Standardization of MIMO-OFDM Technology

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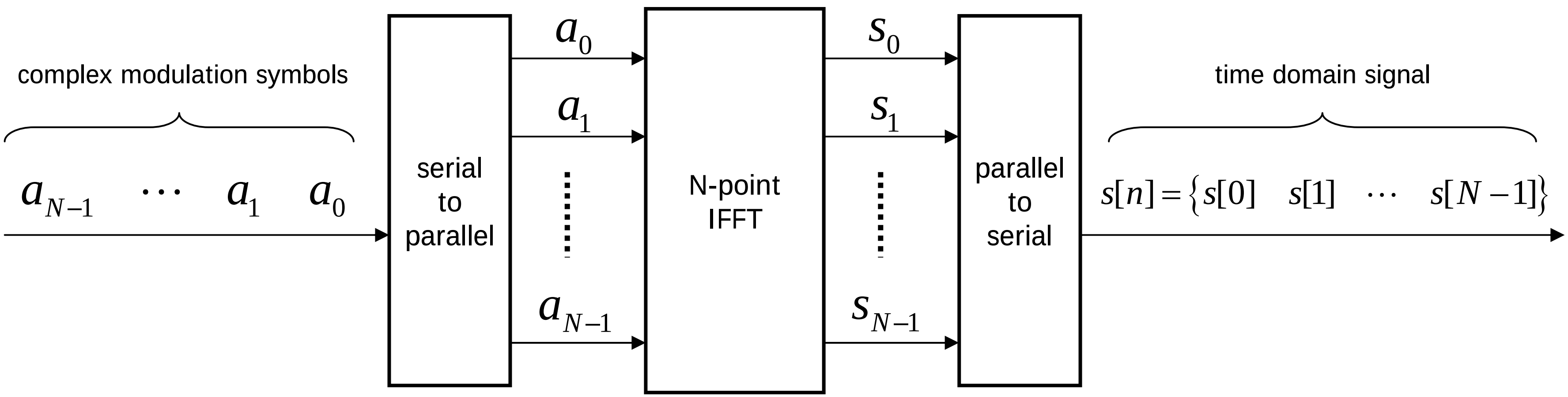
Outline

- OFDM basics
- MIMO basics
- 3GPP LTE standard
- IEEE 802.11n standard
- IEEE 802.16e standard

What is OFDM

- OFDM = Orthogonal Frequency Division Multiplexing
- OFDM is a bandwidth-efficient technique for multi-carrier modulation
- The IFFT operation in OFDM partitions a wideband channel into multiple narrowband sub-channels



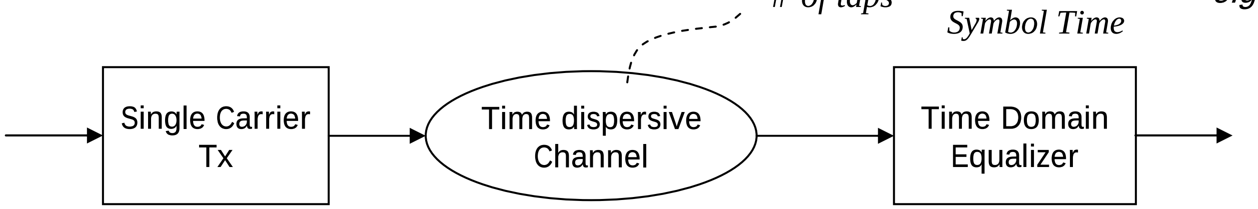
$$s[n]=\sum_{k=0}^{N-1} a[k]\cdot e^{j2\pi kn/N} \Leftrightarrow \begin{pmatrix} s_0 \\ s_1 \\ \vdots \\ s_{N-1} \end{pmatrix} = \underbrace{\begin{pmatrix} e^{j2\pi(0)(0)/N} & e^{j2\pi(1)(0)/N} & \cdots & e^{j2\pi(N-1)(0)/N} \\ e^{j2\pi(0)(1)/N} & e^{j2\pi(1)(1)/N} & \cdots & e^{j2\pi(N-1)(1)/N} \\ \vdots & \vdots & \vdots & \vdots \\ e^{j2\pi(0)(N-1)/N} & e^{j2\pi(1)(N-1)/N} & \cdots & e^{j2\pi(N-1)(N-1)/N} \end{pmatrix}}_{\text{NxN IDFT matrix}} \cdot \begin{pmatrix} a_0 \\ a_1 \\ \vdots \\ a_{N-1} \end{pmatrix}$$

Advantages of OFDM

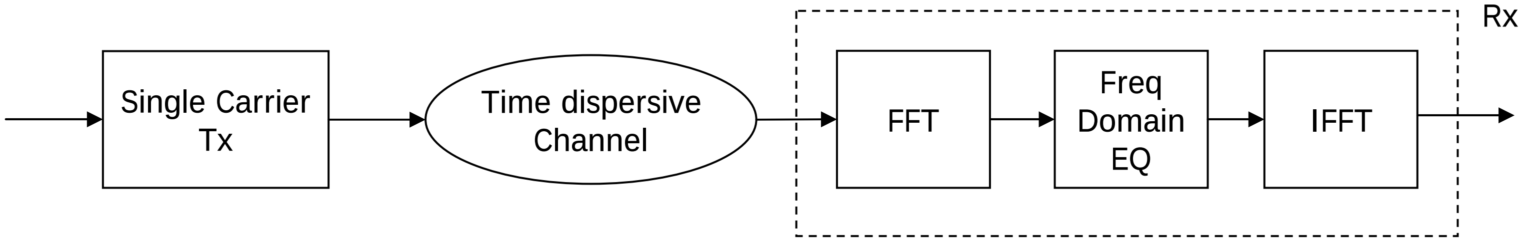
Time domain equalization in a time dispersive channel becomes prohibitively expensive as data rates increase

$$\# \ of \ taps = \frac{Delay \ spread}{Symbol \ Time}$$

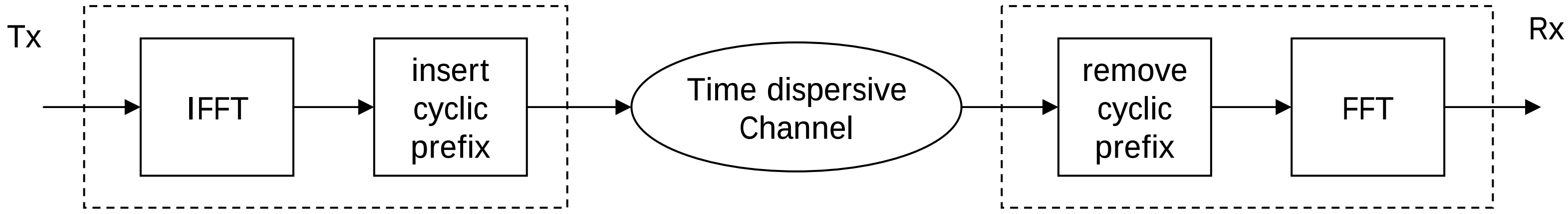
e.g. LTE, > 100 taps at 20MHz



To mitigate complexity, frequency domain equalization is an attractive alternative to time domain equalization



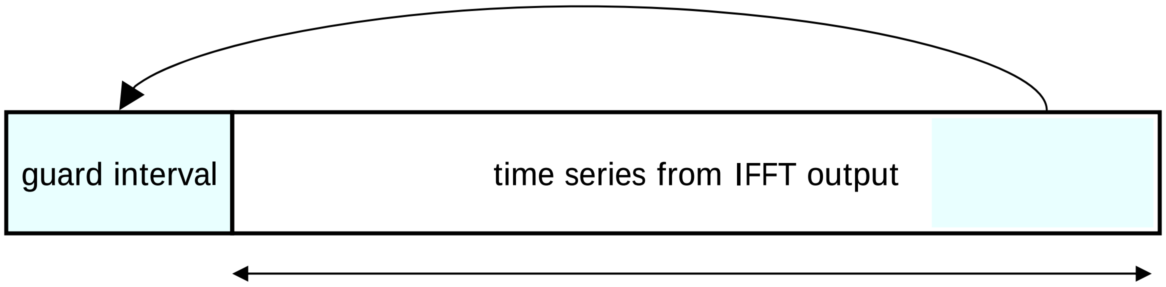
OFDM moves the IFFT operation to the transmitter to load balance complexity between the Tx and the Rx



Drawbacks of OFDM

- **Peak-to-Average Power Ratio (PAPR)**
  - Since the IFFT operation is a weighted summation of a large number of input values, certain input combination could result in a spike at the output
  - Large PAPR poses difficulties for power amplifiers operating in the linear region, which have to back off from P_sat by the PAPR amount
- **Frequency Offset**
  - OFDM demodulation (via the FFT) is susceptible to frequency offsets. There are three sources
    - slowly varying frequency offset between transmit and receive crystals
    - phase noise at the receiver
    - Doppler spread
  - Frequency offset causes inter-carrier interference, which results in an irreducible error floor
- **Length of delay spread**
  - The length of the delay spread in the channel can not exceed the guard interval (i.e. cyclic prefix).
  - If delay spread exceeds the guard interval, OFDM demodulation experiences inter-symbol interference, which results in an irreducible error floor

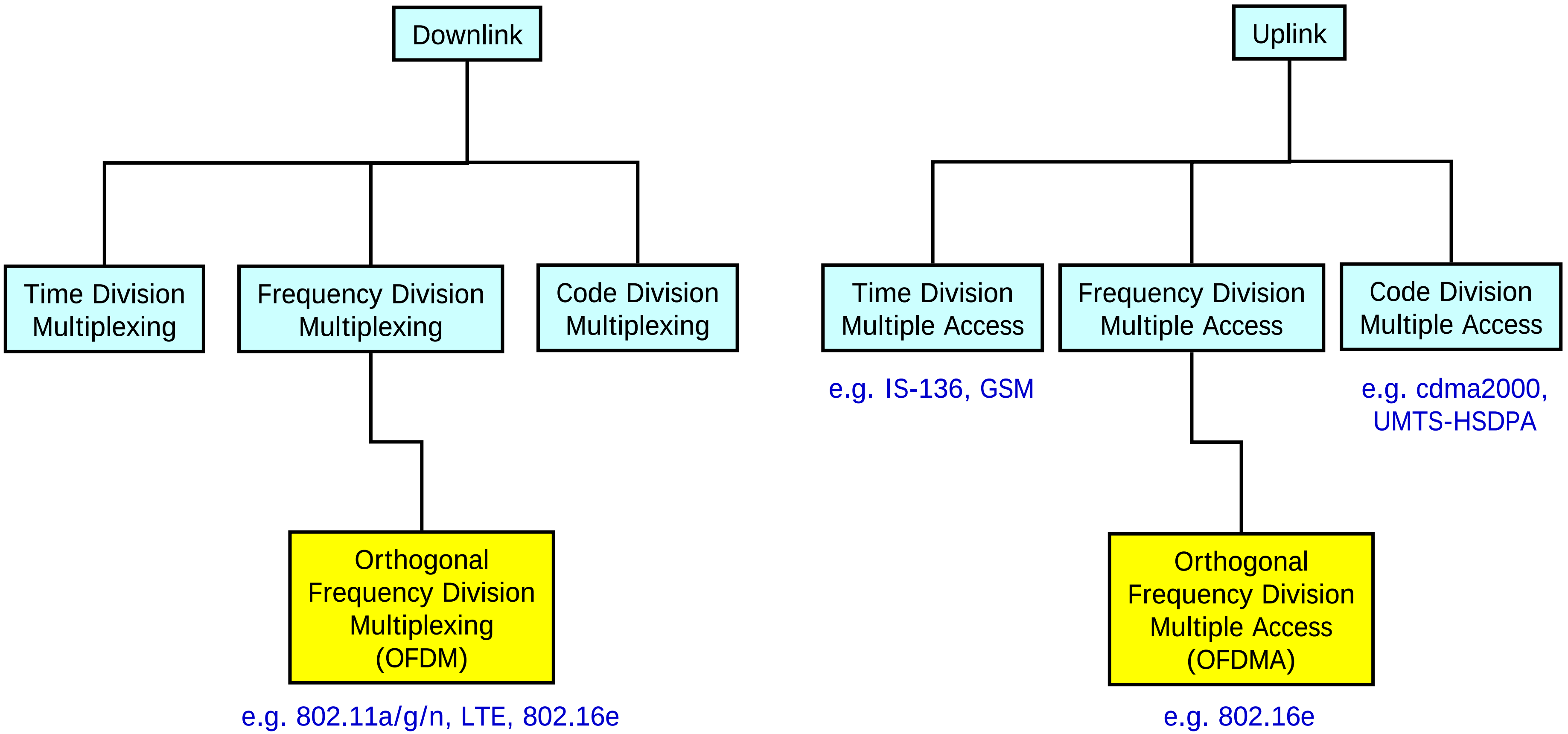
Tradeoffs in OFDM symbol design



$$Length = \frac{1}{sub\text{-}carrier\ \ spacing}$$

- Guard interval is an overhead, which reduces the spectral efficiency
- However, guard interval simplifies equalization at the Rx if guard interval > delay spread
- Hence, to reduce GI overhead, OFDM symbol length has to be increased
- However, increasing the symbol length decreases the sub-carrier spacing (Δf)
- Smaller Δf will make the OFDM symbol more susceptible to Doppler, Phase Noise, and XO offsets

OFD-Multiplexing/Multiple Access



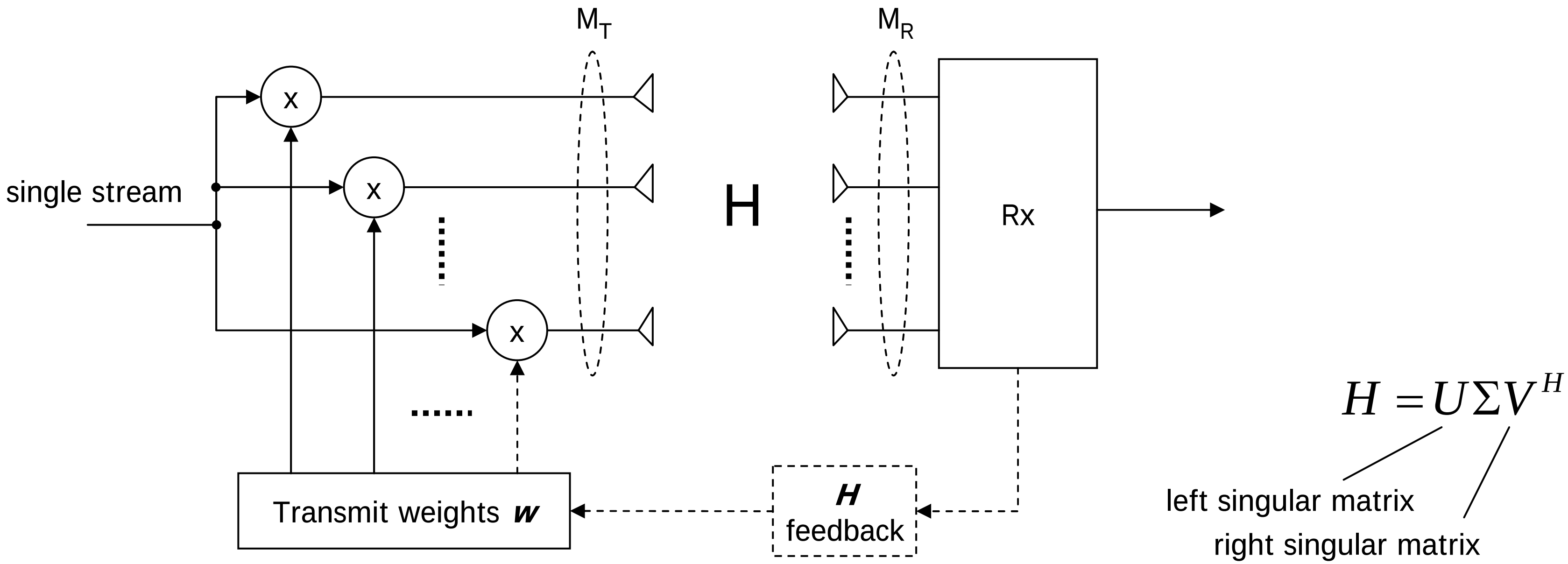
MIMO basics

- Multiple antennas can:
  - increase capacity – both at link level and at system level
    - multiplexing gain
  - increase reliability by combating signal fading
    - array (combining) gain and diversity (independent fading) gain
  - increase transmission range/reach
    - array gain and diversity gain
  - suppress interfering signals
  - use a combination of the above!
- Performance of multiple antennas techniques is optimal if:
  - for single-user scenarios, the channel transfer matrix is full rank
  - for multi-user scenarios, the users are evenly distributed around the base station

Open Loop vs. Closed Loop

- **Closed loop operation**
  - requires feedback from Rx – could be long term or short term
    - sounding packet → CSI construction at Tx (only possible for TDD)
    - quantized CSI (explicit feedback)
    - pointer to a quantized codebook of pre-coding matrices
  - beamforming mode
    - single spatial stream
    - beamwidth should be wider than the angular spread of the dominant angle of departure → antennas should be closely spaced
  - Pre-coded spatial division multiplexing mode
    - SVD is a linear precoder that is optimal in AWGN with fading
    - quantized codebooks with unitary precoders are commonly used to limit signaling overhead
- **Open loop operation**
  - No feedback required from the Rx
  - Transmit diversity
    - single spatial stream
    - e.g. space-time block codes, space-time trellis codes, delay diversity etc.
  - Switched beams
  - Spatial division multiplexing (SDM)
    - pre-coding matrix is an identity matrix, or randomly chosen from the codebook
  - Hybrid schemes – SDM combined with Tx diversity

Beamforming

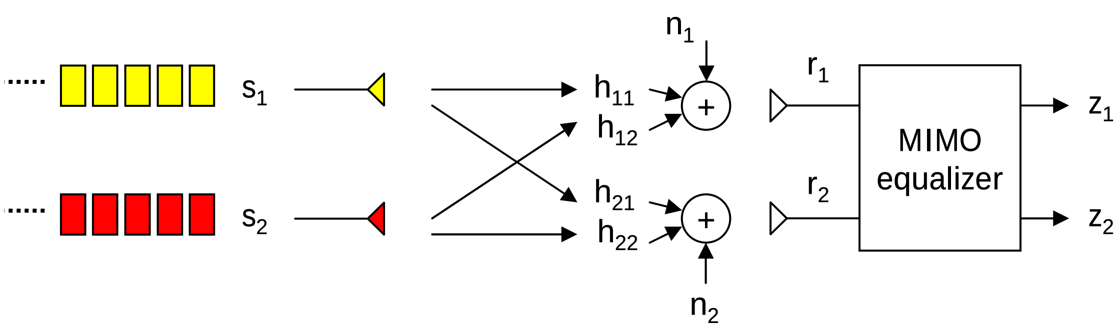


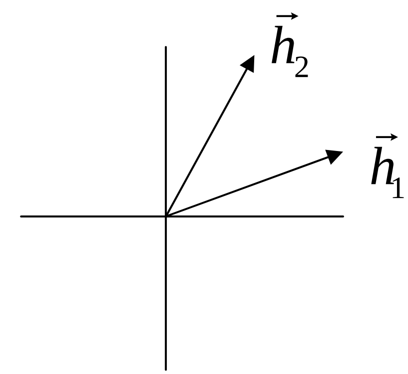
- **For narrowband channels with AWGN:**
  - optimum **w** is the right singular vector corresponding to the largest singular value of **H**
  - the receiver is linear – Rx weights are the left singular vector corresponding to the largest singular value of **H**
  - in the limit that $M_R = 1$, the transmit weights are the complex conjugate of the channel vector. This is also termed as maximal ratio transmission, which is the inverse of MRC (maximal ratio combining)

- **For narrowband channels with AWGN and co-channel interference:**
  - Transmit weights could be the right singular vector
  - However, the receiver should perform interference cancellation or joint detection for optimal performance

Spatial Division Multiplexing (SDM)

- An independent data stream is mapped to each transmit antenna
- The data streams experience spatial cross-talk in the MIMO channel, which has to be equalized at the receiver
- The number of independent data streams ≤ number of transmit antennas
- However, linear equalizers require that the number of independent data streams ≤ min {num of Tx antennas, num of Rx antennas}
    - non-linear equalizers do not place this constraint
- The “degree” of spatial cross-talk is related to the singular value spread of the channel transfer function matrix
- In the limit, if the channel matrix is unitary, there is no cross-talk in the channel





$$\vec{r} = s_1 \cdot \vec{h}_1 + s_2 \cdot \vec{h}_2 + \vec{n}$$

$$\vec{h}_1 = \begin{pmatrix} h_{11} \\ h_{21} \end{pmatrix}, \vec{h}_2 = \begin{pmatrix} h_{12} \\ h_{22} \end{pmatrix}$$

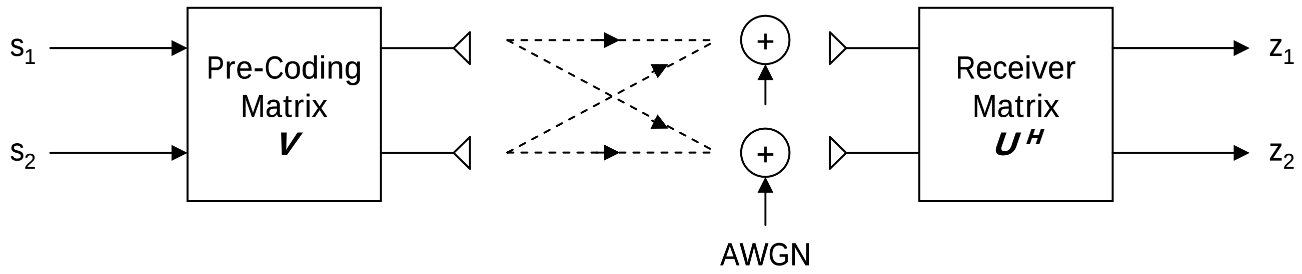
ideal channel $\left\langle \vec{h}_1, \vec{h}_2 \right\rangle = 0$

Pre-Coded SDM

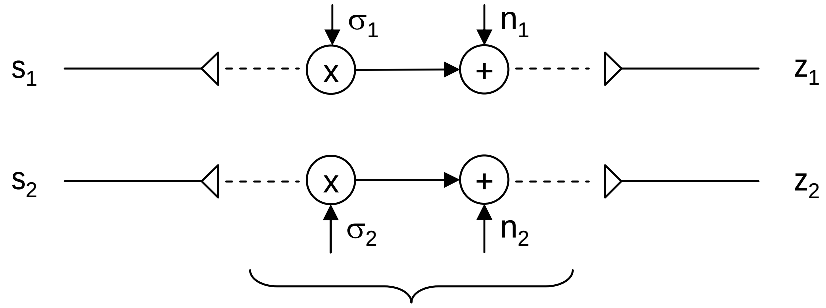
- The motivation for pre-coding is to minimize spatial cross-talk in the MIMO channel
- The right singular matrix, *V*, of the MIMO channel transfer function, *H*, is the optimum pre-coding matrix in AWGN

Note: *U* and *V* are unitary matrices.

$$H = U\Sigma V^H$$



Pre-coding at the transmitter, and linear equalization at the receiver results in an effective channel that is free of spatial cross talk. The MIMO channel transforms into a set of independent parallel "virtual" channels



Transmit Diversity

- Transmit Diversity techniques are well-suited for high Doppler
- **Cyclic Delay Diversity**
  - introduces multipath to increase frequency selectivity of the channel
    - enhances frequency diversity
    - improves performance of channel decoder
  - can improve the performance of multi-user frequency domain scheduling in OFDM
- **Orthogonal Space-Time/Freq Codes**
  - Provide diversity gain, but no array gain
  - Most popular is 2x1 Alamouti code
    - linear receiver achieves ML performance
    - incorporated in several standards now
  - For more than 2 Tx antennas, orthogonal codes do not exist for complex constellations
- **Space-Time/Freq Trellis Codes**
  - Provide both coding and diversity gain
  - receiver has to be ML to extract performance gains – hence not used by any standard

