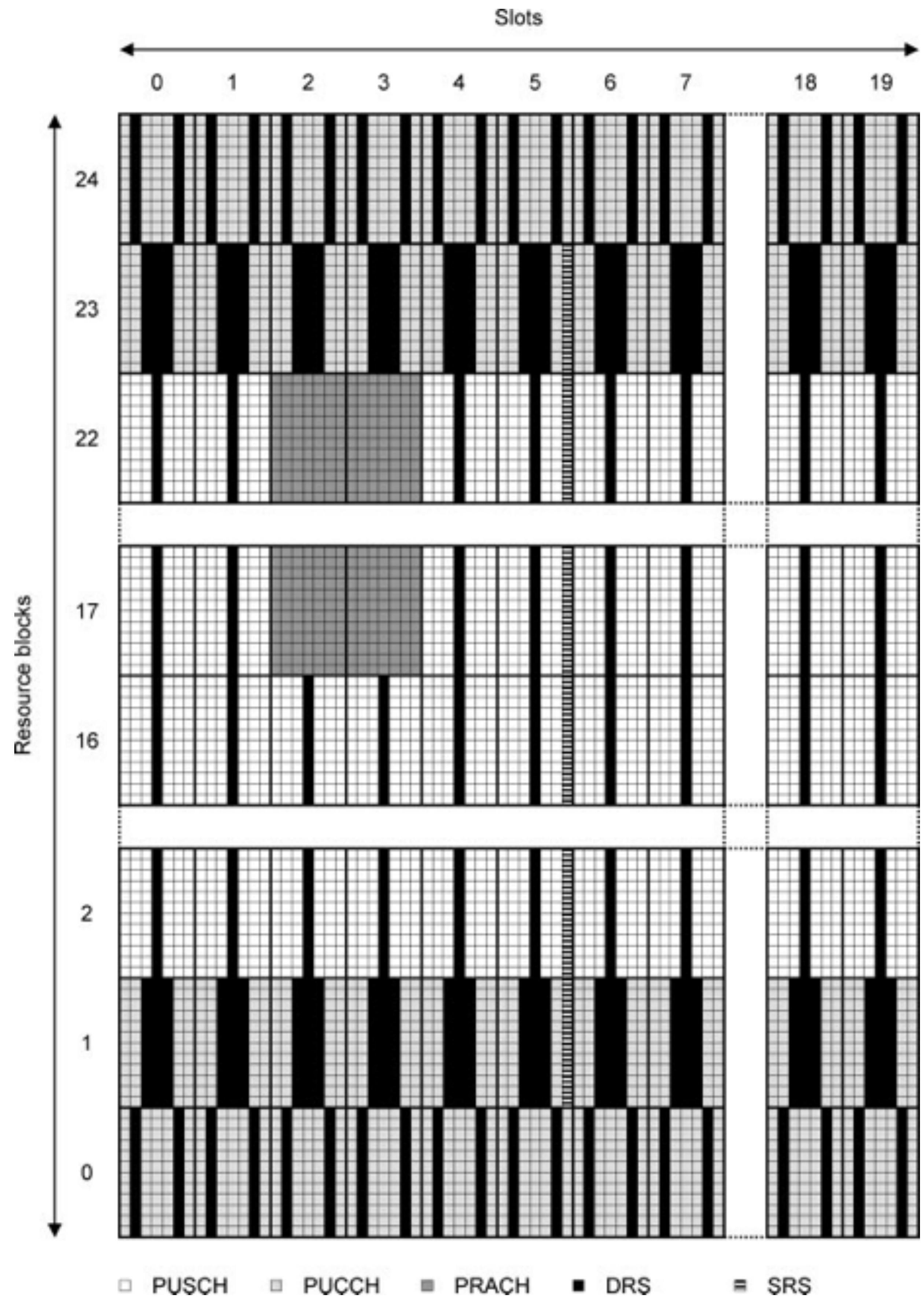
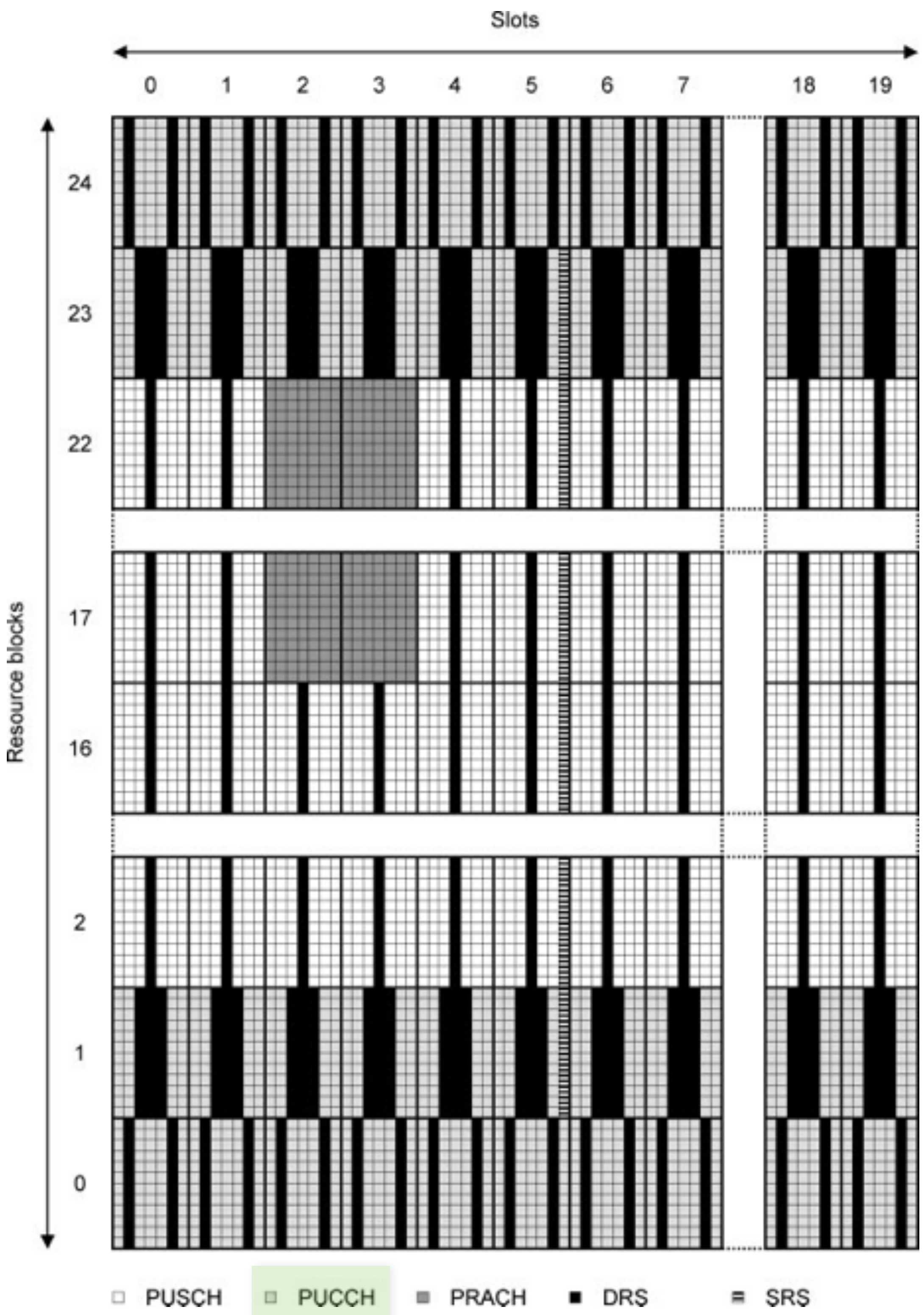
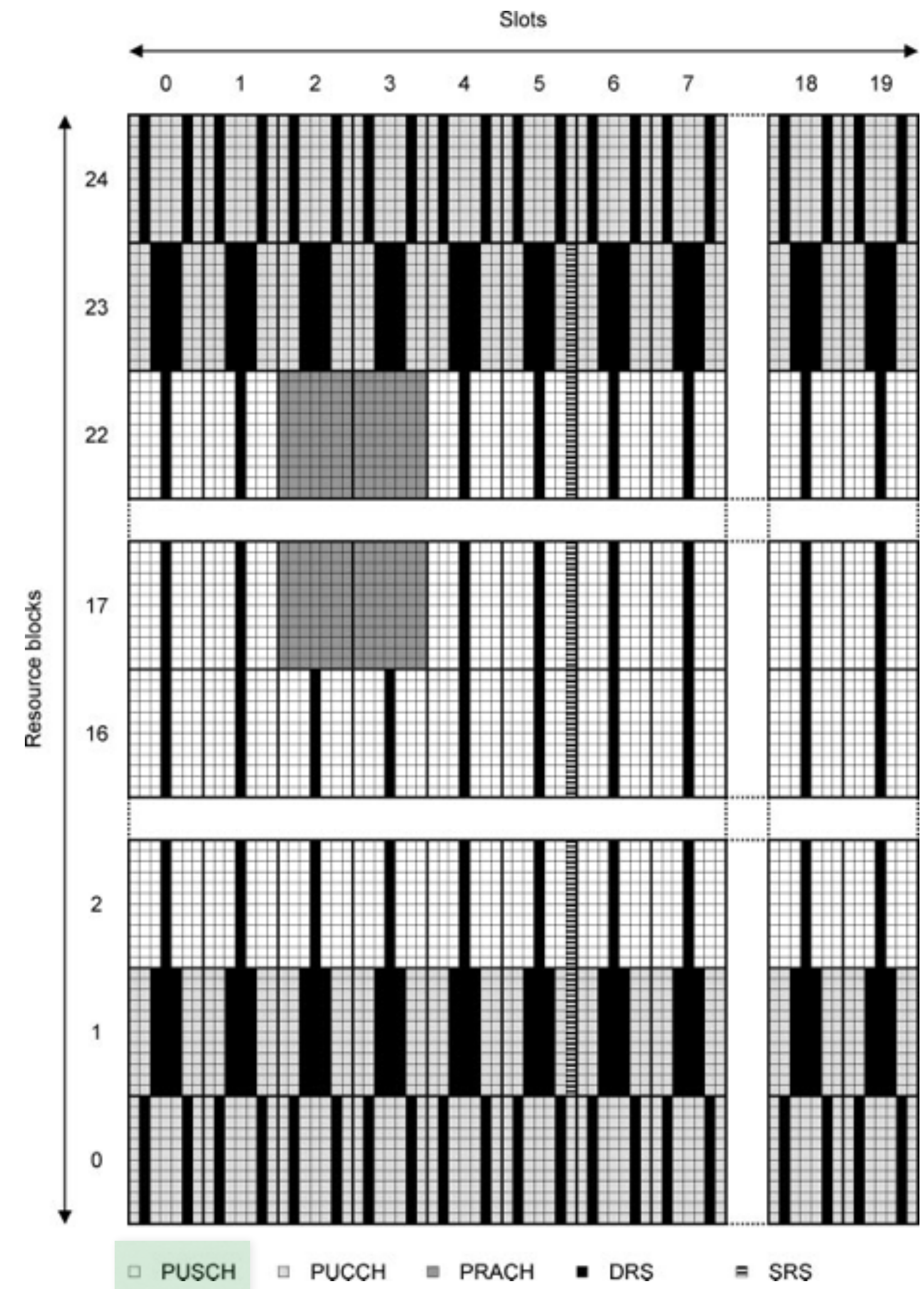


Figure 6.11 shows the corresponding situation on the uplink. The figure assumes the use of FDD mode, the normal cyclic prefix and a bandwidth of 5MHz.

- PUCCH (Physical Uplink Control CHannel)
  - ✓ PUCCH can be sent in various different formats, depending on the information that the mobile has to transmit, for example
    - PUCCH formats 1, 1a and 1b
      - Four control symbols per slot
      - Three reference symbols
    - PUCCH formats known as 2, 2a and 2b
      - Five control symbols per slot
      - Two reference symbols



- PUSCH (Physical Uplink Shared CHannel)
  - ✓ The rest of the band is mainly used by the PUSCH and is allocated to <u>individual mobiles</u> in units of RBs within each <u>subframe</u>
  - ✓ PUSCH transmissions contain
    - Six data symbols per slot
    - One reference symbol



- PRACH (Physical Random Access CHannel)
  - ✓ The BS also reserves certain RBs for <u>random access transmissions</u> on the PRACH
  - ✓ The PRACH has a bandwidth of <u>six RBs</u> and a <u>duration</u> from one to three subframes, while its locations in the resource grid are configured by the BS