3GPP LTE
(Long Term Evolution)

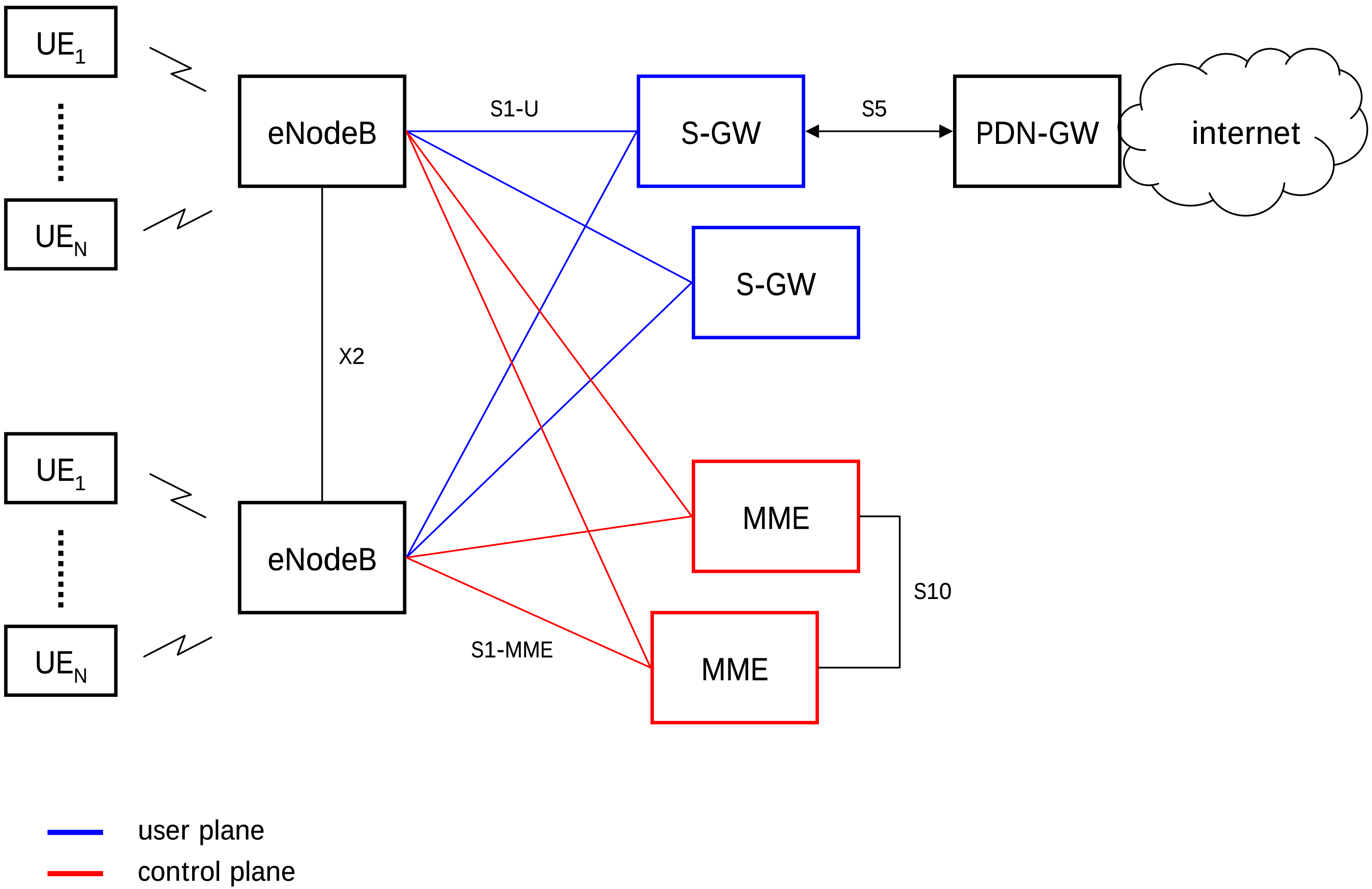
Outline

- LTE Systems Architecture
- OFDM aspects
- MIMO aspects
- Control Signaling aspects

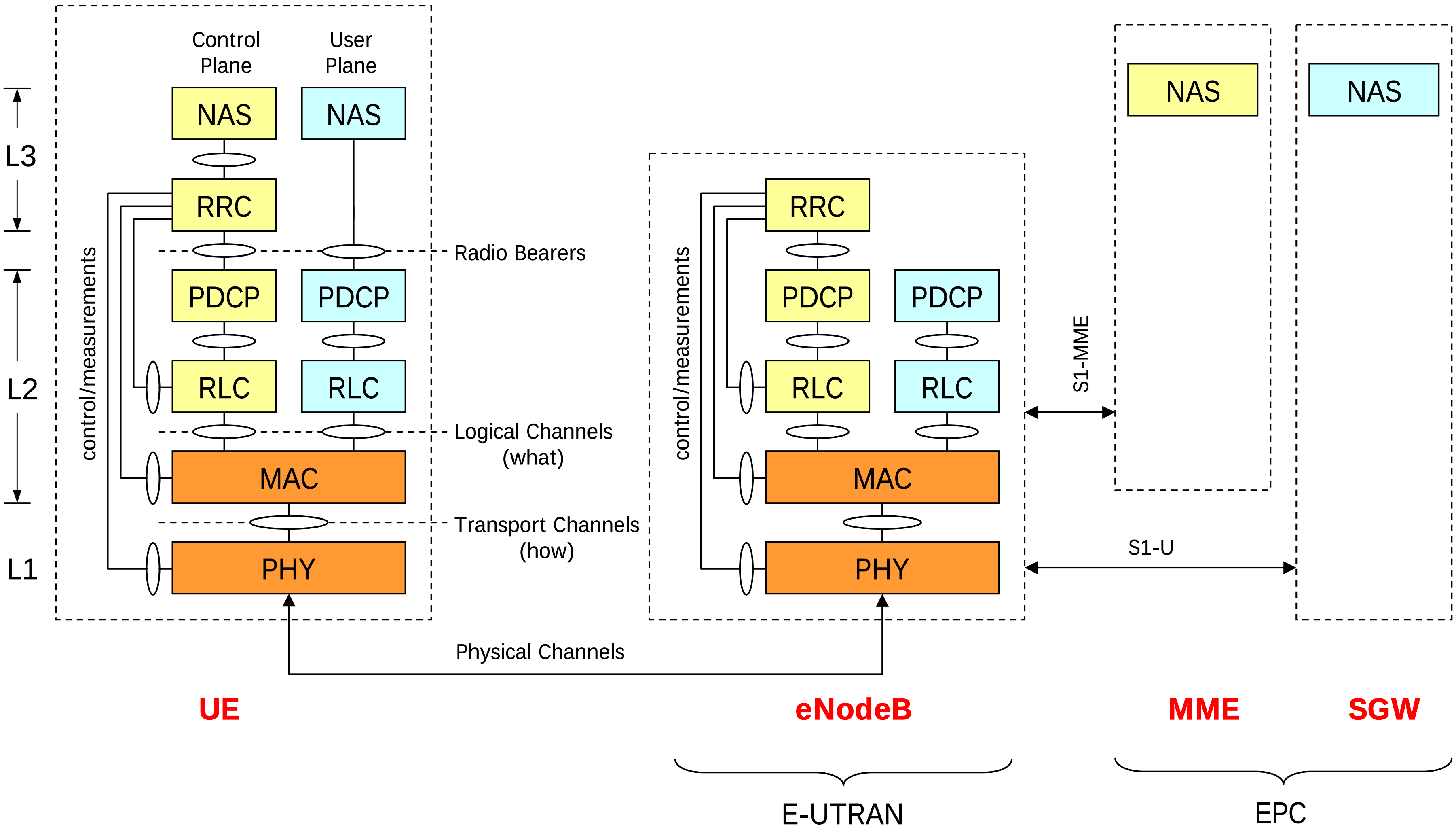
LTE - High Level Requirements

- Standardization effort for LTE was launched in Nov 2004
  - expected to complete in 1H2008
- Peak data rate
  - 100Mbps in 20MHz in the downlink (with 2x2 MIMO)
  - 50Mbps in 20MHz in the uplink (without MIMO)
- Control plane latency
  - transition time from idle to active state ≤ 100ms
  - transition time from dormant to active state ≤ 50ms
- User plane latency
  - measured from UE to edge of Radio Access Network (one way)
  - shall be less than 5ms for single user for small IP packet
- Control plane capacity
  - at least 200 active voice calls / cell / 5MHz
- Mobility
  - optimum performance at low speeds – from 0 to 15km/hr
  - high performance at higher speeds – from 15 to 120km/hr
- Spectrum flexibility
  - 1.25MHz, 1.6MHz, 2.5MHz, 5MHz, 10MHz, 15MHz, and 20MHz
- All IP network
  - All services in the packet switched domain
  - No circuit switched domain

LTE – Functional Architecture



LTE - Protocol Architecture



Services and Functions of Layers (1)

- **NAS (control plane)**
  - user authentication
  - UE idle state mobility control
  - paging origination in LTE idle state (downlink from MME)
  - ciphering of signaling messages
  - SAE bearer control
- **NAS (user plane)**
  - routes and forwards user data packets between eNB and PDN-GW
  - mobility anchor during inter-eNB and inter-RAT handovers
- **RRC (control plane only)**
  - broadcast of system information
  - paging
  - establishment, maintenance, and release of RRC connection between UE and E-UTRAN/eNB
  - inter-cell handover decisions based on UE measurements
  - control of UE measurement reporting
  - control of UE cell selection and re-selection
  - RRC states: idle or connected

Services and Functions of Layers (2)

- **PDCP (control plane)**
  - ciphering/deciphering
- **PDCP (user plane)**
  - Robust header compression/decompression (ROHC)
  - ciphering/deciphering of user data
  - in-sequence delivery of PDCP-SDUs to upper layers
- **RLC**
  - supports three reliability modes for data transfer:
    - acknowledged (AM) — for non-real time data transfer
    - unacknowledged (UM) — for real time data transfer
    - transparent (TM) — for SDUs whose sizes are known a-priori, such as for broadcasting system information
  - SDU segmentation according to size of Transport Block (TB)
  - error correction through ARQ (CRC check provided by PHY)
    - only for AM data transfer
  - in-sequence delivery of RLC-SDUs to upper layers
  - duplicate detection, and discarding of duplicate RLC SDUs
    - only for AM data transfer

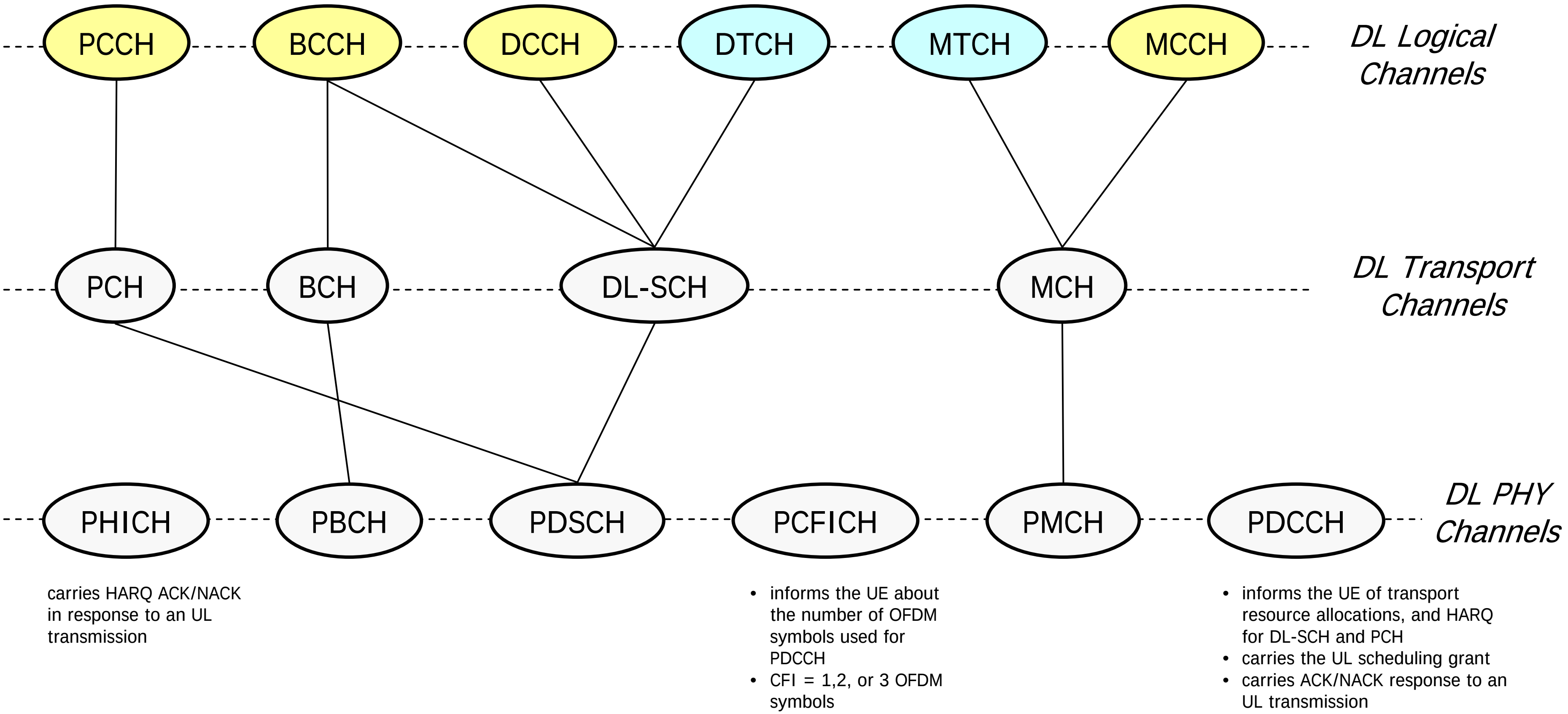
Services and Functions of Layers (3)

- **MAC**
  - mapping between logical channels and transport channels
  - error correction through Hybrid ARQ (HARQ)
  - multiplexing of RLC PDUs (MAC SDUs) from one or more logical channels onto transport blocks (TB)
  - priority handling between logical channels of one UE
  - priority handling among UEs via dynamic scheduling
  - transport format selection
    - block size, code selection, coding rate, CRC size etc.

Logical Channels

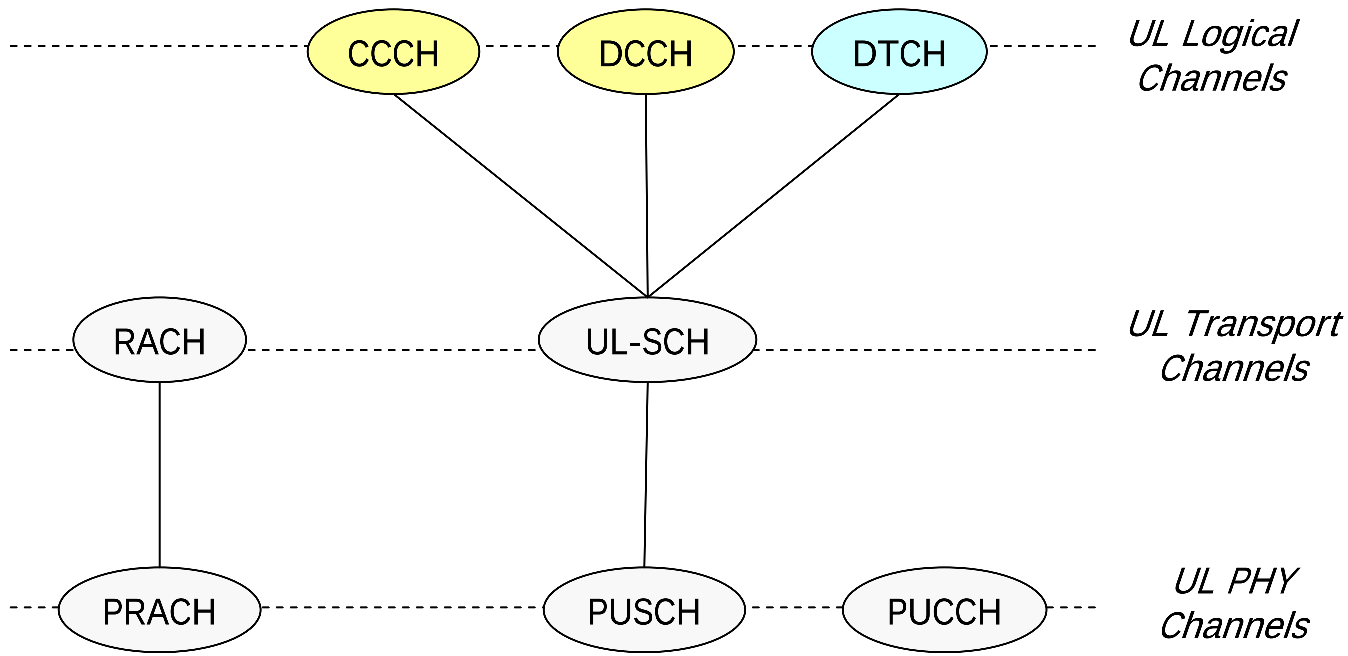
	Downlink (DL)	Uplink (UL)	Description
Control Channel (control plane)	Broadcast Control Channel (BCCH)		for broadcasting system information from the network to the UEs
	Paging Control Channel (PCCH)		for paging a UE when its exact cell location is unknown. Originates in NAS/MME
	Multicast Control Channel (MCCH)		for transmitting MBMS control information from network to multiple UEs
		Common Control Channel (CCCH)	for transmitting control information from the UE to the network when the UE has no RRC connection
	Dedicated Control Channel (DCCH)		point-to-point channel for transmitting dedicated control info between the UE and the network, when the UE has an RRC connection
Traffic Channels (user plane)	Dedicated Traffic Channel (DTCH)		point-to-point channel for transmitting dedicated user information between the UE and the network.
	Multicast Traffic Channel (MTCH)		for transmitting MBMS traffic information from network to multiple UEs

DL: Logical → Transport → Physical Channels



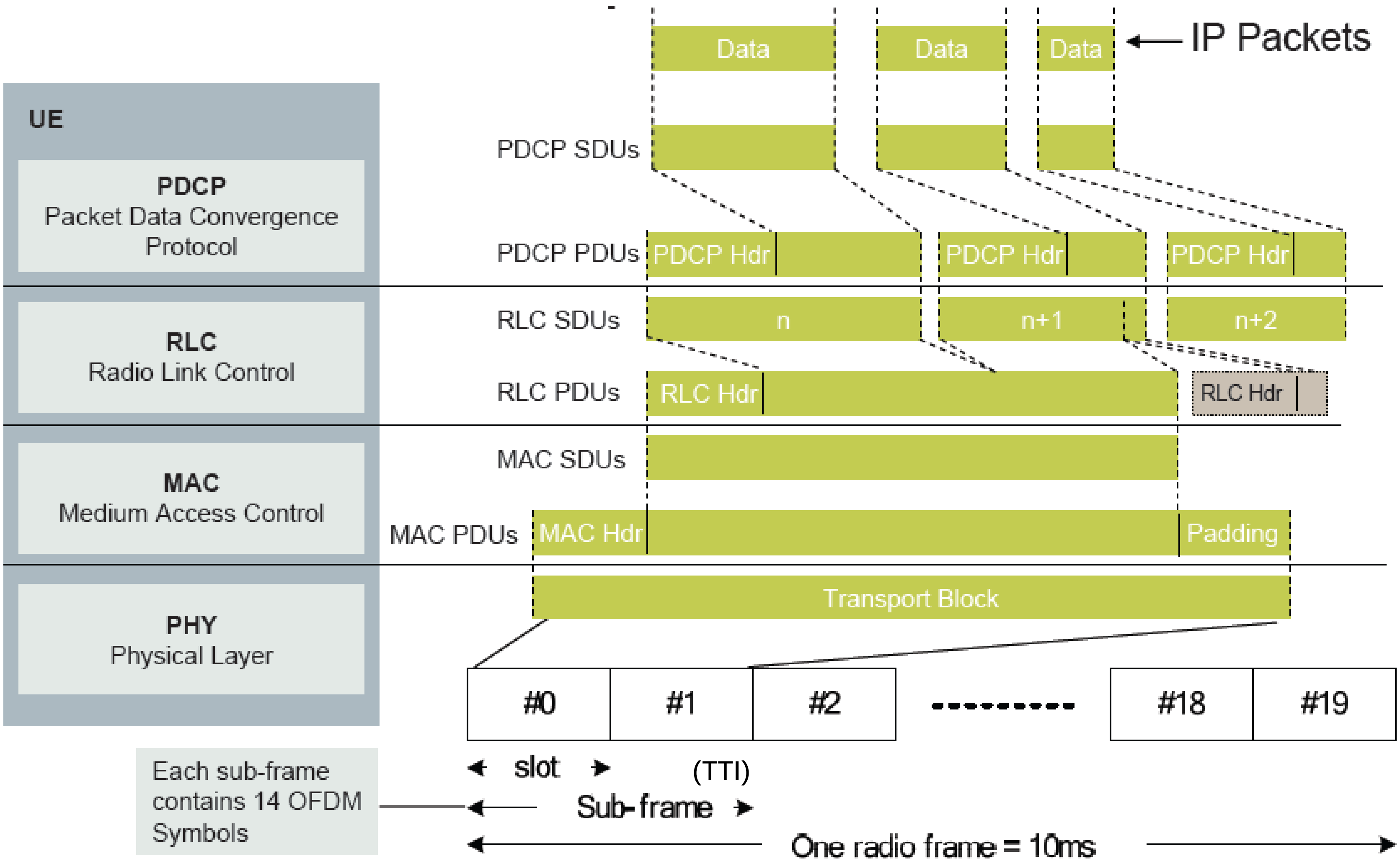
Physical Signals
- reference signals (for channel estimation)
- synchronization signals (primary and secondary)

UL: Logical → Transport → Physical

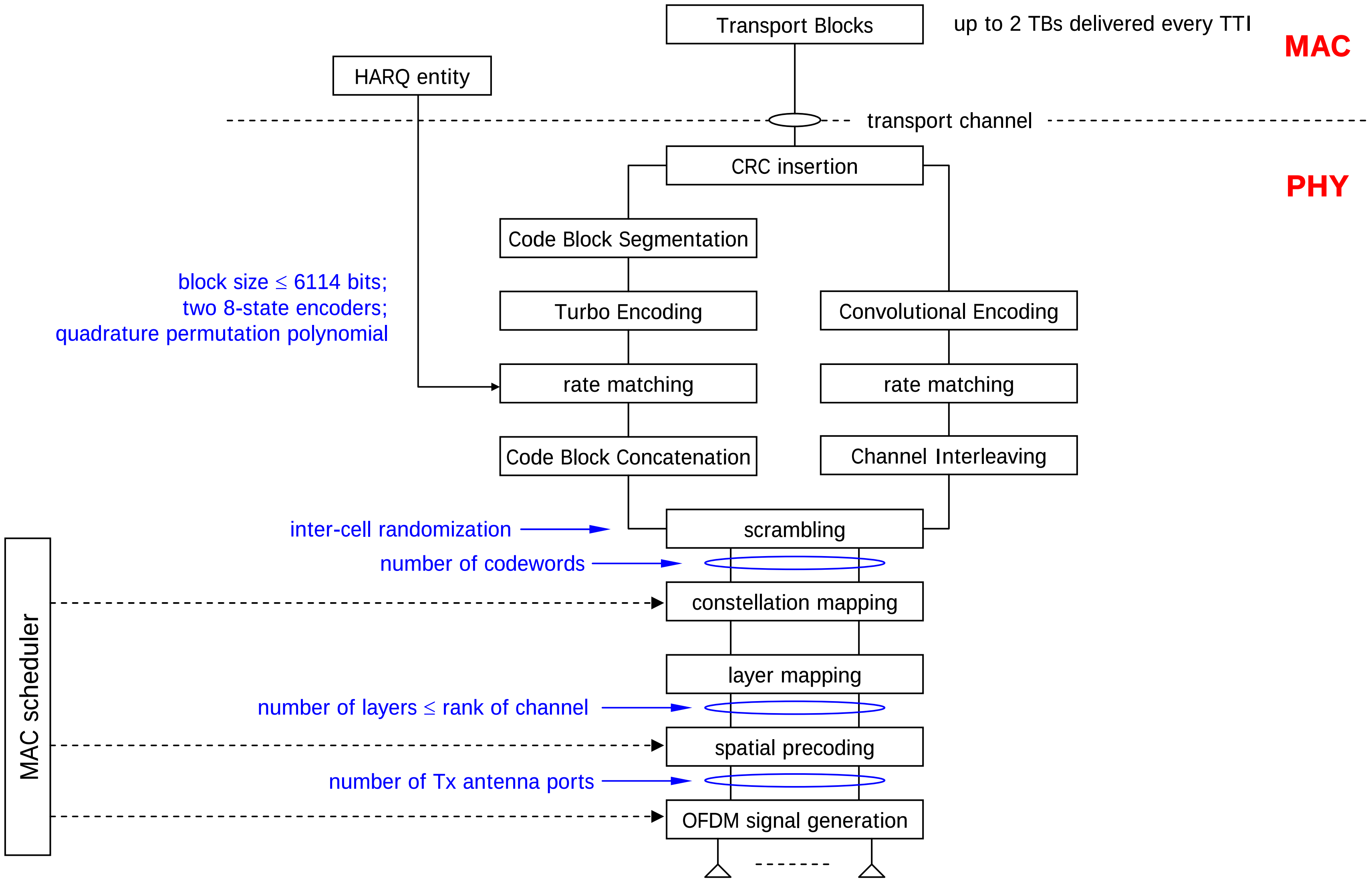


- carries ACK/NACK in response to DL transmissions
- carries CQI reports and MIMO related feedbacks (such as PMI and channel rank)
- never transmitted simultaneously with PUSCH

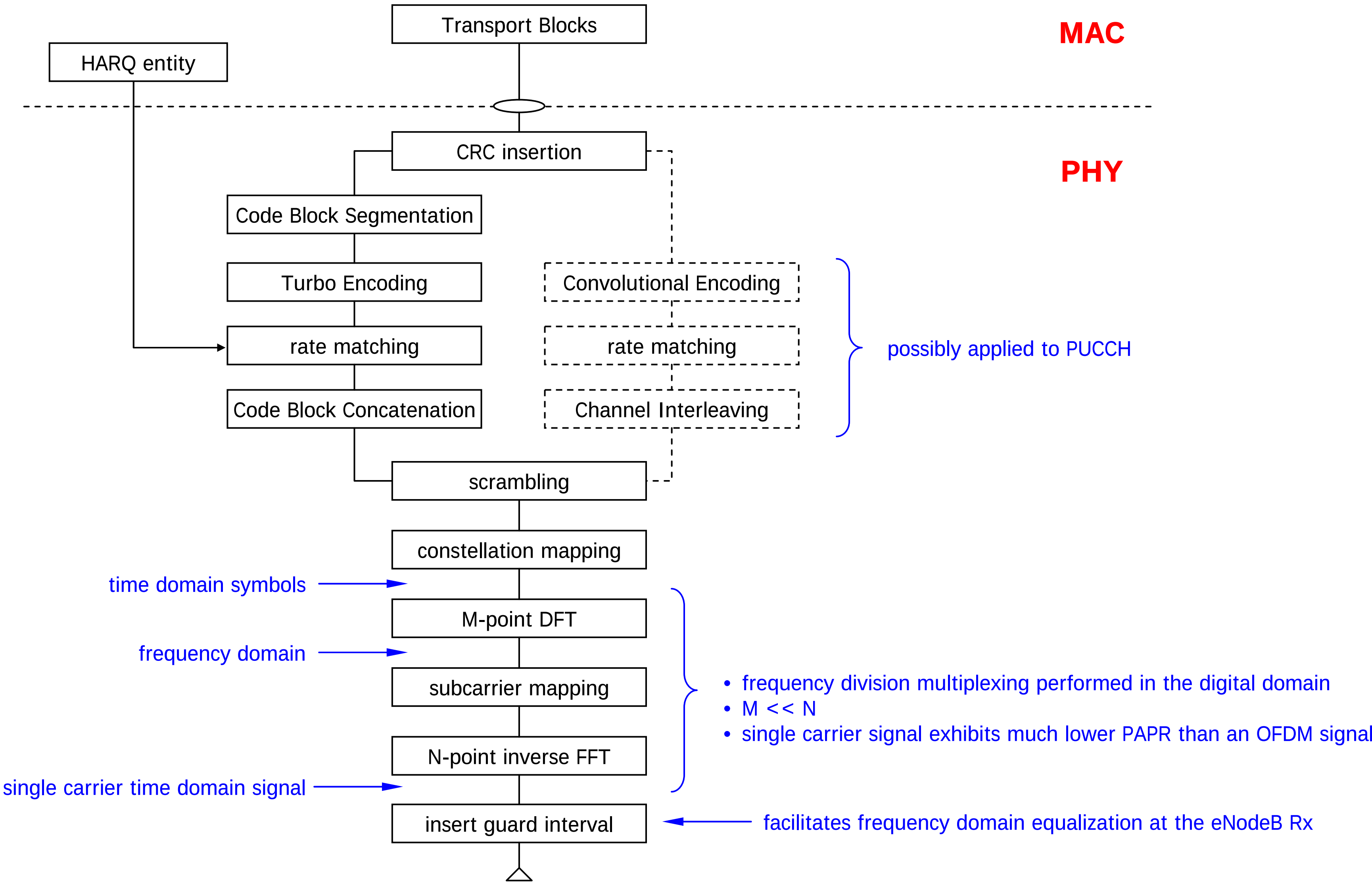
Frame Formats



DL PHY Architecture: MIMO-OFDM



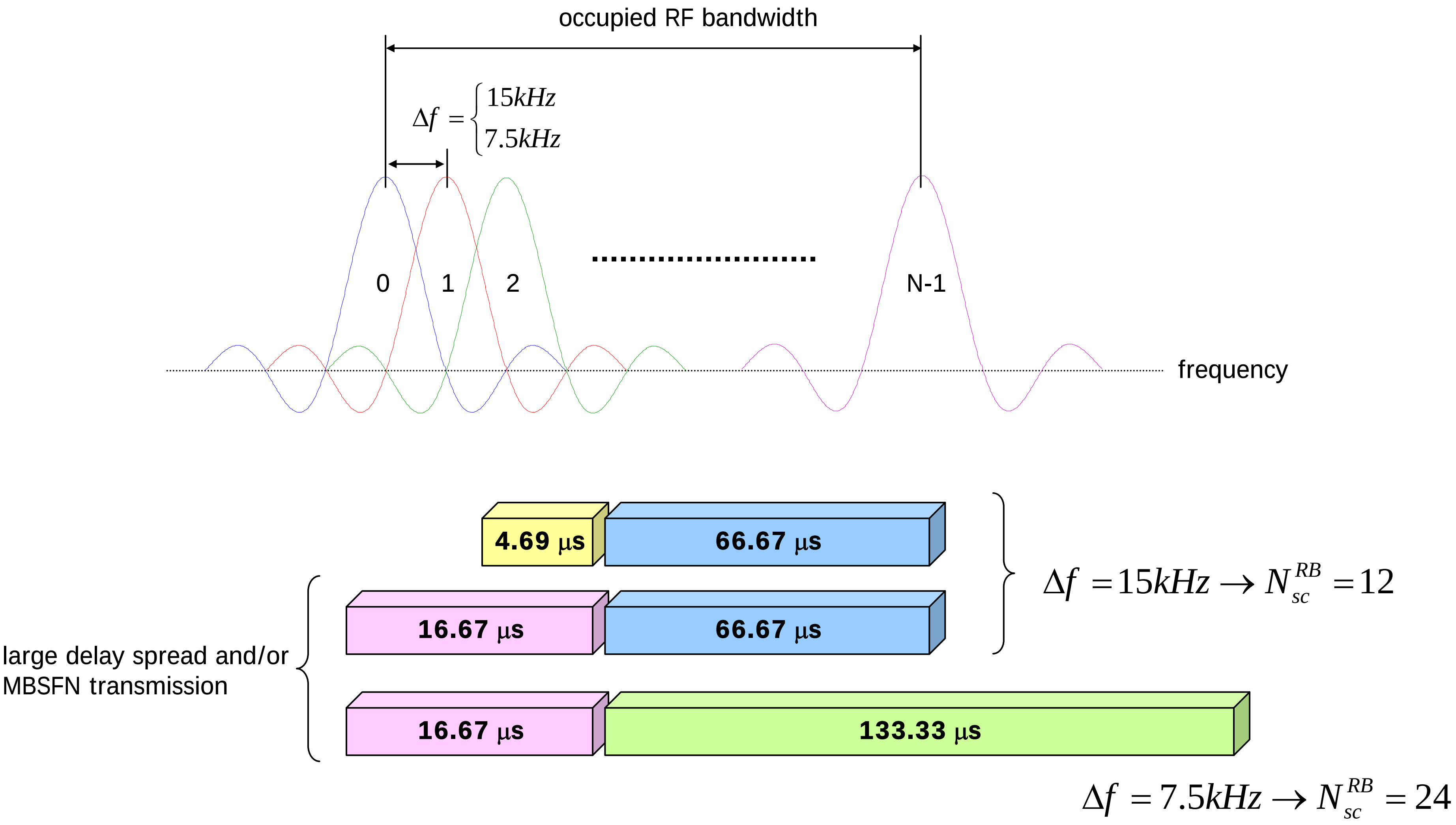
UL PHY Architecture: SC-FDMA



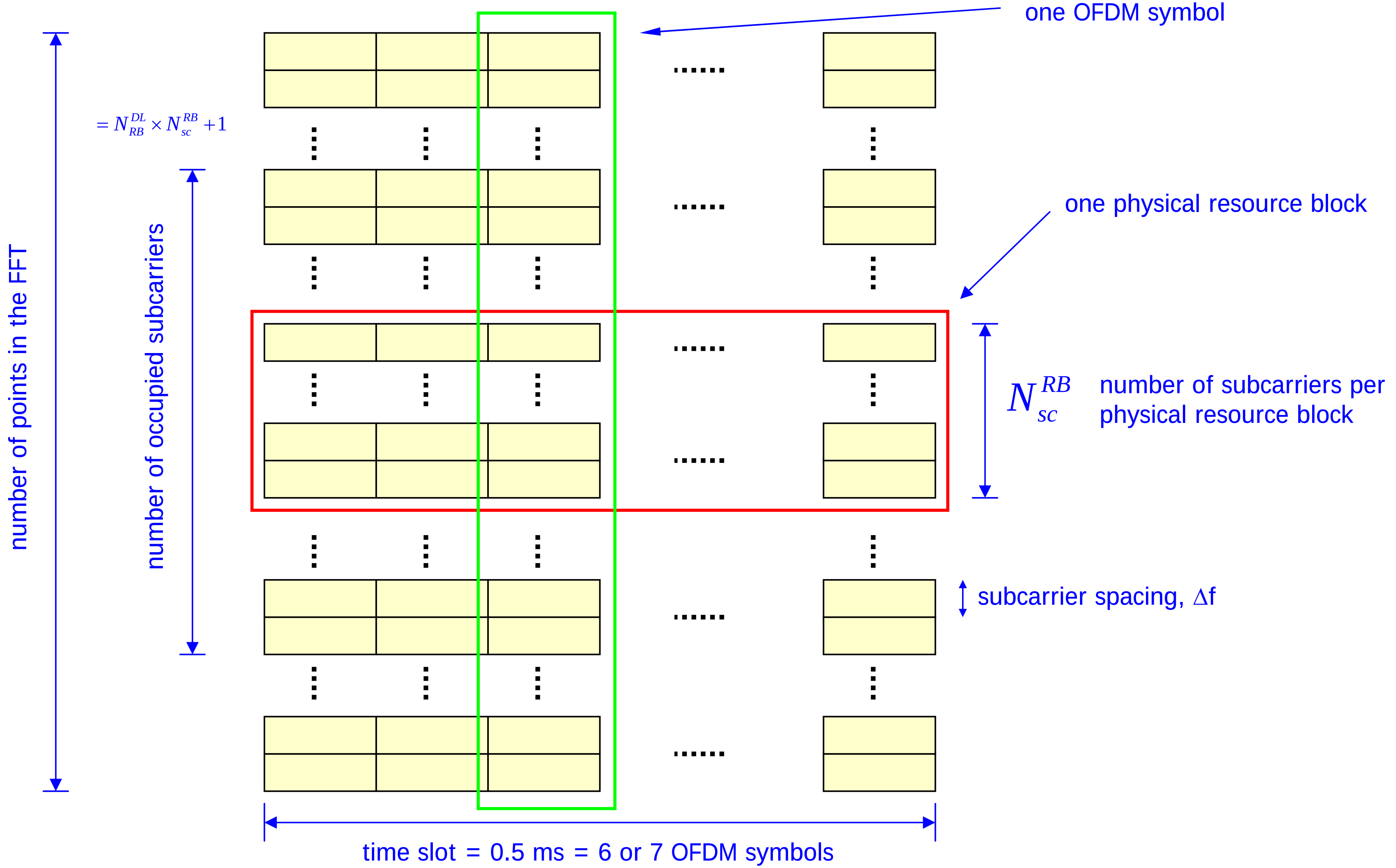
Transport Format of Channels

Transport Channel	Physical Channel	CRC	Encoding	Number of Codewords	HARQ	Constellation
DL-SCH	PDSCH	24 bits	R=1/3 Turbo	2	yes	QPSK, 16QAM, 64QAM
PCH		24 bits	R=1/3 Turbo	1	no	QPSK, 16QAM, 64QAM
MCH	PMCH	24 bits	R=1/3 Turbo	1	no	QPSK, 16QAM, 64QAM
BCH	PBCH	16 bits	R=1/3 Convolutional	1	no	QPSK
	PDCCH	16 bits	R=1/3 Convolutional			QPSK
	PHICH	none	R=1/3 repetition			
	PCFICH	none	R=1/16 block code			QPSK
UL-SCH	PUSCH	24 bits	R=1/3 Turbo	1	yes	QPSK, 16QAM, 64QAM (optional)
RACH	PRACH			1		
	PUCCH	for further study	for further study			BPSK, QPSK

OFDM Symbol Parameters



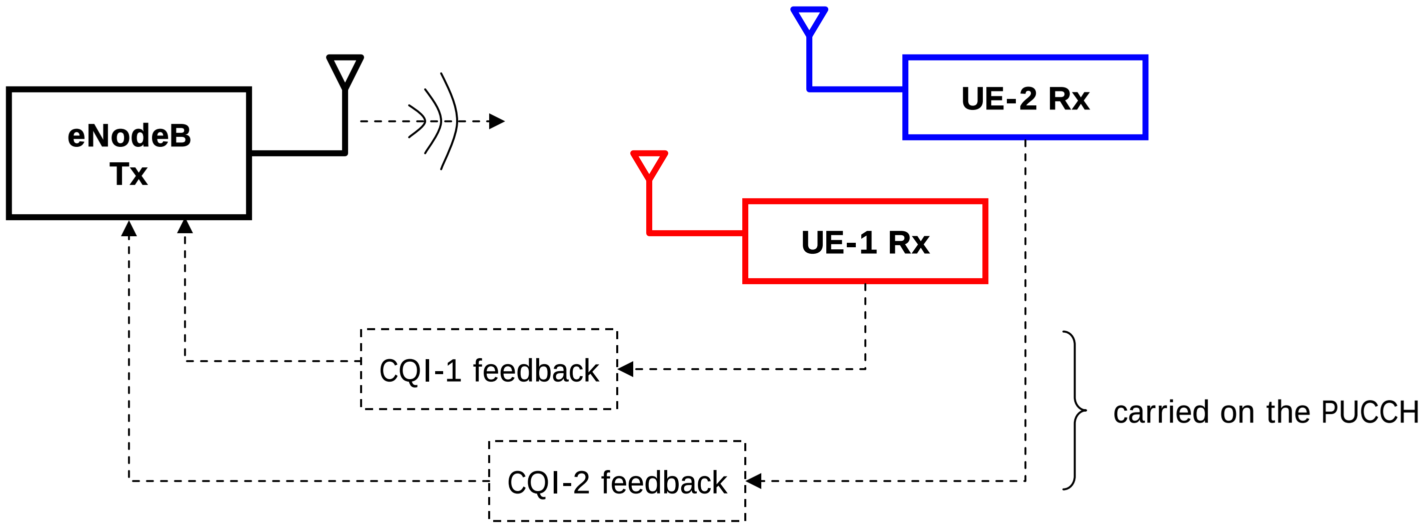
OFDM Time-Frequency Grid

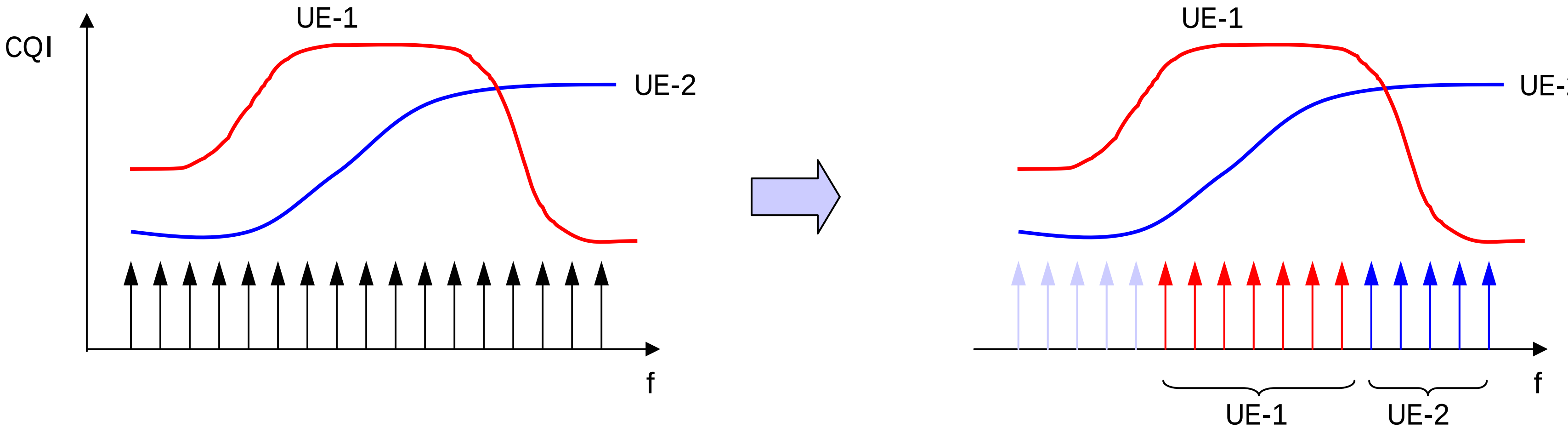


OFDM Numerology

Channelization BW	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Slot duration	0.5 ms					
subcarrier spacing	15 kHz					
sampling frequency	1.92 MHz (0.5x3.84MHz)	3.84 MHz	7.68 MHz (2x3.84MHz)	15.37 MHz (4x3.84MHz)	23.04 MHz (6x3.84MHz)	30.72 MHz (8x3.84MHz)
FFT size	128	256	512	1024	1536	2048
Number of Resource Blocks	6	15	25	50	75	100
Number of occupied subcarriers	73	181	301	601	901	1201
RF BW	1.1 MHz	2.7 MHz	4.5 MHz	9 MHz	13.5 MHz	18 MHz
Short CP 7 OFDM symbols (μs,samples)	(4.69,9)x6 (5.21,10)x1	(4.69,18)x6 (5.21,20)x1	(4.69,36)x6 (5.21,40)x1	(4.69,72)x6 (5.21,80)x1	(4.69,108)x6 (5.21,120)x1	(4.69,144)x6 (5.21,160)x1
Long CP 6 OFDM symbols (μs,samples)	(16.67,32)x6	(16.67,64)x6	(16.67,128)x6	(16.67,256)x6	(16.67,384)x6	(16.67,512)x6

Multi-User Frequency Domain Scheduling



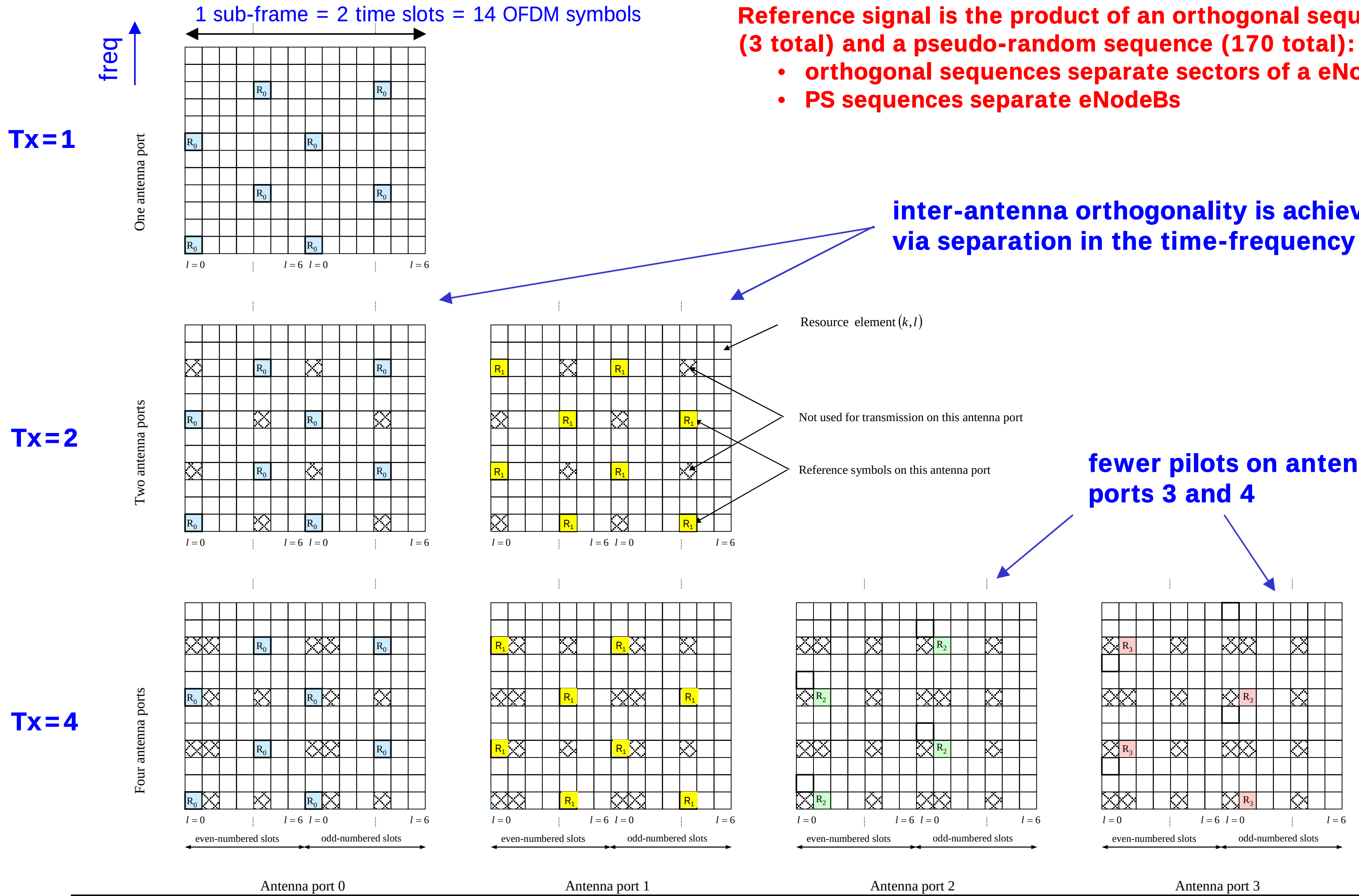


Cell-specific Reference Signals for MIMO-OFDM

Reference signal is the product of an orthogonal sequence (3 total) and a pseudo-random sequence (170 total):
- **orthogonal sequences separate sectors of a eNodeB**
- **PS sequences separate eNodeBs**

inter-antenna orthogonality is achieved via separation in the time-frequency grid

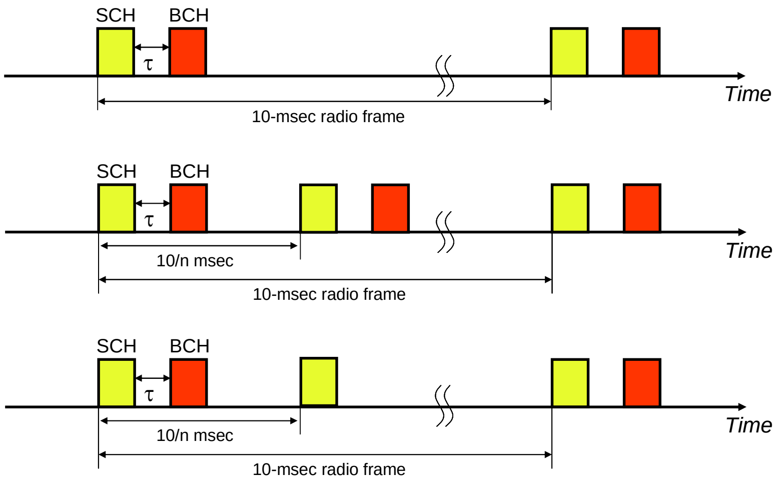
fewer pilots on antenna ports 3 and 4

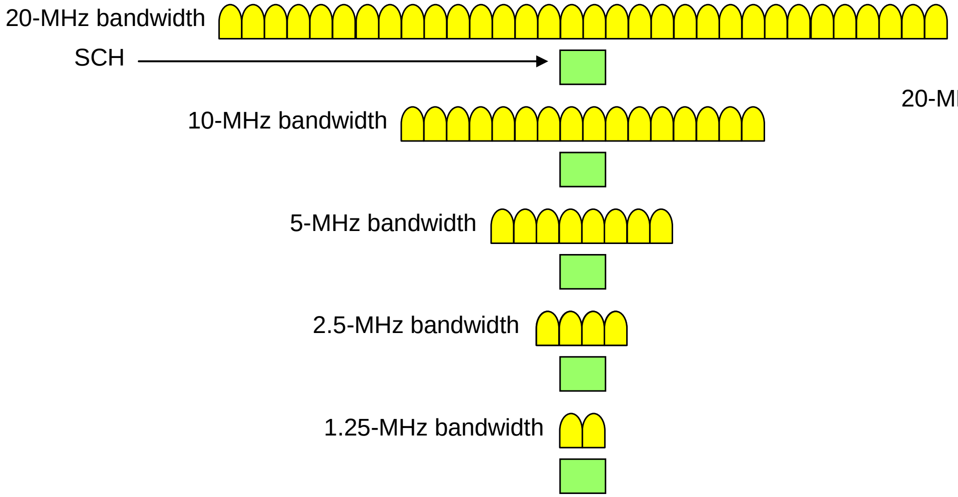


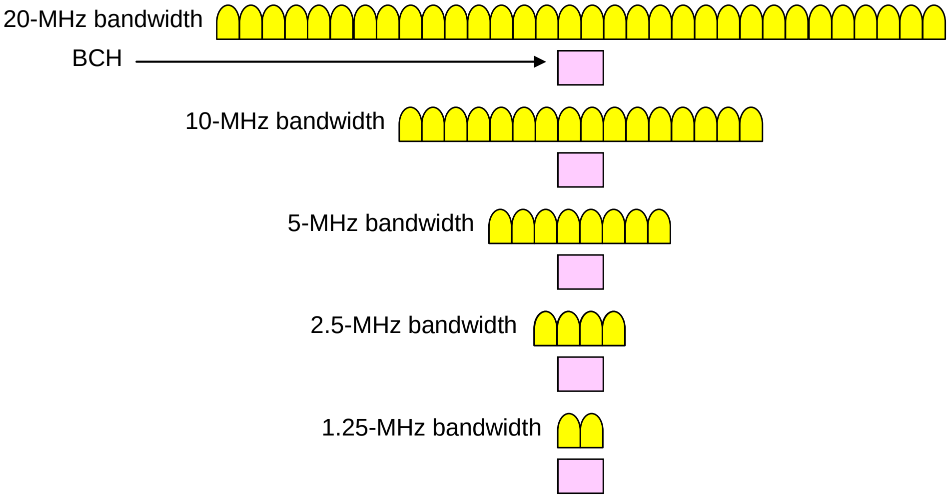
Synchronization Signals

Cell Search is performed using primary and secondary synchronization signals, that are transmitted over the center 72 subcarriers in the 1st and 6th sub-frame of each radio frame

Information carried on the BCH includes:
- **DL system BW**
- **Number of Transmit Antennas**
- **Reference Signal Transmit Power**
- **Cell ID**
- **CP length etc.**



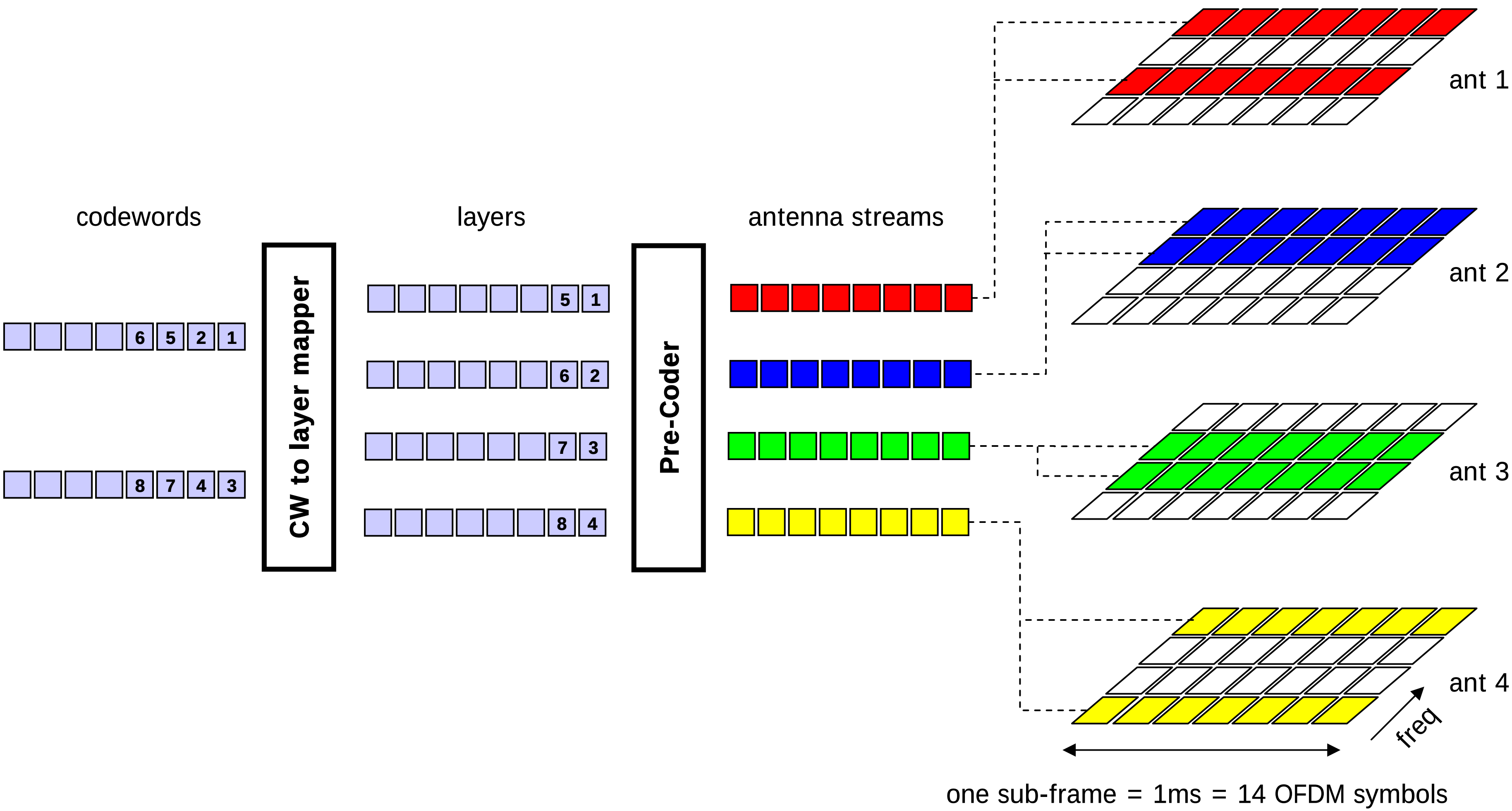




DL MIMO options

- Baseline configuration:
  - 2 Tx antennas at eNode B, and 2 Rx antennas at UE
- Optional extensions:
  - 4 Tx antennas at eNodeB, and 2 Rx antennas at UE
  - 4 Tx antennas at eNodeB, and 4 Rx antennas at UE
- Closed Loop
  - pre-coded spatial division multiplexing (SDM)
    - single-user vs multi-user scheduling
    - zero/small delay CDD vs large delay CDD
    - single vs dual codewords
  - beamforming
- Open Loop
  - single codeword
  - 2 Tx antennas: SFBC
  - 4 Tx antennas: SFBC-FSTD

SDM: Codeword →RB mapping



Codeword → Layer mapping

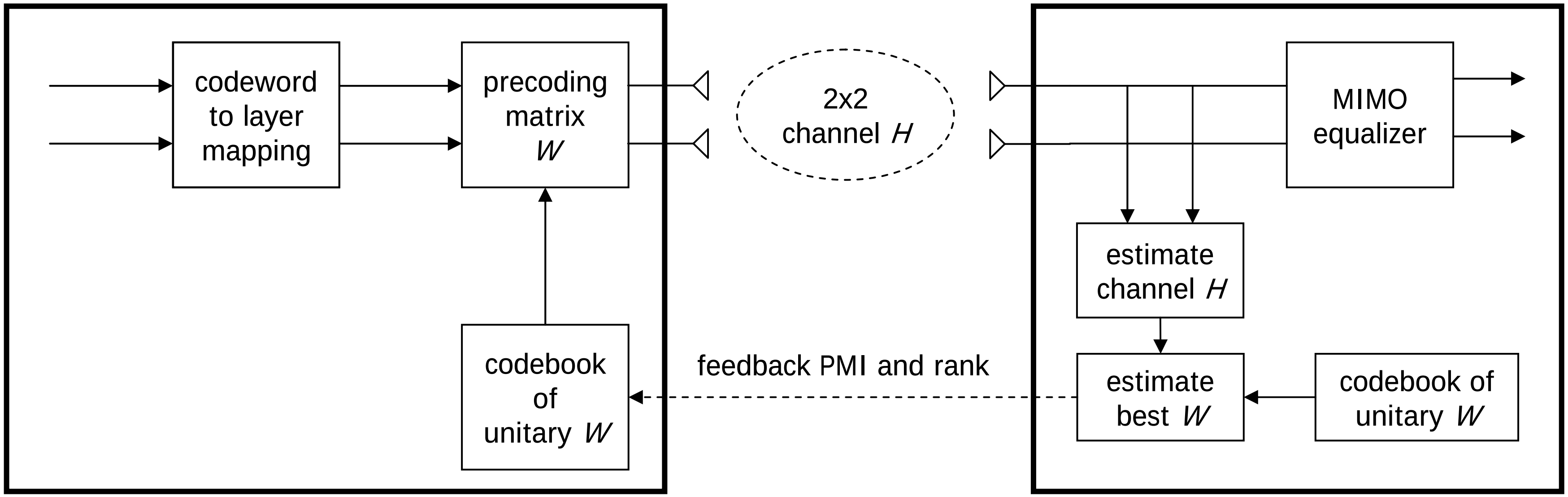
Spatial Division Multiplexing

Number of codewords	Number of Layers	Mapping
1	1	CW(0) → L(0)
2	2	CW(0) → L(0) CW(1) → L(1)
2	3	CW(0) → L(0) CW(1) → L(1) , L(2)
2	4	CW(0) → L(0) , L(1) CW(1) → L(2) , L(3)

Transmit Diversity

Number of Codewords	Number of Layers	Mapping
1	2	CW(0) → L(0) , L(1)
1	4	CW(0) → L(0), L(1), L(2), and L(3)

Pre-coded SDM 2x2



Precoding matrices for 2 layers:

$$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix},\ \frac{1}{2}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix},\ \frac{1}{2}\begin{bmatrix}1 & 1\\ j & -j\end{bmatrix}$$

PMI estimation

{

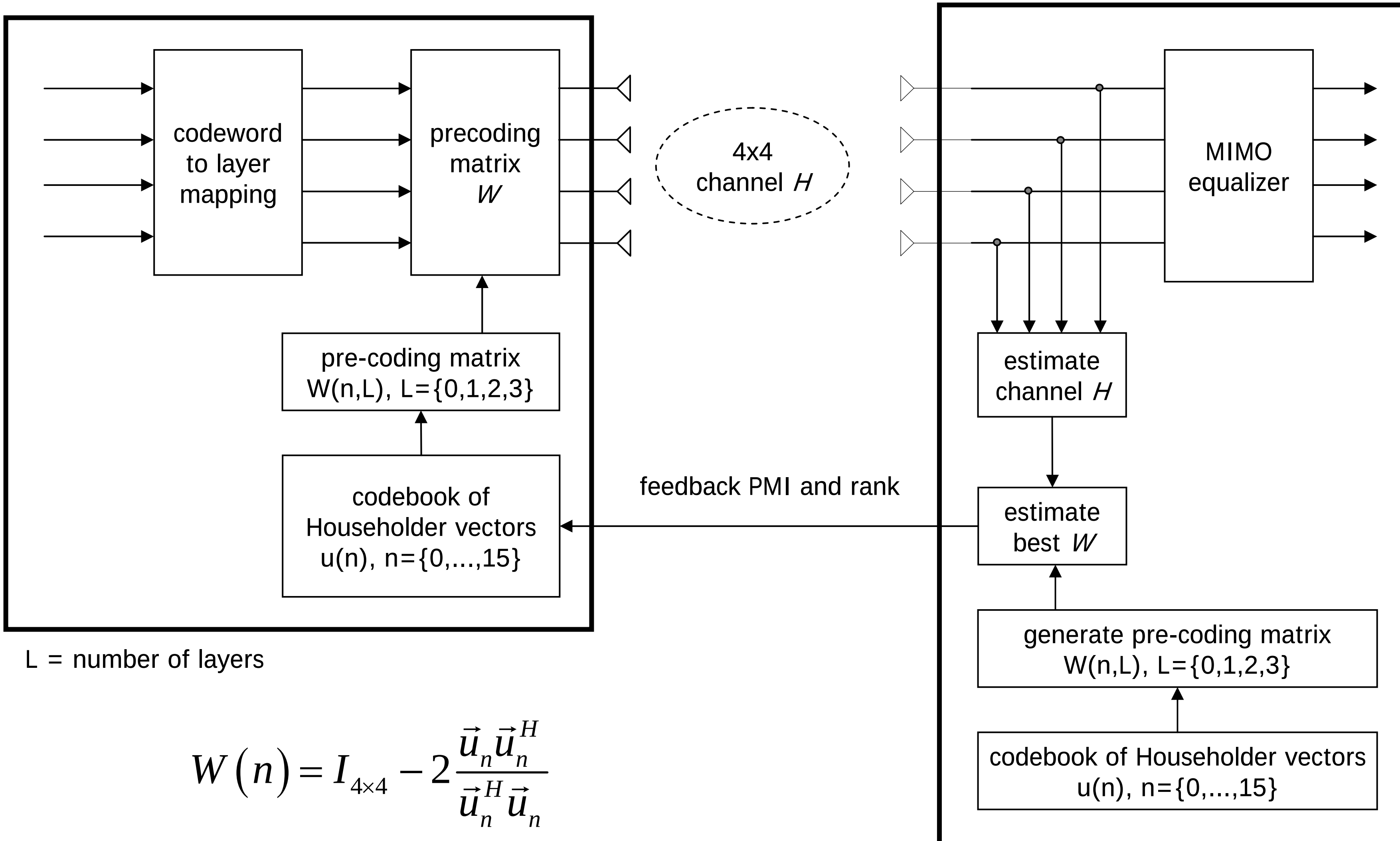
for each W in the code book

compute $\Omega = W\cdot\left(H^H\cdot H\right)\cdot W^H$

select W that minimizes off-diagonal entries of Ω

}

Pre-Coded SDM (4x2 and 4x4)



L = number of layers

$$W(n) = I_{4\times4} - 2\frac{\vec{u}_n \vec{u}_n^H}{\vec{u}_n^H \vec{u}_n}$$

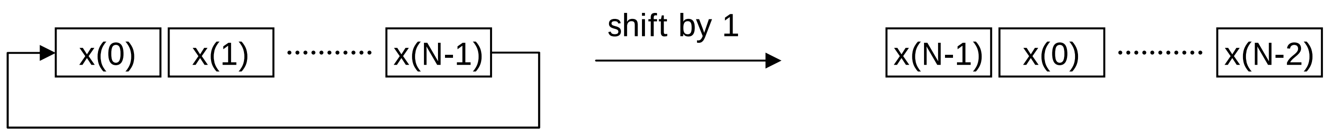
Householder vectors for 4 Tx

Codebook index	u_n	Number of layers υ			
		1	2	3	4
0	$u_0 = \begin{bmatrix}1 & -1 & -1 & -1\end{bmatrix}^T$	$W_0^{\{1\}}$	$W_0^{\{14\}}/\sqrt{2}$	$W_0^{\{124\}}/\sqrt{3}$	$W_0^{\{1234\}}/2$
1	$u_1 = \begin{bmatrix}1 & -j & 1 & j\end{bmatrix}^T$	$W_1^{\{1\}}$	$W_1^{\{12\}}/\sqrt{2}$	$W_1^{\{123\}}/\sqrt{3}$	$W_1^{\{1234\}}/2$
2	$u_2 = \begin{bmatrix}1 & 1 & -1 & 1\end{bmatrix}^T$	$W_2^{\{1\}}$	$W_2^{\{12\}}/\sqrt{2}$	$W_2^{\{123\}}/\sqrt{3}$	$W_2^{\{3214\}}/2$
3	$u_3 = \begin{bmatrix}1 & j & 1 & -j\end{bmatrix}^T$	$W_3^{\{1\}}$	$W_3^{\{12\}}/\sqrt{2}$	$W_3^{\{123\}}/\sqrt{3}$	$W_3^{\{3214\}}/2$
4	$u_4 = \begin{bmatrix}1 & (-1-j)/\sqrt{2} & -j & (1-j)/\sqrt{2}\end{bmatrix}^T$	$W_4^{\{1\}}$	$W_4^{\{14\}}/\sqrt{2}$	$W_4^{\{124\}}/\sqrt{3}$	$W_4^{\{1234\}}/2$
5	$u_5 = \begin{bmatrix}1 & (1-j)/\sqrt{2} & j & (-1-j)/\sqrt{2}\end{bmatrix}^T$	$W_5^{\{1\}}$	$W_5^{\{14\}}/\sqrt{2}$	$W_5^{\{124\}}/\sqrt{3}$	$W_5^{\{1234\}}/2$
6	$u_6 = \begin{bmatrix}1 & (1+j)/\sqrt{2} & -j & (-1+j)/\sqrt{2}\end{bmatrix}^T$	$W_6^{\{1\}}$	$W_6^{\{13\}}/\sqrt{2}$	$W_6^{\{134\}}/\sqrt{3}$	$W_6^{\{1324\}}/2$
7	$u_7 = \begin{bmatrix}1 & (-1+j)/\sqrt{2} & j & (1+j)/\sqrt{2}\end{bmatrix}^T$	$W_7^{\{1\}}$	$W_7^{\{13\}}/\sqrt{2}$	$W_7^{\{134\}}/\sqrt{3}$	$W_7^{\{1324\}}/2$
8	$u_8 = \begin{bmatrix}1 & -1 & 1 & 1\end{bmatrix}^T$	$W_8^{\{1\}}$	$W_8^{\{12\}}/\sqrt{2}$	$W_8^{\{124\}}/\sqrt{3}$	$W_8^{\{1234\}}/2$
9	$u_9 = \begin{bmatrix}1 & -j & -1 & -j\end{bmatrix}^T$	$W_9^{\{1\}}$	$W_9^{\{14\}}/\sqrt{2}$	$W_9^{\{134\}}/\sqrt{3}$	$W_9^{\{1234\}}/2$
10	$u_{10} = \begin{bmatrix}1 & 1 & 1 & -1\end{bmatrix}^T$	$W_{10}^{\{1\}}$	$W_{10}^{\{13\}}/\sqrt{2}$	$W_{10}^{\{123\}}/\sqrt{3}$	$W_{10}^{\{1324\}}/2$
11	$u_{11} = \begin{bmatrix}1 & j & -1 & j\end{bmatrix}^T$	$W_{11}^{\{1\}}$	$W_{11}^{\{13\}}/\sqrt{2}$	$W_{11}^{\{134\}}/\sqrt{3}$	$W_{11}^{\{1324\}}/2$
12	$u_{12} = \begin{bmatrix}1 & -1 & -1 & 1\end{bmatrix}^T$	$W_{12}^{\{1\}}$	$W_{12}^{\{12\}}/\sqrt{2}$	$W_{12}^{\{123\}}/\sqrt{3}$	$W_{12}^{\{1234\}}/2$
13	$u_{13} = \begin{bmatrix}1 & -1 & 1 & -1\end{bmatrix}^T$	$W_{13}^{\{1\}}$	$W_{13}^{\{13\}}/\sqrt{2}$	$W_{13}^{\{123\}}/\sqrt{3}$	$W_{13}^{\{1324\}}/2$
14	$u_{14} = \begin{bmatrix}1 & 1 & -1 & -1\end{bmatrix}^T$	$W_{14}^{\{1\}}$	$W_{14}^{\{13\}}/\sqrt{2}$	$W_{14}^{\{123\}}/\sqrt{3}$	$W_{14}^{\{3214\}}/2$
15	$u_{15} = \begin{bmatrix}1 & 1 & 1 & 1\end{bmatrix}^T$	$W_{15}^{\{1\}}$	$W_{15}^{\{12\}}/\sqrt{2}$	$W_{15}^{\{123\}}/\sqrt{3}$	$W_{15}^{\{1234\}}/2$

columns of the 4x4 matrix

SDM with small cyclic delay

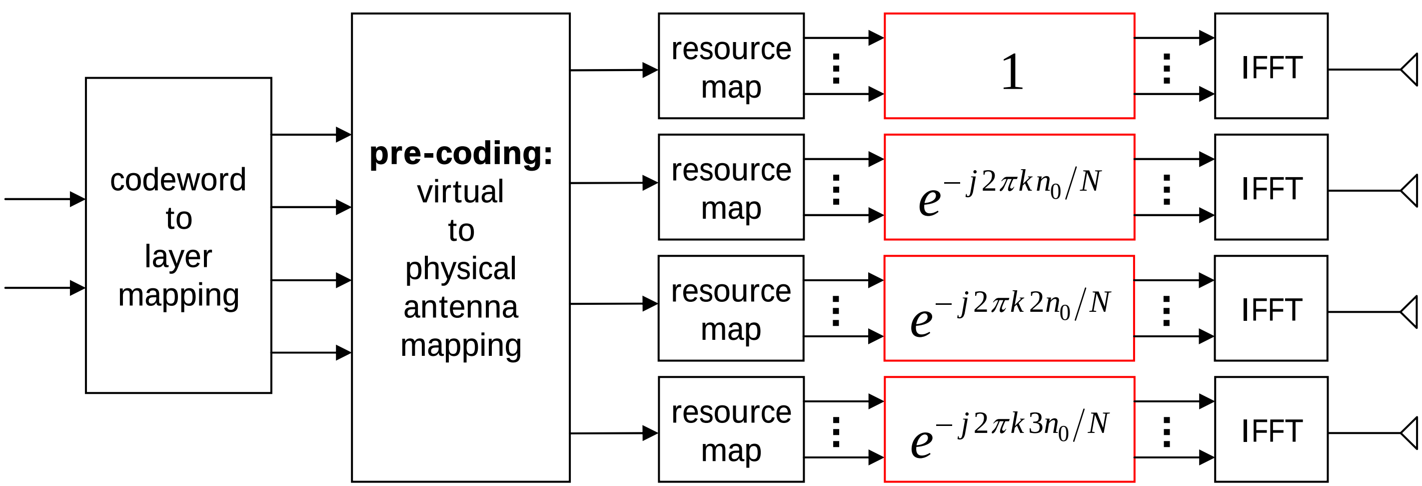
- Motivation for introducing cyclic delay is to increase the frequency selectivity of the channel
  - The channel decoder may improve link performance by exploiting frequency diversity
  - Or, achieve gains from multi-user scheduling
- Cyclic shift after the IFFT is equivalent to a linear phase ramp prior to the IFFT (in the freq domain)



circular delay operation in time domain

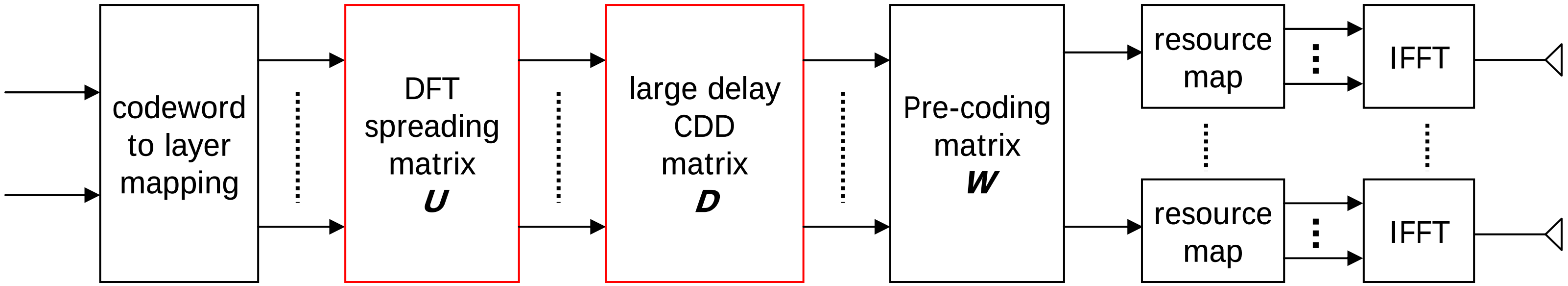
$$x\left[\left(n-n_0\right)\bmod N\right] \leftrightarrow e^{-j2\pi k n_0/N} X\left[k\right]$$

For 2 Tx, n_0 = 2
For 4 Tx, n_0 = 1



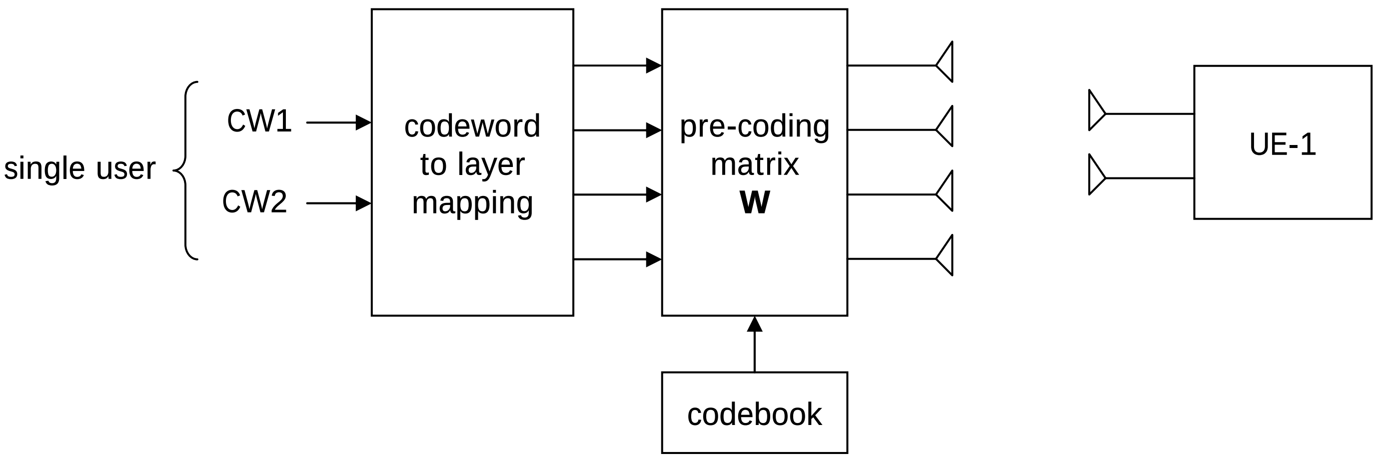
SDM with large cyclic delay

- By virtue of pre-coding, the MIMO channel *approximately* transforms into a set of non-interfering virtual channels
- Each layer is mapped to a virtual channel, with an associated SNR
- The SNR spread across the virtual channels is proportional to the singular value spread of $\boldsymbol{H}$
- To avoid HARQ signaling per layer and/or reduce error from codebook selection at high Doppler, each layer is spread across all virtual channels to equalize their SNR

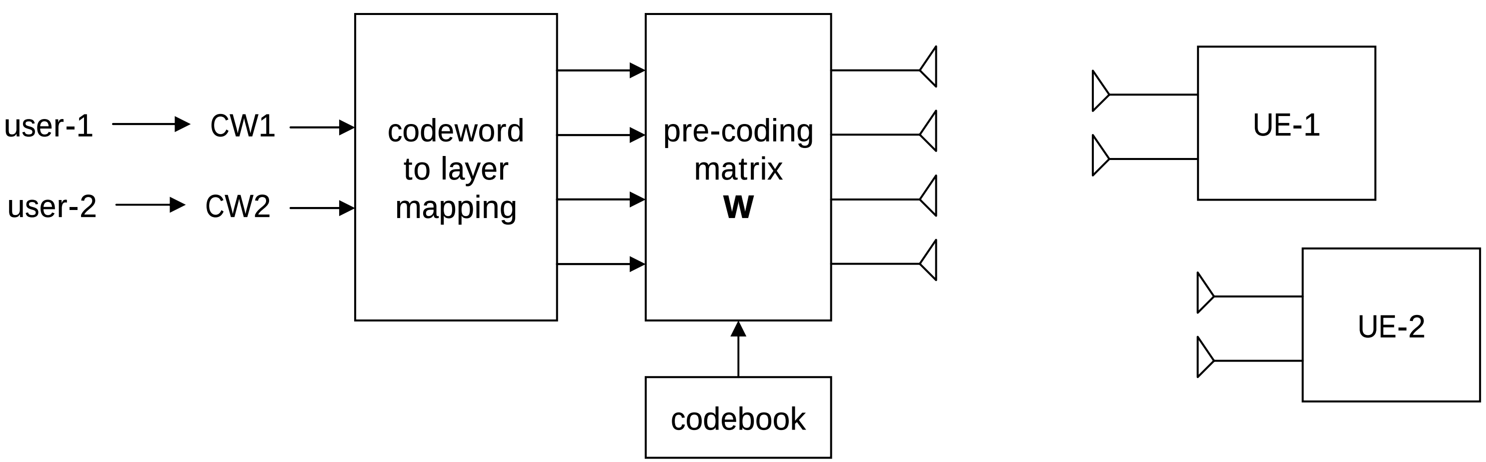


Number of layers υ	U	$D(i)$
1	$[1]$	$[1]$
2	$\begin{bmatrix}1 & 1\\ 1 & e^{-j2\pi/2}\end{bmatrix}$	$\begin{bmatrix}1 & 0\\ 0 & e^{-j2\pi i/2}\end{bmatrix}$
3	$\begin{bmatrix}1 & 1 & 1\\ 1 & e^{-j2\pi/3} & e^{-j4\pi/3}\\ 1 & e^{-j4\pi/3} & e^{-j8\pi/3}\end{bmatrix}$	$\begin{bmatrix}1 & 0 & 0\\ 0 & e^{-j2\pi i/3} & 0\\ 0 & 0 & e^{-j4\pi i/3}\end{bmatrix}$
4	$\begin{bmatrix}1 & 1 & 1 & 1\\ 1 & e^{-j2\pi/4} & e^{-j4\pi/4} & e^{-j6\pi/4}\\ 1 & e^{-j4\pi/4} & e^{-j8\pi/4} & e^{-j12\pi/4}\\ 1 & e^{-j6\pi/4} & e^{-j12\pi/4} & e^{-j18\pi/4}\end{bmatrix}$	$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & e^{-j2\pi i/4} & 0 & 0\\ 0 & 0 & e^{-j4\pi i/4} & 0\\ 0 & 0 & 0 & e^{-j6\pi i/4}\end{bmatrix}$

SU-MIMO vs MU-MIMO



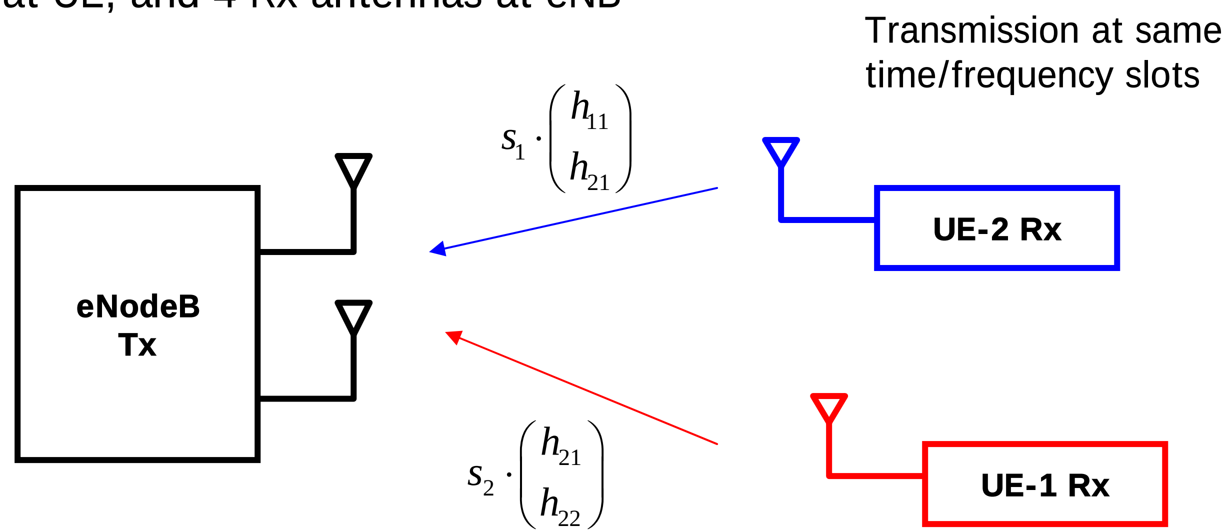
If two users request the same pre-coding matrix **W**, then they can be scheduled on the same Physical Resource Block (PRB)



UL MU-MIMO

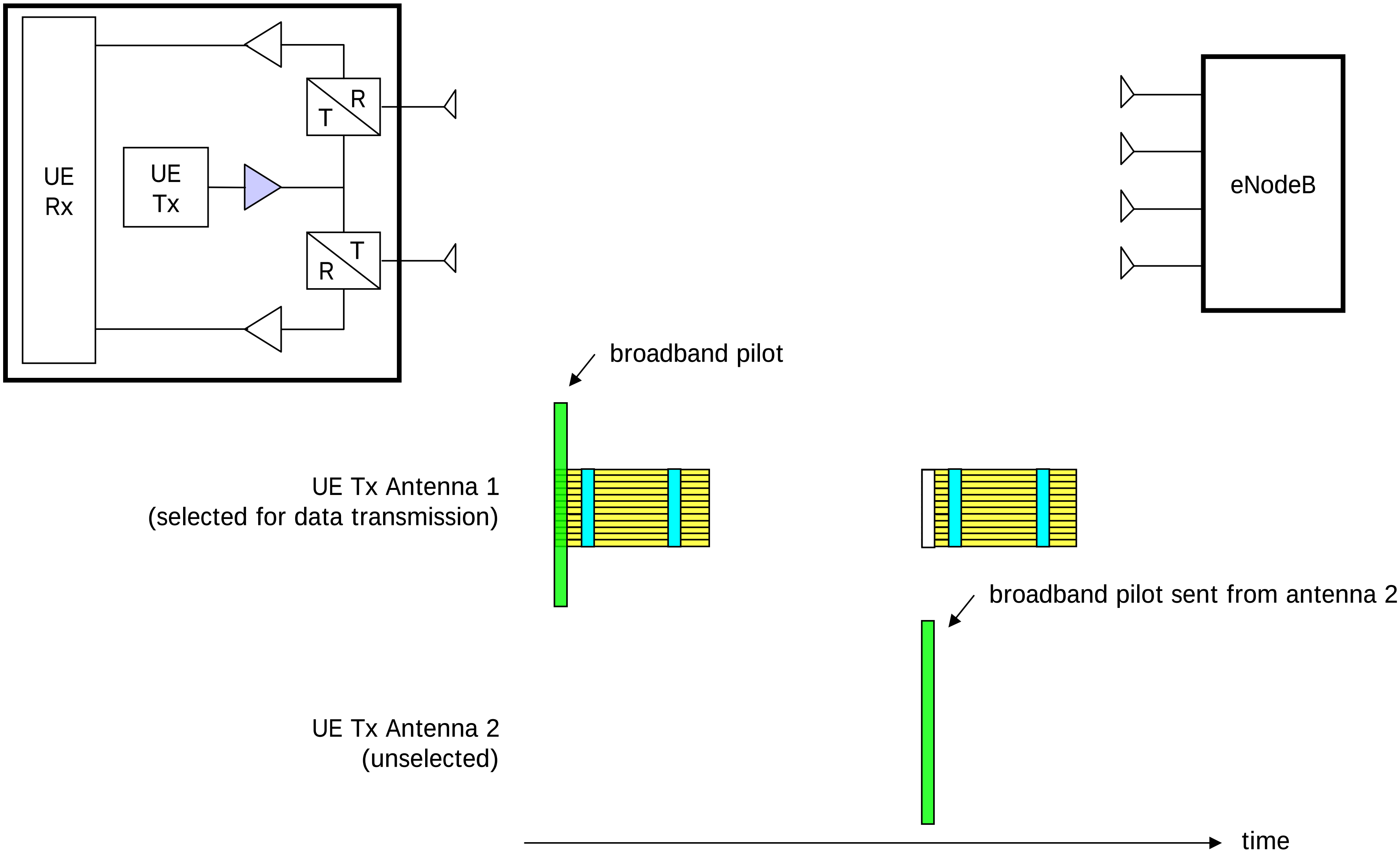
- Baseline configuration:
  - 1 Tx antenna at UE, and 2 Rx antennas at eNB
- Optional extension:
  - 1 Tx antenna at UE, and 4 Rx antennas at eNB

$$\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \underbrace{\begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix}}_{H} \cdot \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}$$



- Optimal performance if the columns of ***H*** are orthogonal
- No feedback channel needed for UL MU-MIMO

Closed Loop Up Link Antenna Selection



DL L1/L2 control signaling (PDCCH)

1. DL scheduling information

	Field		Size	Comment
Cat. 1 (Resource indication)	ID (UE or group specific)		[8-9]	Indicates the UE (or group of UEs) for which the data transmission is intended
	Resource assignment		FFS	Indicates which (virtual) resource units (and layers in case of multi-layer transmission) the UE(s) shall demodulate.
	Duration of assignment		2-3	The duration for which the assignment is valid, could also be used to control the TTI or persistent scheduling.
Cat. 2 (transport format)	Multi-antenna related information		FFS	Content depends on the MIMO/beamforming schemes selected.
	Modulation scheme		2	QPSK, 16QAM, 64QAM. In case of multi-layer transmission, multiple instances may be required.
	Payload size		6	Interpretation could depend on e.g. modulation scheme and the number of assigned resource units (c.f. HSDPA). In case of multi-layer transmission, multiple instances may be required.
Cat. 3 (HARQ)	asynchronous hybrid ARQ	Hybrid ARQ process number	3	Indicates the hybrid ARQ process the current transmission is addressing.
		Redundancy version	2	To support incremental redundancy.
		New data indicator	1	To handle soft buffer clearing.

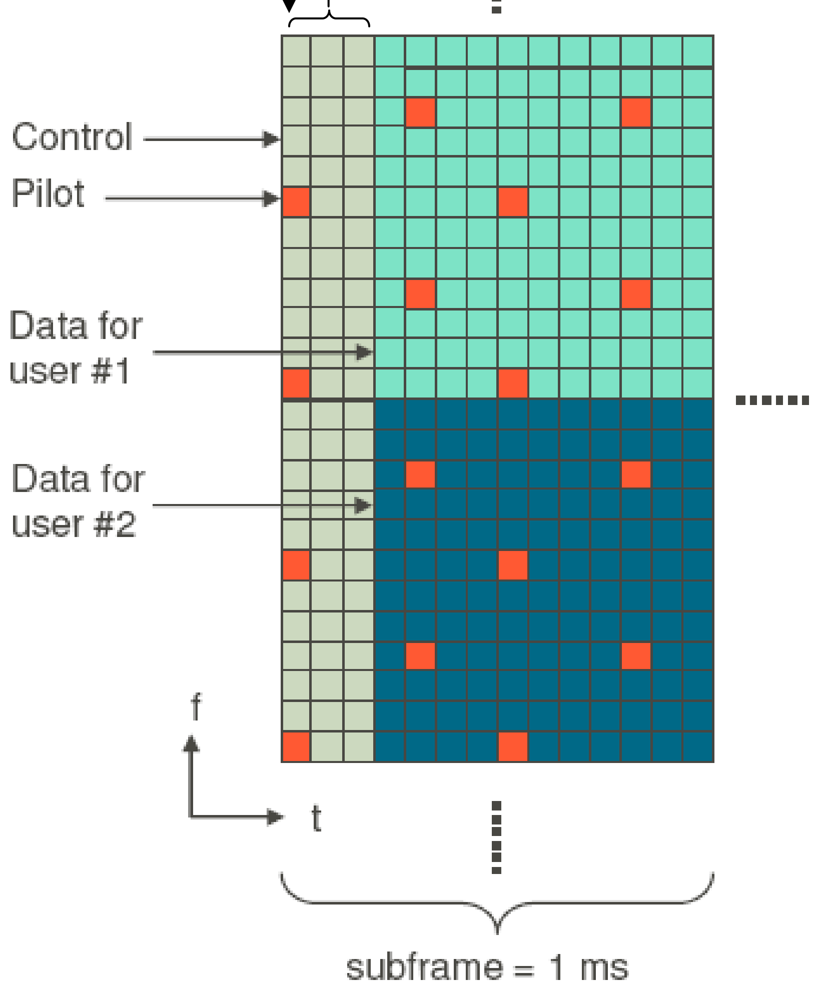
2. UL scheduling grant information

3. ACK/NACK in response to UL transmission

Mapping Control/Data in the Time-Freq grid

pilots used from first OFDM symbol to demodulate PDCCH

PDCCH can span up to the first three symbols in a sub-frame

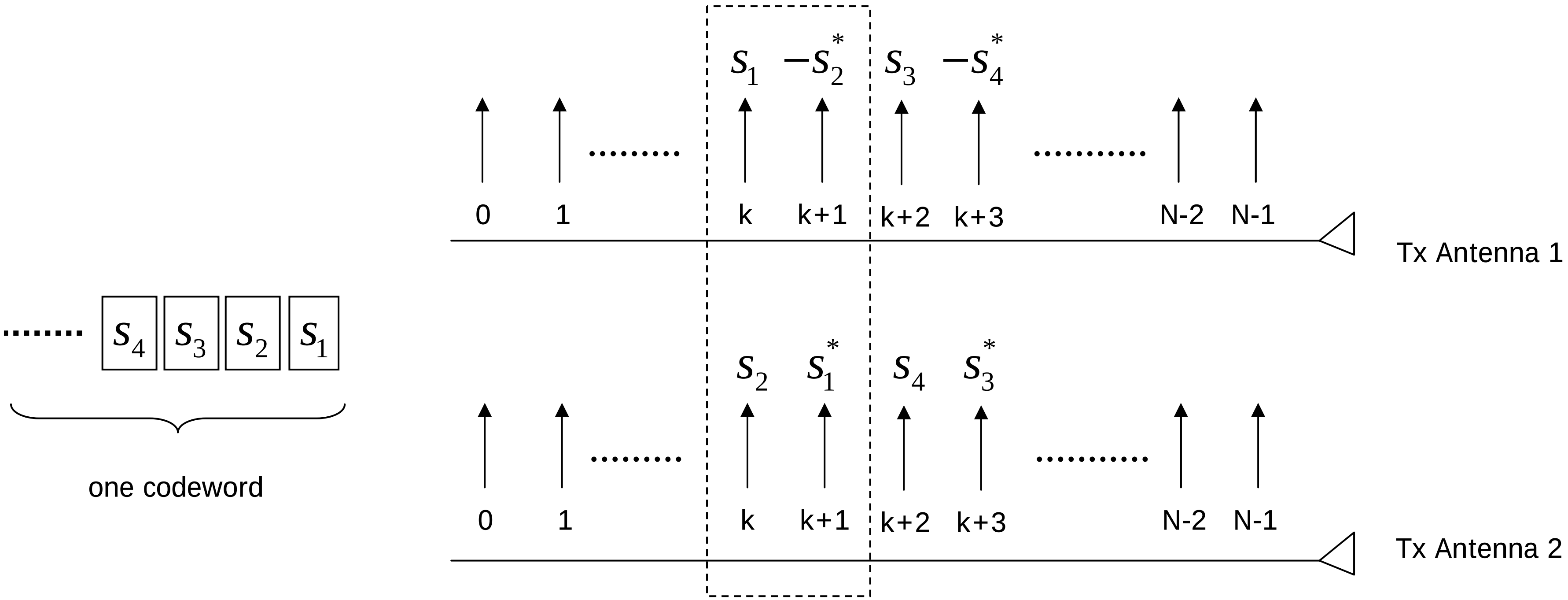


Link Adaptation related control signaling

- Link adaptation is performed in the eNodeB MAC, based on info received via the PUCCH
- The two codewords (in PDSCH) have independent coding rates and modulation levels
- CQI
  - one CQI is signaled back for ***n*** adjacent RBs
  - exact value of ***n*** is under study
  - compromise between signaling overhead and scheduling granularity
  - exploit coherence BW of channel
    - one RB = 180 kHz
- PMI (pre-coding matrix indicator)
  - one PMI is signaled back for 5 adjacent RBs, provided the system BW is larger than 12 RBs. Else, only one PMI is fed back
- Rank
  - only one rank value if signaled back for the entire BW

SFBC (2x2)

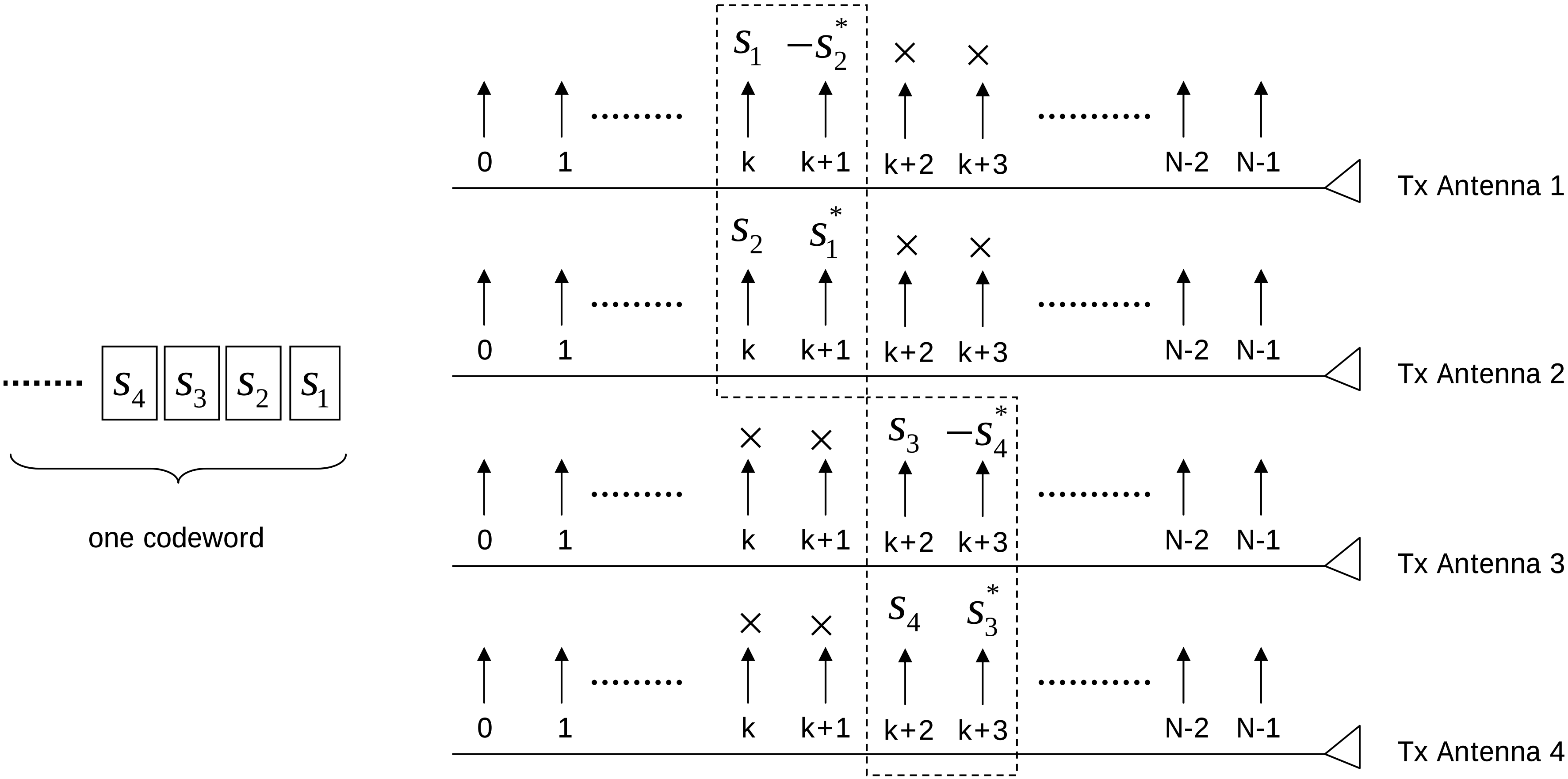
- SFBC = space frequency block code
- For 2 Tx antennas at eNodeB, and 2 Rx antennas at the UE, Alamouti code in the frequency domain is used.



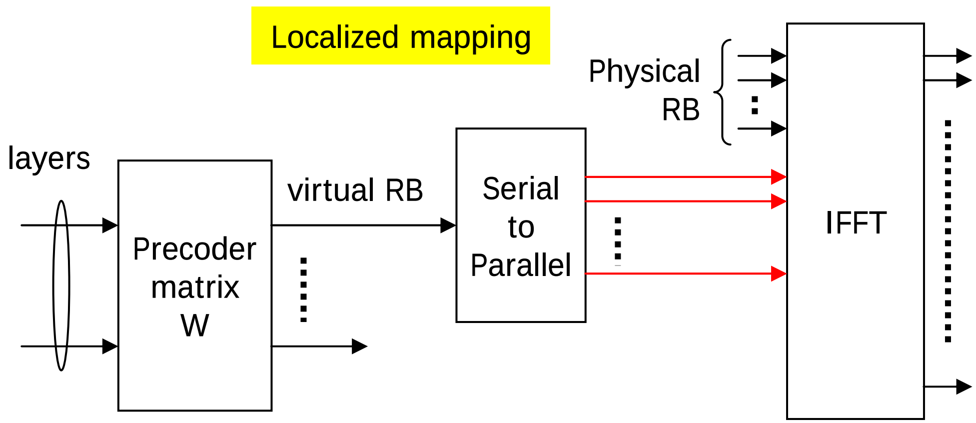
- Rate of the code = 1 (two symbols transmitted over two subcarriers)
- If the channel across two subcarriers is constant, then the virtual channel for an Alamouti code is orthogonal. Hence, a linear receiver provides ML performance!

SFBC-FSTD (4x2)

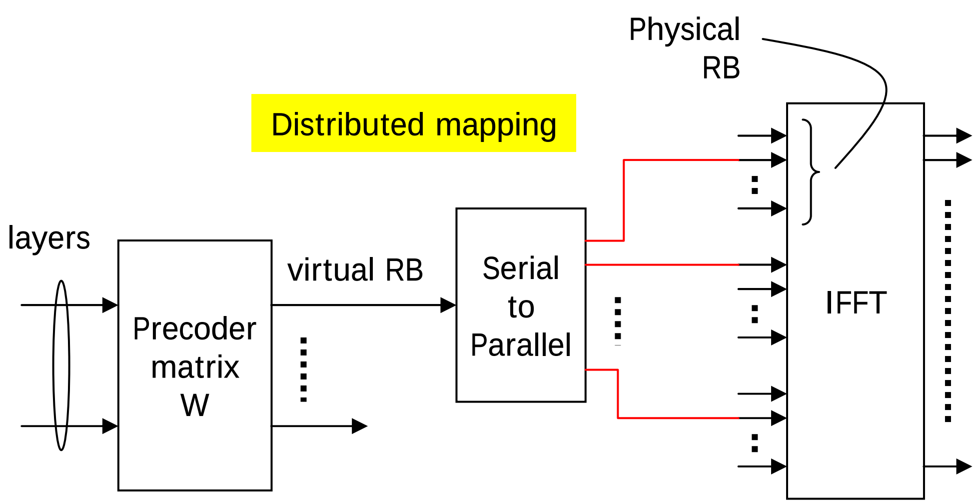
- SFBC-FSTD = Space Frequency Block Code with Frequency Switched Transmit Diversity
- For 4 Tx antennas at eNodeB, and 2 Rx antennas at the UE, Alamouti code with subcarrier interleaving in the frequency domain is used.



Localized vs Distributed RB mapping



- For pre-coded SDM, localized mapping from VRB to PRB is used
- Feedback of PMI from the UE is valid for 5 adjacent PRBs
- Since the pre-coding matrix is frequency dependent, distributed mapping is not an option



- For transmit diversity, distributed mapping from VRB to PRB is used
- Since the pre-coding matrix for transmit diversity is independent of frequency, better performance is obtained by spreading out the VRB.

MIMO schemes for Transport Channels

DL-SCH (shared channel)	SU-MIMO, MU-MIMO, Beamforming, TxD
BCH (broadcast)	only TxD (broadcast to entire cell)
PCH (paging)	only TxD (broadcast to entire cell)
MCH (multicast)	only TxD (broadcast to entire cell)
UL-SCH (shared channel)	MU-MIMO (i.e. SDMA)

LTE acronyms

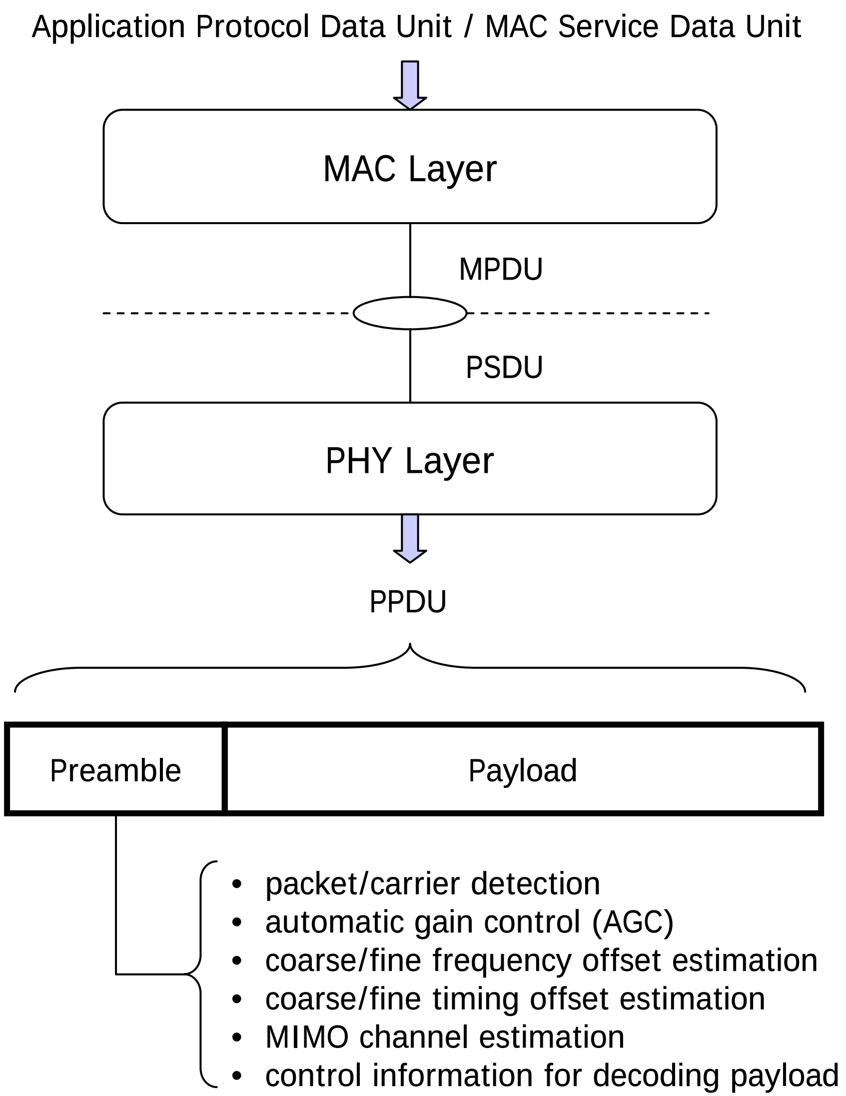
UE	User Equipment (i.e. mobile station)
eNodeB	Evolved Node B (i.e. base station)
MME	Mobility Management Entity
SGW	Serving Gateway
PDN-GW	Packet Data Network Gateway
NAS	Non-access Stratum
RRC	Radio Resource Control
PDCP	Packet Data Convergence Protocol
RLC	Radio Link Control
MAC	Medium Access Control
EPC	Evolved Packet Core (i.e. the core network)
EUTRAN	Evolved Universal Terrestrial Radio Access Network (i.e. collection of eNodeBs)
RAT	Radio Access Technology (such as GSM, EDGE, WCDMA)
MBMS	Multimedia Broadcast and Multicast Service
PMI	Pre-Coding Matrix indicator (for closed loop spatial division multiplexing)
SAE	System Architecture Evolution

IEEE 802.11n

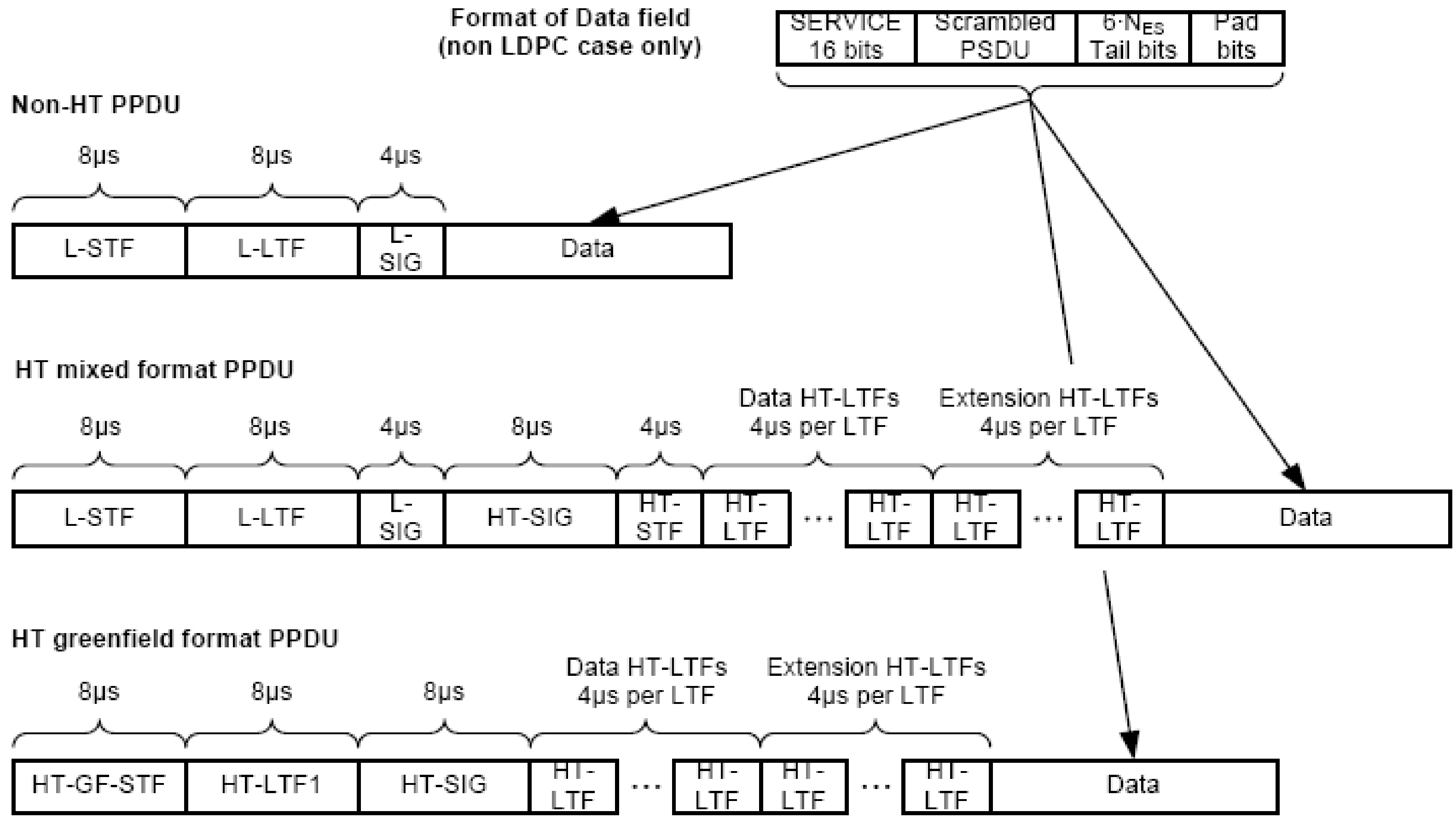
Feature Overview

- Baseline configuration
  - 2 Tx and 2 Rx antennas
  - 20 MHz operation with a 64-point IFFT
  - Mixed mode preamble recognizable by legacy APs
  - Open loop SDM with cyclic delay
  - Max PHY data rate ~ 130 Mbps
- Optional extensions
  - 4 Tx and 4 Rx antennas
  - 40 MHz operation with a 128 point IFFT
  - Greenfield preamble for pure 11n networks
  - Closed loop SDM
    - explicit feedback
    - implicit feedback
  - Space time block coding (STBC)
  - Shorter GI (400ns)

802.11n Layered Model



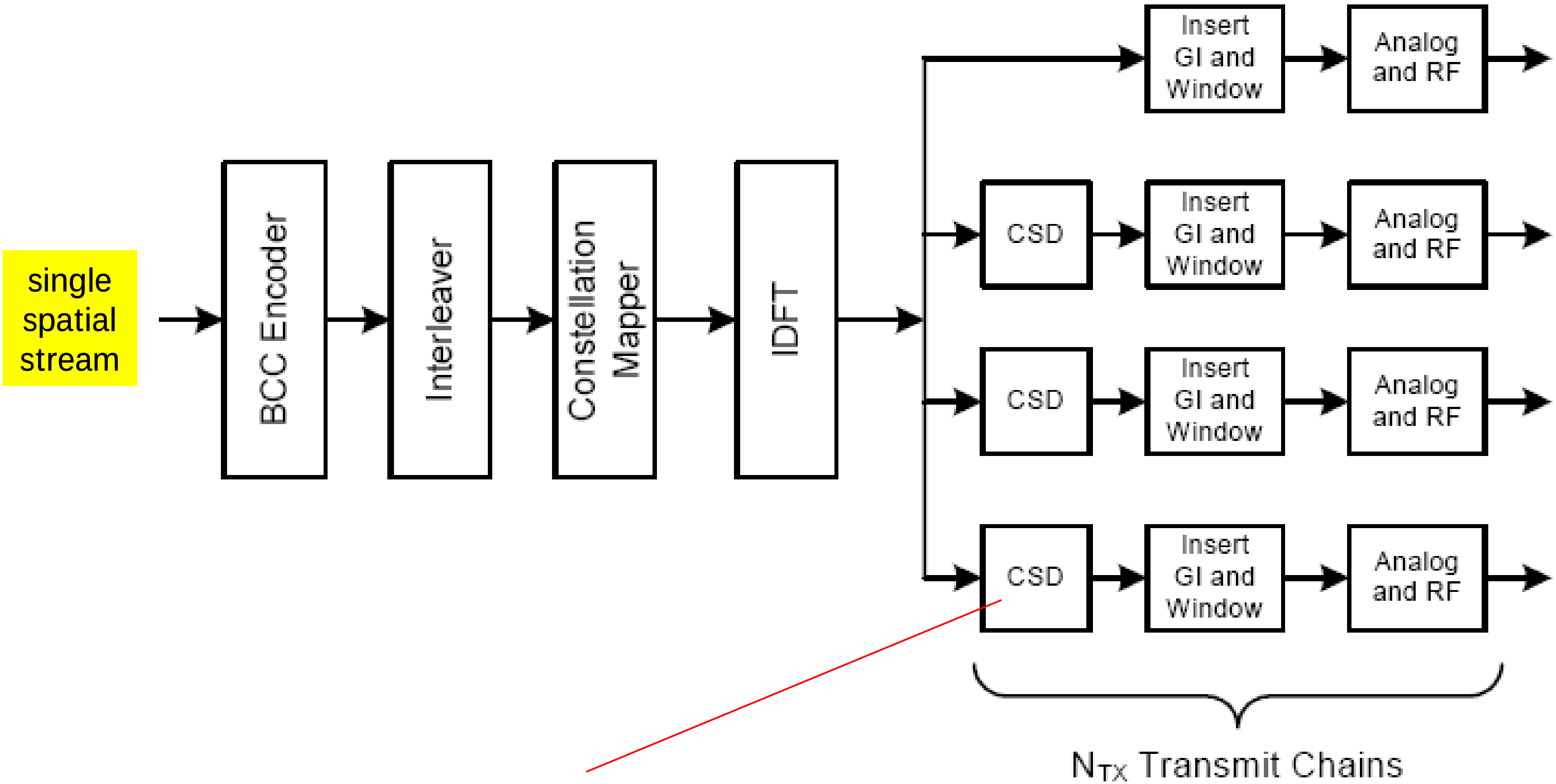
PPDU Formats



PPDU acronyms

Element	Description
L-STF	Non-HT Short Training Field (backwards compatible with 802.11a/g STF)
L-LTF	Non-HT Long Training Field (backwards compatible with 802.11a/g LTF)
L-SIG	Non-HT SIGNAL Field (backwards compatible with 802.11a/g SF)
HT-SIG	HT SIGNAL Field
HT-STF	HT Short Training Field (refines AGC training during MIMO mode, especially with beamforming)
HT-GF-STF	HT greenfield Short Training Field
HT-LTF1	First HT Long Training Field (Data HT-LTF) (helps decode HT-SIG in GF-PPDU)
HT-LTFs	Additional HT Long Training Fields (Data HT-LTFs and Extension HT-LTFs)
Data	The data field includes the PSDU (PHY Service Data Unit)

Tx datapath – Non-HT PPDU/HT-SIG

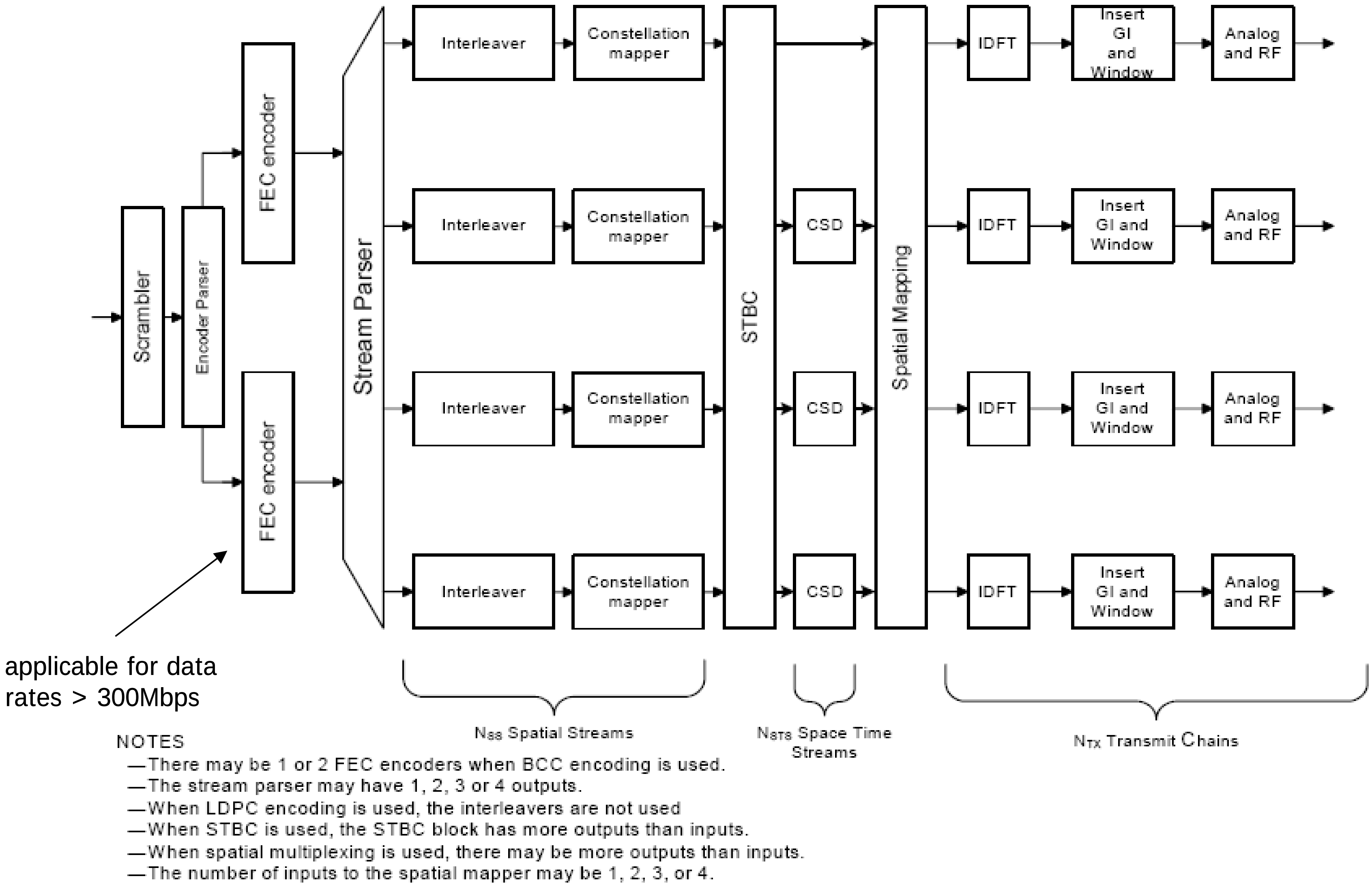


purpose of cyclic shift delay (CSD) is two-folds:

(1) when the same signal is transmitted on multiple antennas, there is potential for power fluctuation at the Rx, which is mitigated via CSD.

(2) CSD enhances the frequency selectivity of the channel → improves performance of the channel decoder

Tx datapath – HT portion/GF PPDU



OFDM Numerology

	non-HT PPDU	HT-PPDU	HT-PPDU
Channelization BW	20MHz	20MHz	40MHz
FFT points	64	64	128
Number of Data Subcarriers	48	52	108
Number of Pilot Subcarriers	4	4	6
Subcarrier Spacing	312.5kHz	312.5kHz	312.5kHz
Useful symbol length	3200ns	3200ns	3200ns
GI length	800ns	800ns, 400ns	800ns, 400ns
Coding Rates	1/2, 2/3, 3/4	1/2, 2/3, 3/4, 5/6	1/2, 2/3, 3/4, 5/6
Modulation levels	BPSK, QPSK, 16-QAM, 64-QAM	BPSK, QPSK, 16-QAM, 64-QAM	BPSK, QPSK, 16-QAM, 64-QAM

Total number of modulation and coding schemes across all spatial streams = 77

Modulation & Coding Set (1)

20MHz, 1 BCC encoder and 2 spatial streams, with equal modulation on each spatial stream

MCS Index	Modulation	R	$N_{BPSCS}(i_{SS})$	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
								800 ns GI	400 ns GI See NOTE
8	BPSK	1/2	1	52	4	104	52	13.0	14.4
9	QPSK	1/2	2	52	4	208	104	26.0	28.9
10	QPSK	3/4	2	52	4	208	156	39.0	43.3
11	16-QAM	1/2	4	52	4	416	208	52.0	57.8
12	16-QAM	3/4	4	52	4	416	312	78.0	86.7
13	64-QAM	2/3	6	52	4	624	416	104.0	115.6
14	64-QAM	3/4	6	52	4	624	468	117.0	130.0
15	64-QAM	5/6	6	52	4	624	520	130.0	144.4

NOTE—The 400 ns GI rate values are rounded to 1 decimal place

Modulation & Coding Set (2)

20MHz, 1 BCC encoder and 3 spatial streams, with unequal modulation across spatial streams

MCS Index	Modulation			R	N_{BPSC}	N_{SD}	N_{SP}	N_{CBPS}	N_{DBPS}	Data rate (Mb/s)	
	Stream 1	Stream 2	Stream 3							800 ns GI	400 ns GI
39	16-QAM	QPSK	QPSK	1/2	8	52	4	416	208	52	57.8
40	16-QAM	16-QAM	QPSK	1/2	10	52	4	520	260	65	72.2
41	64-QAM	QPSK	QPSK	1/2	10	52	4	520	260	65	72.2
42	64-QAM	16-QAM	QPSK	1/2	12	52	4	624	312	78	86.7
43	64-QAM	16-QAM	16-QAM	1/2	14	52	4	728	364	91	101.1
44	64-QAM	64-QAM	QPSK	1/2	14	52	4	728	364	91	101.1
45	64-QAM	64-QAM	16-QAM	1/2	16	52	4	832	416	104	115.6
46	16-QAM	QPSK	QPSK	3/4	8	52	4	416	312	78	86.7
47	16-QAM	16-QAM	QPSK	3/4	10	52	4	520	390	97.5	108.3
48	64-QAM	QPSK	QPSK	3/4	10	52	4	520	390	97.5	108.3
49	64-QAM	16-QAM	QPSK	3/4	12	52	4	624	468	117	130.0
50	64-QAM	16-QAM	16-QAM	3/4	14	52	4	728	546	136.5	151.7
51	64-QAM	64-QAM	QPSK	3/4	14	52	4	728	546	136.5	151.7
52	64-QAM	64-QAM	16-QAM	3/4	16	52	4	832	624	156	173.3

useful for beamforming or STBC modes

Cyclic Delay Parameters

$T_{CS}^{i_{TX}}$ values for the non-HT portion of the packet				
Number of transmit Chains	**Cyclic shift for transmit chain 1**	**Cyclic shift for transmit chain 2**	**Cyclic shift for transmit chain 3**	**Cyclic shift for transmit chain 4**
1	0ns	-	-	-
2	0ns	-200 ns	-	-
3	0ns	-100 ns	-200 ns	-
4	0ns	-50ns	-100 ns	-150ns

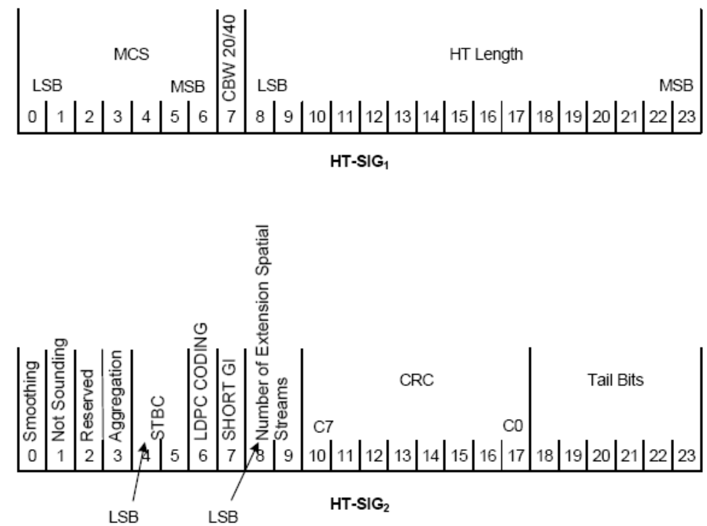
Small delays allow a legacy Rx to acquire time sync using L-STF. Large cyclic delay on L-STF negatively impacts cross correlation receivers.

$T_{CS}^{i_{STS}}$ values for HT portion of the packet				
Number of space time streams	**Cyclic shift for space time stream 1**	**Cyclic shift for space time stream 2**	**Cyclic shift for space time stream 3**	**Cyclic shift for space time stream 4**
1	0ns	-	-	-
2	0ns	-400 ns	-	-
3	0ns	-400 ns	-200 ns	-
4	0ns	-400 ns	-200 ns	-600 ns

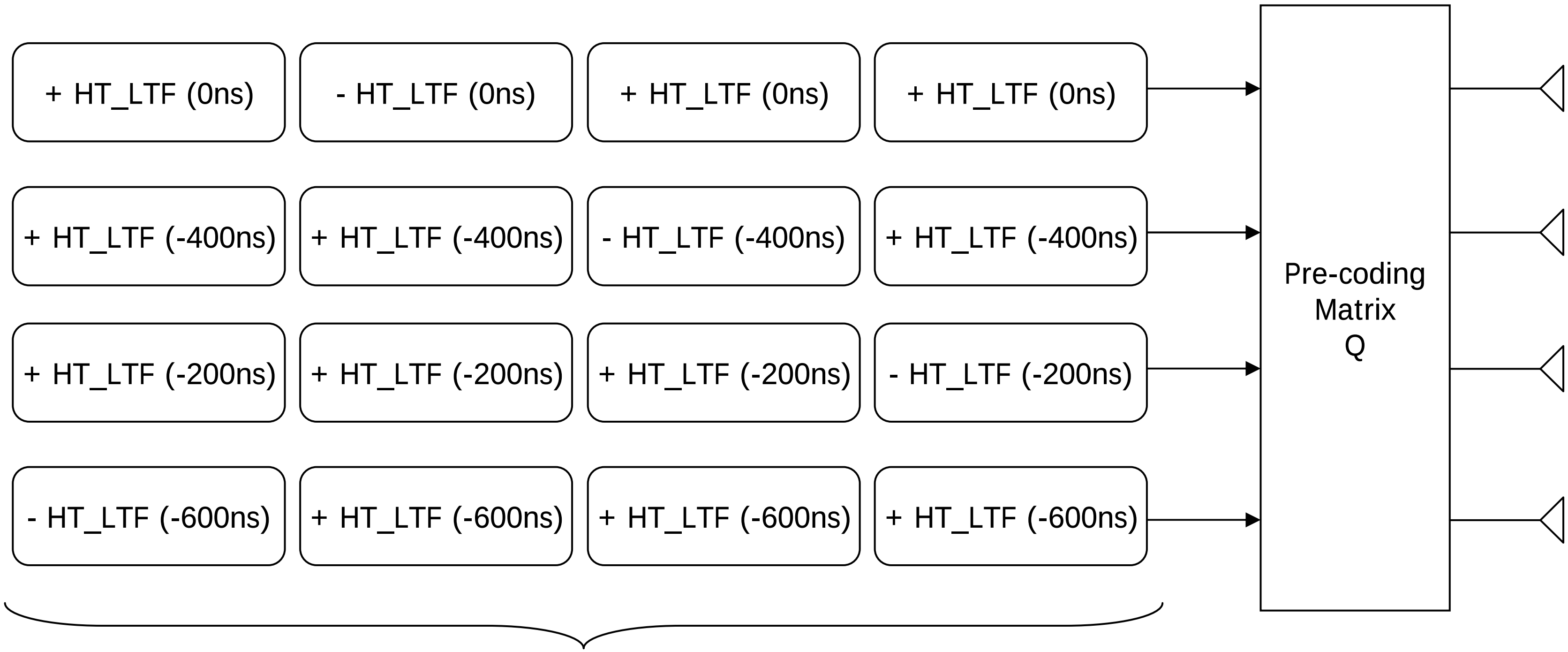
Large delays are better at reducing power fluctuation than small delays. HT portion of the PPDU is not constrained by backwards compatibility.

HT Signal Field

Field Name	Number of bits	Explanation and coding
Modulation and Coding Scheme	7	Index into the MCS table, See NOTE 1.
CBW 20/40	1	Set to 0 for 20 MHz or 40 MHz upper/lower Set to 1 for 40 MHz
HT Length	16	The number of octets of data in the PSDU in the range 0-65535 See NOTE 1 and NOTE 2.
Smoothing	1	Set to 1 indicates that channel estimate smoothing is recommended Set to 0 indicates that only per-carrier independent (unsmoothed) channel estimate is recommended
Not Sounding	1	Set to 0 indicates that PPDU is a Sounding PPDU Set to 1 indicates that the PPDU is not a sounding PPDU When Length = 0 then Not Sounding shall be set to 0.
Reserved	1	Set to 1
Aggregation	1	Set to 1 to indicate that the PPDU in the data portion of the packet contains an A-MPDU; otherwise, set to 0.
STBC	2	Set to a non-zero number, to indicate the difference between the number of space time streams (N_{STS}) and the number of spatial streams (N_{SS}) indicated by the MCS. Set to 00 to indicate no STBC ($N_{STS} = N_{SS}$) See NOTE 1.
FEC coding	1	Set to 1 for LDPC Set to 0 for BCC
Short GI	1	Set to 1 to indicate that the short GI is used after the HT training. Set to 0 otherwise
Number of extension spatial streams	2	Indicates the Number of extension spatial streams (N_{ESS}). Set to 0 for no extension spatial stream Set to 1 for 1 extension spatial stream Set to 2 for 2 extension spatial streams Set to 3 for 3 extension spatial streams See NOTE 1
CRC	8	CRC of bits 0-23 in HT-SIG$_1$ and bits 0-9 in HT-SIG$_2$—see 20.3.9.4.4 (CRC calculation for the HT SIGNAL field). The first bit to be transmitted is bit C7 as explained in 20.3.9.4.4 (CRC calculation for the HT SIGNAL field).
Tail Bits	6	Used to terminate the trellis of the convolution coder. Set to 0.



Mapping HT-LTF to Antennas



$$W = \begin{bmatrix} +1 & -1 & +1 & +1 \\ +1 & +1 & -1 & +1 \\ +1 & +1 & +1 & -1 \\ -1 & +1 & +1 & +1 \end{bmatrix}$$

W is an orthogonal matrix. The cyclic delays serve to reduce power fluctuation

Received Signal $Y = HQW \quad \Rightarrow \quad (HQ)_{estimate} = YW^T$

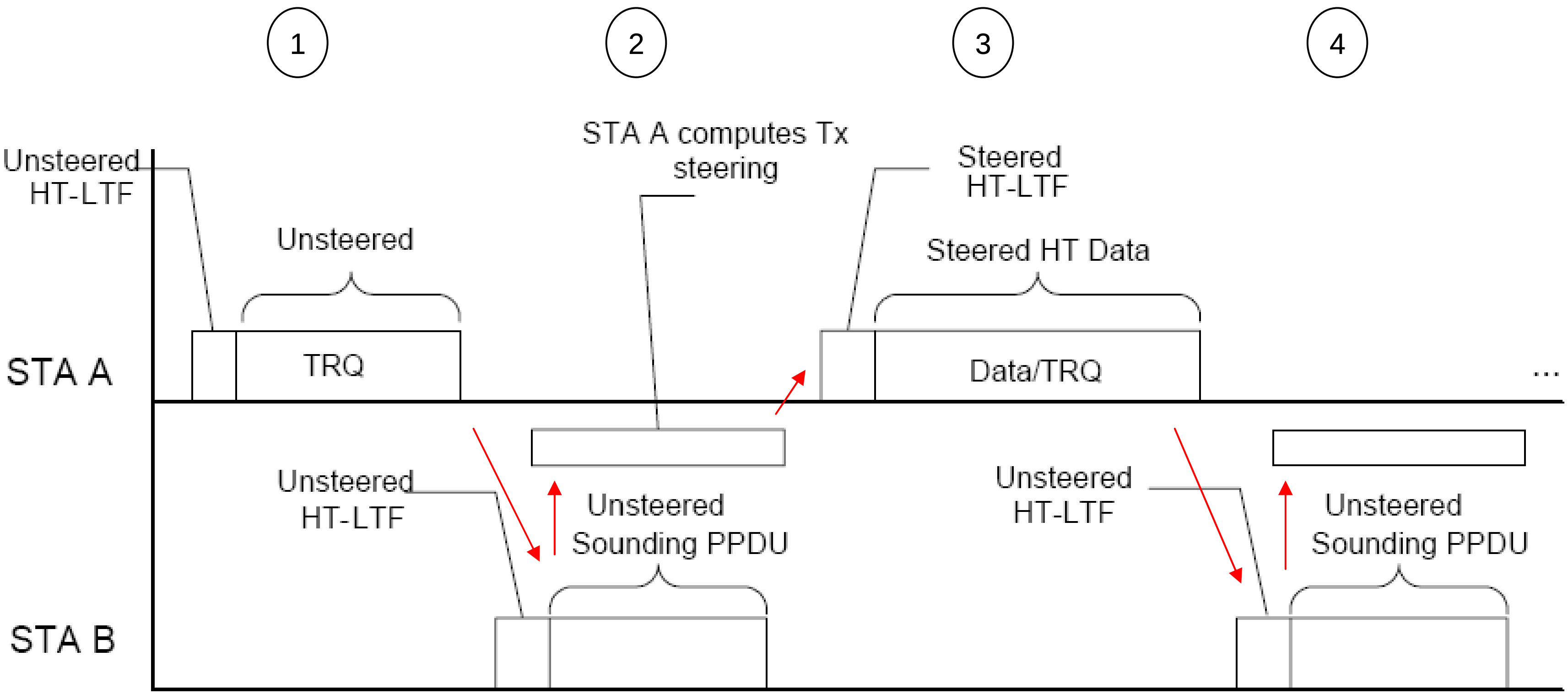
STBC mapping

N_{STS}	HT-SIG MCS field (bits 0-6 in HT-SIG$_1$)	N_{SS}	HT-SIG STBC field (bits 4–5 in HT-SIG$_2$)	i_{STS}	$\tilde{d}_{k,i,2m}$	$\tilde{d}_{k,i,2m+1}$	
2	0-7	1	1	1	$d_{k,1,2m}$	$d_{k,1,2m+1}$	Alamouti
				2	$-d^*_{k,1,2m+1}$	$d^*_{k,1,2m}$	
3	8-15, 33-38	2	1	1	$d_{k,1,2m}$	$d_{k,1,2m+1}$	pass through
				2	$-d^*_{k,1,2m+1}$	$d^*_{k,1,2m}$	Alamouti
				3	$d_{k,2,2m}$	$d_{k,2,2m+1}$	
4	8-15	2	2	1	$d_{k,1,2m}$	$d_{k,1,2m+1}$	Alamouti
				2	$-d^*_{k,1,2m+1}$	$d^*_{k,1,2m}$	
				3	$d_{k,2,2m}$	$d_{k,2,2m+1}$	Alamouti
				4	$-d^*_{k,2,2m+1}$	$d^*_{k,2,2m}$	
4	16-23, 39, 41, 43, 46, 48, 50	3	1	1	$d_{k,1,2m}$	$d_{k,1,2m+1}$	Alamouti
				2	$-d^*_{k,1,2m+1}$	$d^*_{k,1,2m}$	
				3	$d_{k,2,2m}$	$d_{k,2,2m+1}$	pass through
				4	$d_{k,3,2m}$	$d_{k,3,2m+1}$	

Beamforming

- Beamforming in 802.11n is closed-loop spatial division multiplexing
- Two flavors supported – implicit and explicit
- **Implicit beamforming**
  - channel reciprocity is assumed (TDD transmission)
  - beamformer estimates CSI based upon a sounding PPDU sent from the beamformee
  - calibration is required to account for RFIC mismatches
- **Explicit Beamforming**
  - Explicit beamforming uses one of three methods to determine the transmit weights:
    - Channel State Information from the beamformee
    - Non-compressed beamforming matrices from the beamformee
    - Compressed beamforming matrices from the beamformee
  - The beamformee must inform the beamformer as to what technique it can use, along with whether it is capable to respond as:
    - Immediate
    - Delayed
    - Immediate and delayed

Implicit Beamforming



STA A is the beamformer, and STA B is the beamformee

IEEE 802.16e

802.16

- The Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) sought to make BWA more widely available by developing IEEE Standard 802.16, which specifies the WirelessMAN Air Interface for wireless metropolitan area networks. The standard, which was published on 8 April 2002, was created in a two-year, open-consensus process by hundreds of engineers from the world's leading operators and vendors.
- IEEE 802.16 addresses the "first-mile/last-mile" connection in wireless metropolitan area networks. It focuses on the efficient use of bandwidth between 10 and 66 GHz and defines a medium access control (MAC) layer that supports multiple physical layer specifications customized for the frequency band of use.
- The 10 to 66 GHz standard supports continuously varying traffic levels at many licensed frequencies (e.g., 10.5, 25, 26, 31, 38 and 39 GHz) for two-way communications. It enables interoperability among devices, so carriers can use products from multiple vendors and warrants the availability of lower cost equipment.

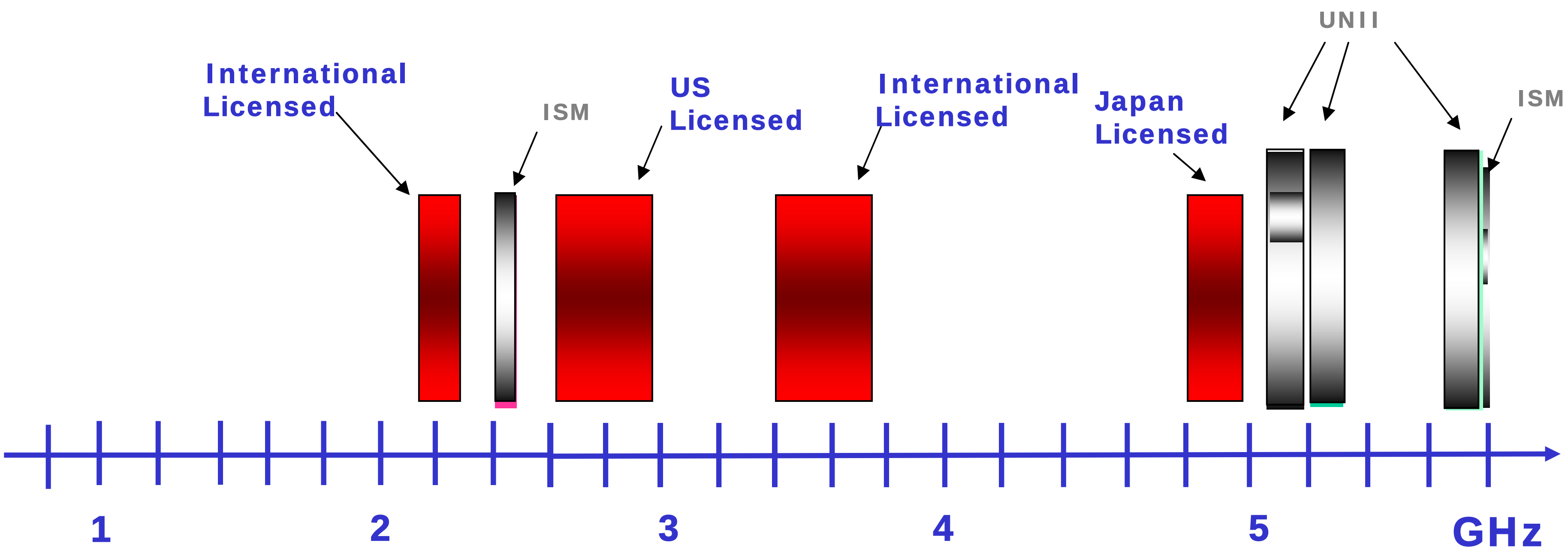
802.16 Standards

- 802.16: LOS, 10-66 GHz (70-Mbit/s up to 30 miles)
- 802.16a: NLOS, 2-11 GHz
- 802.16b, c: extensions for QoS, testing, and interoperability
- 802.16d – Fixed extension
- 802.16e: 2-6 GHz, mobility
- 802.16m: higher data rates (under development)
- WiMAX forum http://www.wimaxforum.org/home

802.16 Overview

- OFDM-based
- Carrier frequencies:
  - .7 GHz - US to be allocated
  - .9, 1.9 GHz
  - 2.3-2.4 TDD band (China, Korea-primary interest)
  - 2.5 MMDS band
  - 3.4-3.6 licensed outside US
  - 5.2-5.8 unlicensed (3.5 and 5.8 GHz of primary interest in China)
  - Japan (no 2.5/3.5 GHz): 4.9-5.1GHz
- Bandwidths: 1.25, 2.5, 5, 10, 20
- TDD, with FDD optional
- Access is OFDM or OFDMA
- Data rates to 75 Mbps (802.16d), 30 Mbps (802.16e), range to 30 mi (licensed bands)
- Coding and modulation up to 64 QAM

802.11/802.16 Spectrum



802.16 has both licensed and license-exempt options

ISM: Industrial, Scientific & Medical Band – Unlicensed band

UNII: Unlicensed National Information Infrastructure band – Unlicensed band

(From Proxim)

Comparison of 802.11 and 802.16

	802.11	802.16
Scalability	20 or 40 MHz channels	1.5 to 20 MHz channels scalable MAC
QoS	Contention-based 802.11e added later (priority-based) TDD	Grant request MAC QoS designed from start (centrally enforced) TDD/FDD/OFDMA Differentiated service levels
Range	100 m (corresponding delays/delay spreads and powers)	50 km (corresponding delays/delay spreads and powers)
Coverage	Indoors (mesh under development)	Outdoors (supports mesh)
Security	WAP and WEP – 802.11i	Triple-DES (128-bit) and RSA (1024-bit)

802.16e

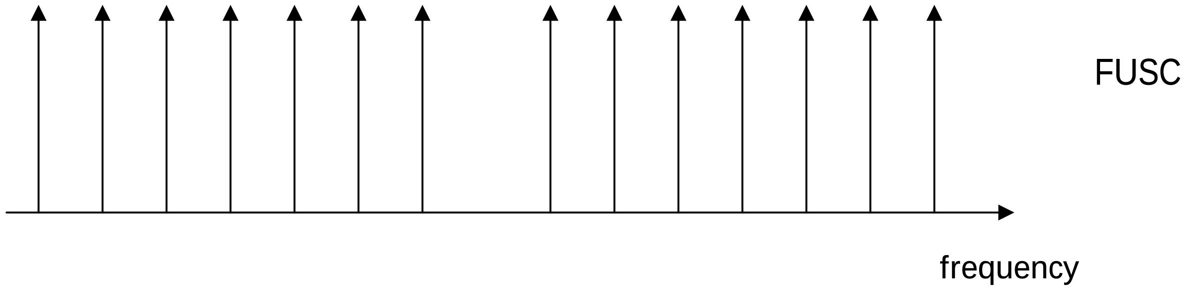
- Scalable OFDM: 1.25, 2.5, 5, 10, 20 MHz (FFT: 256, 1K, single carrier, with added 2K, 512, 128).
- Hybrid-Automatic Repeat Query (H-ARQ) – Chase combining, incremental redundancy)
- Adaptive modulation and coding: QPSK, 16 QAM, 64 QAM, with turbo, low-density parity check, and convolutional coding
- Subchannelization for OFDMA: FUSC, PUSC, AMC
- Transmit beamforming (adaptive antenna systems), space-time coding and spatial multiplexing (MIMO).

802.16e Evolution

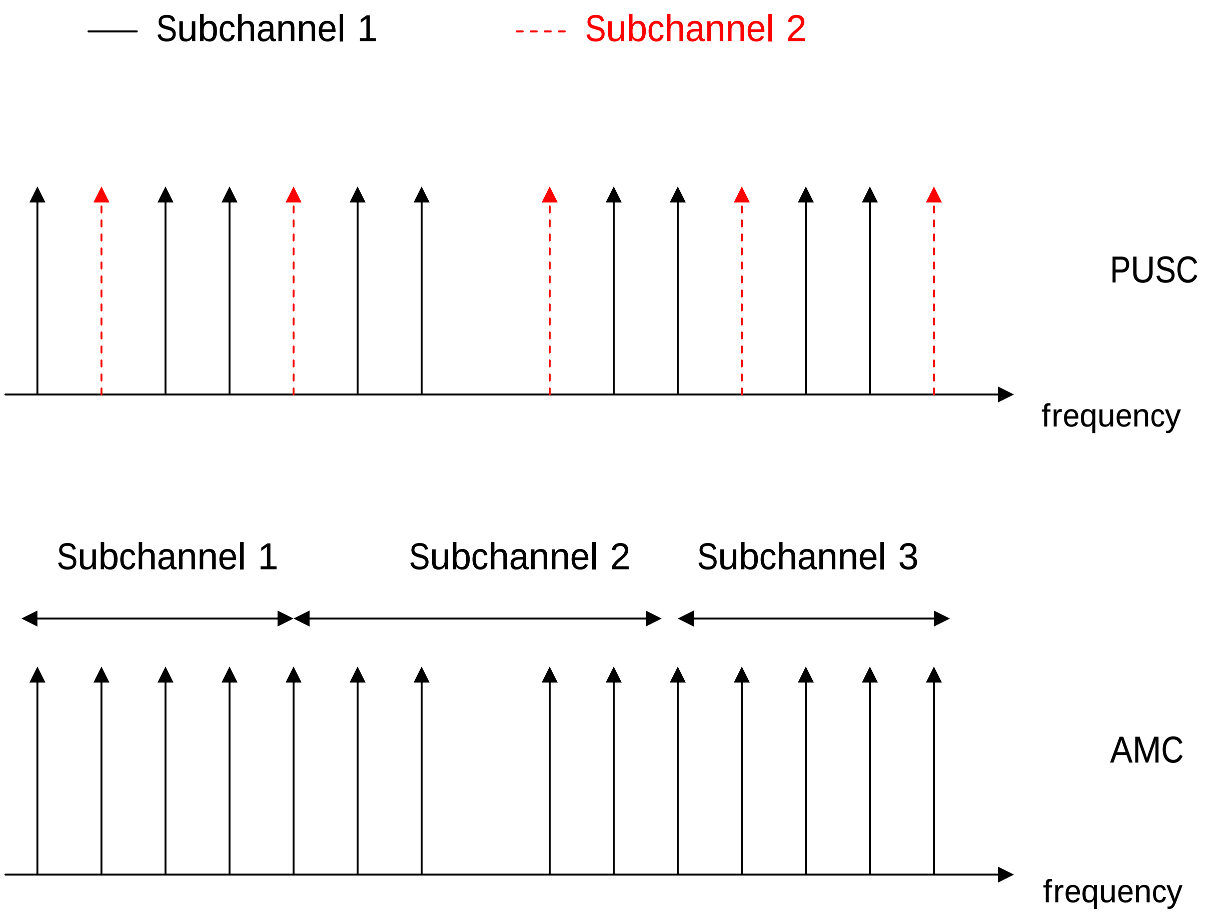
- WAVE 1:
  - DL subcarrier allocation: FUSC, PUSC
  - UL subcarrier allocation: PUSC
  - Fast feedback with 6 bits
  - Modulation:
    - DL – QPSK, 16QAM, 64QAM
    - UL – QPSK, 16QAM
- WAVE 2:
  - MIMO
    - Matrix A/B (STC/MIMO)
    - Collaborative spatial multiplexing (UL)
    - Fast feedback on DL
    - MIMO DL-UL Chase combining
  - MIMO AAS:
    - AMC with dedicated pilots
    - UL sounding (single antenna)

OFDMA Aspects

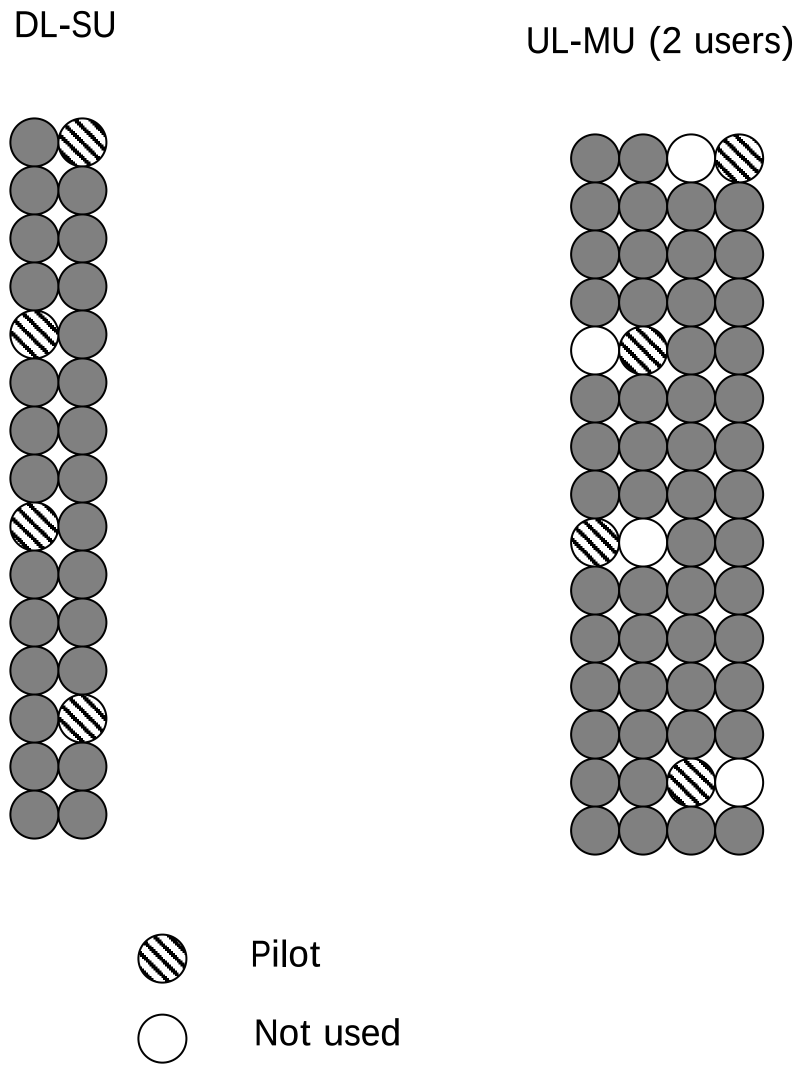
- Subcarrier allocation methods (permutations):
  - FUSC (Full Use of Subchannels)
  - PUSC (Partial Use of Subchannels) – Distributed subcarriers
  - AMC (Adjacent Mode Carriers) – Adjacent subcarriers



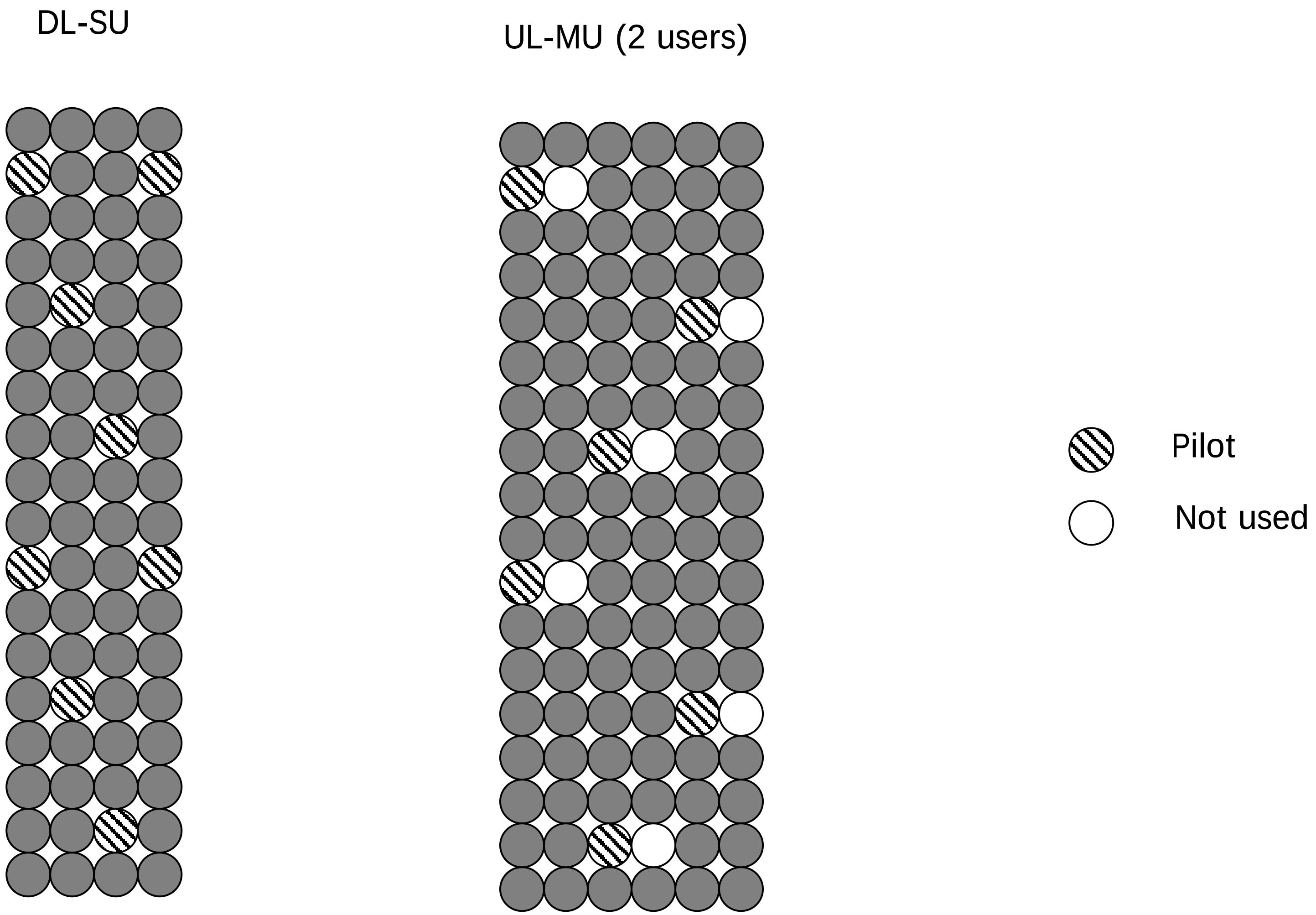
PUSC and AMC structure



PUSC Pilots



AMC Pilots



PUSC and AMC Tradeoffs

- AMC:
  - Frequency selective loading gain (more complicated scheduler needed)
  - Stationary channel
  - Useful with beamforming (AAS), slow users
- PUSC:
  - Frequency diversity (inter-cell interference averaging)
  - Simple scheduler
  - MIMO, fast users

MIMO Aspects

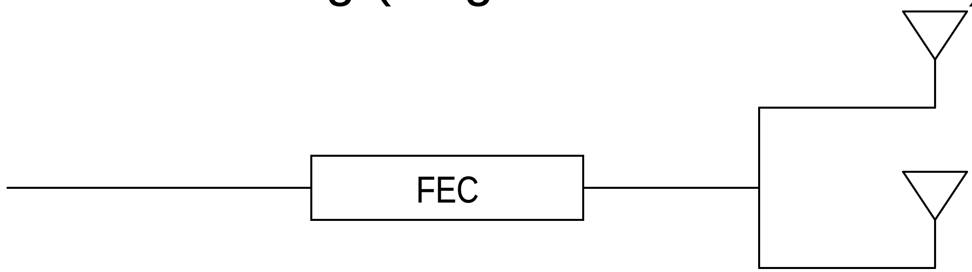
- Downlink:
  - Open loop:
    - Space-time coding – 2X2 Alamouti (Matrix A)
    - Spatial multiplexing (Matrix B)
  - Closed Loop:
    - Feedback (6-bits) from both user antennas
    - Uplink sounding only from one transmit antenna (as user has one transmit, but two receive antennas)
    - PUSC for spatial multiplexing
    - AMC and PUSC for single stream (STC)
  - Multi-user not directly supported

MIMO Aspects

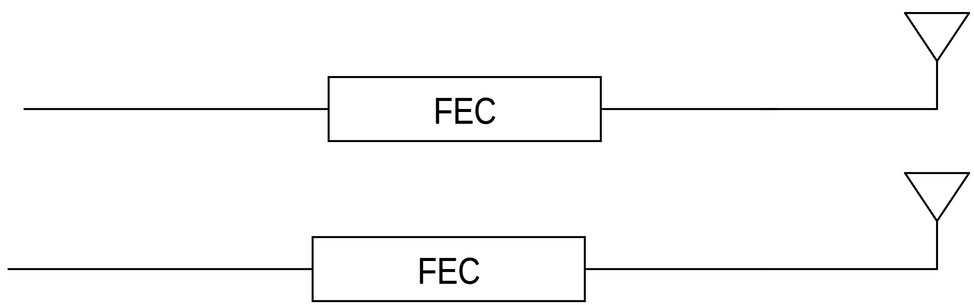
- Uplink:
  - One transmit antenna per user (no MIMO with single user)
  - Multiple users with PUSC (same allocation for each of two users)

MIMO Aspects

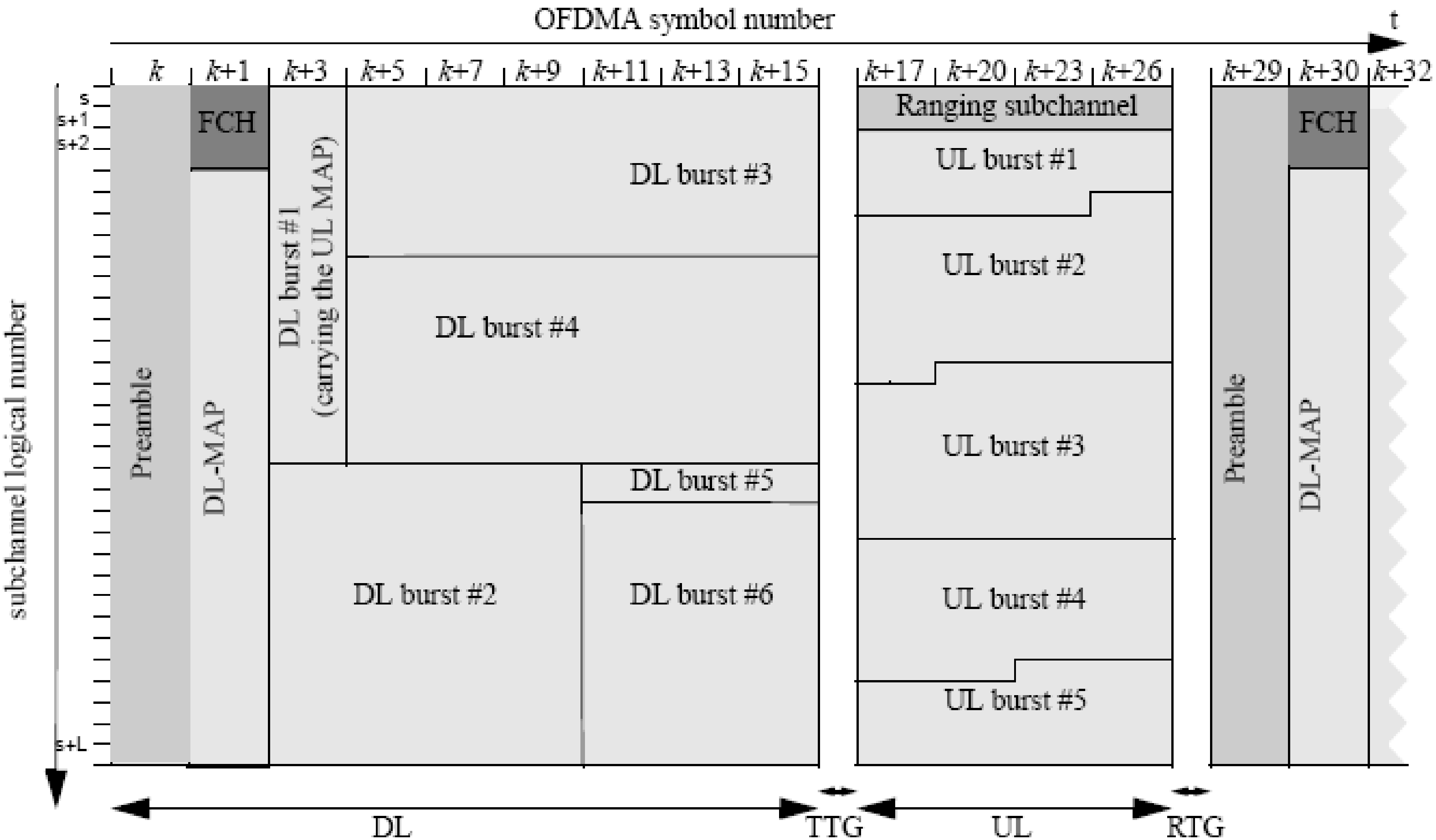
- Spatial multiplexing:
  - Vertical encoding (Single code word – SCW)



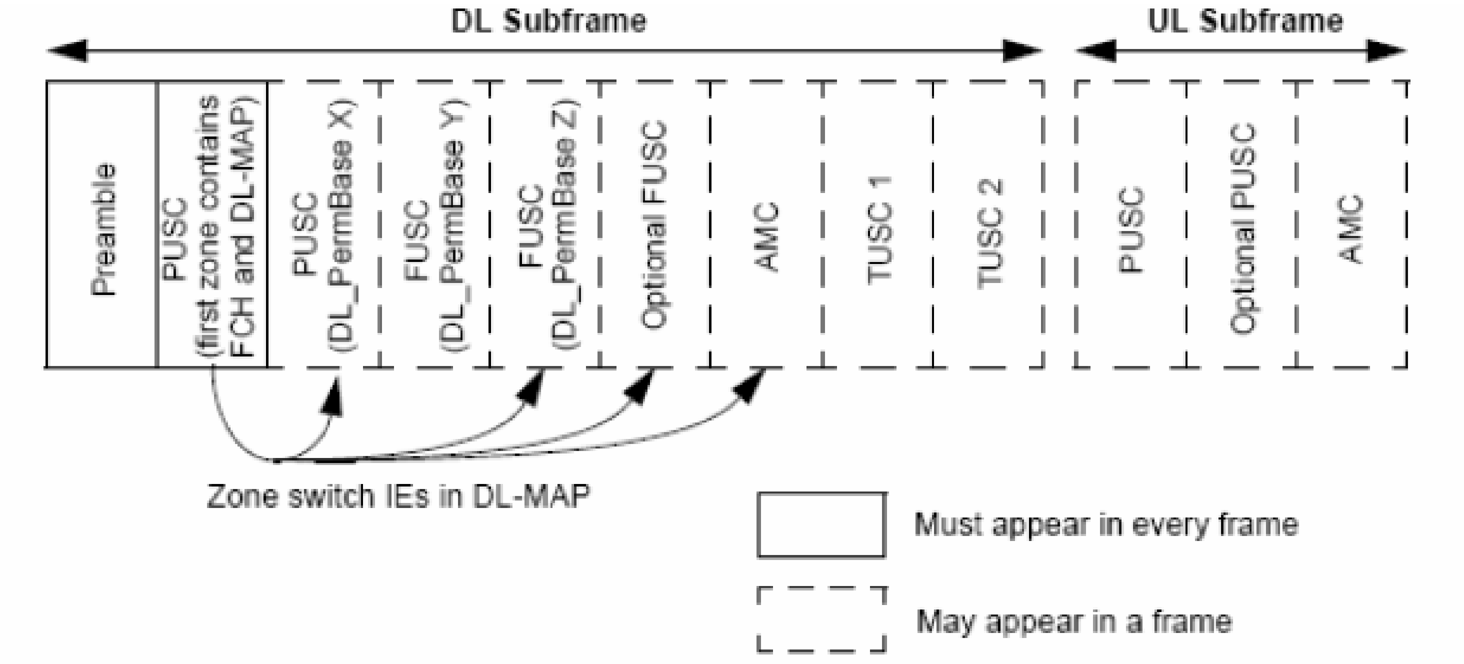
•Horizontal encoding (multi-code word – MCW) – not available for DL



802.16e Frame



Mandatory and Optional Zones



Conclusion

Summary

	LTE	802.16e	802.11n
BW (MHz)	1.25, 2.5, 5, 10, 15, 20	1.25, 2.5, 5, 10, 15, 20	20, 40
FFT size	128, 256, 512, 1024, 2048	128, 256, 512, 1024, 2048	64, 128
GI	5μs, 16μs	Variable length	0.8μs
Number of spatial streams (layers)	DL: 2 baseline, 4 optional UL: 1 baseline	DL: 2 baseline, 4 optional UL: 1 baseline	DL: 2 baseline, 4 optional UL: 2 baseline, 4 optional
Antenna configuration at mobile/station	Rx: 2x baseline, 4x optional Tx: 1x baseline	Rx: 2x baseline, 4x optional Tx: 1x baseline	Rx: 2x baseline, 4x optional Tx: 2x baseline, 4x optional
SDM	pre-coded with unitary codebook (explicit)	pre-coded with explicit or implicit CSIT	pre-coded with explicit or implicit CSIT
Transmit Diversity	CDD, SFBC, SFBC-FSTD	SFBC, FHDC	CDD, STBC
Modulation	QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM	BPSK, QPSK, 16QAM, 64QAM
Channel Estimation	in-band reference signals in space-time-frequency	in-band reference signals in space-time-frequency	preamble reference signals
Coding	Turbo Encoder, Convolutional Encoder	Turbo Encoder, LDPC, Convolutional Encoder	Convolutional Encoder, LDPC