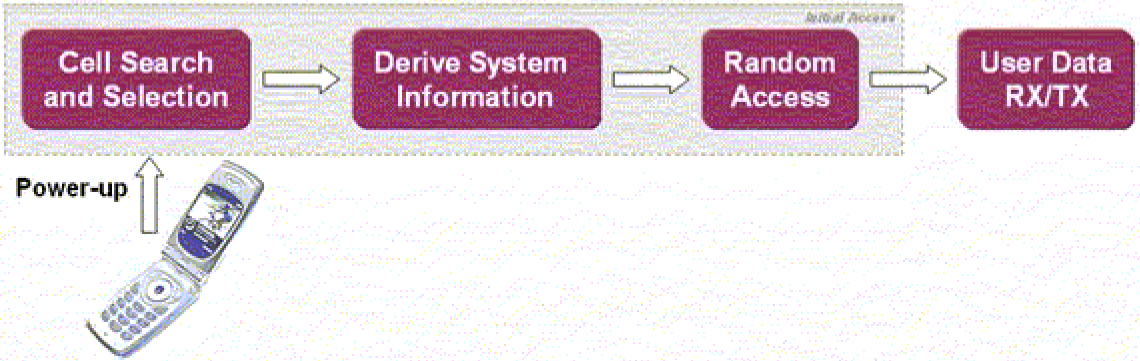
# Outline

- **Motivation for LTE**
- **LTE technology basics**
  - Key parameters
  - OFDMA and downlink frame structure
  - SC-FDMA and uplink frame structure
  - Network and protocol architecture
  - LTE UE categories
- **Radio procedures**
  - Cell search
  - System information broadcast
  - Random access
  - EPS bearer setup
  - Downlink and uplink data transmission
  - Mobility
  - MIMO
- **LTE test requirements**
  - eNodeB RF testing
  - UE RF testing
  - LTE wireless device testing from R&D up to conformance
  - LTE field trial testing and coverage measurements

MIMO = Multiple Input Multiple Output
EPS = Evolved Packet System
UE = User Equipment
RRM = Radio Resource Management
OFDMA = Orthogonal Frequency Division Multiple Access
SC-FDMA = Single Carrier Frequency Division Multiple Access

# Radio procedures

# LTE Initial Access

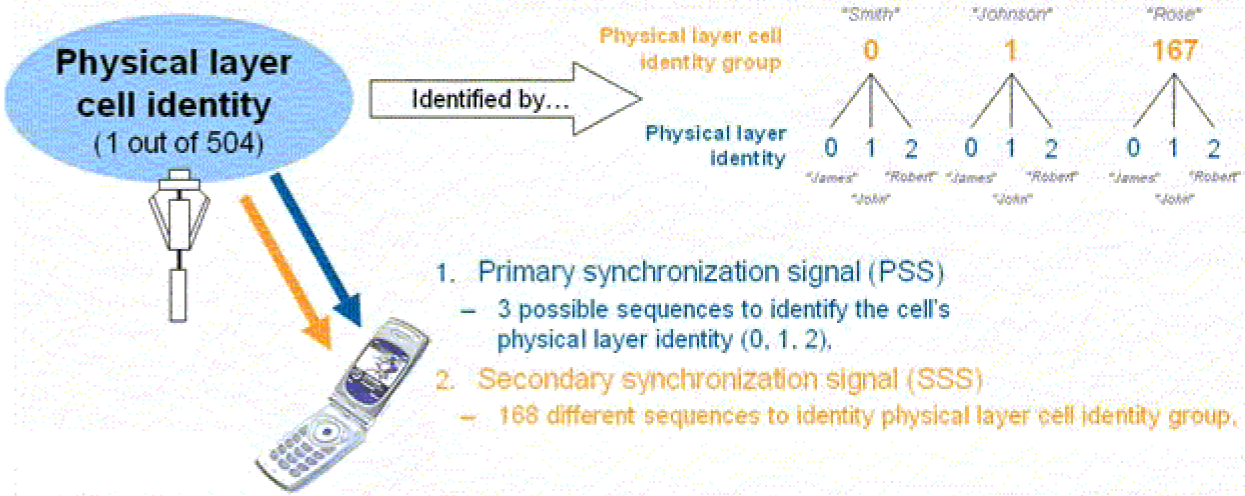


# Downlink physical channels and signals

| LTE Downlink Physical Signals | |
|---|---|
| **Primary and Secondary Synchronization Signal** | Provide acquisition of cell timing and identity during cell search |
| **Downlink Reference Signal** | Cell search, initial acquisition, coherent demod., channel estimation |

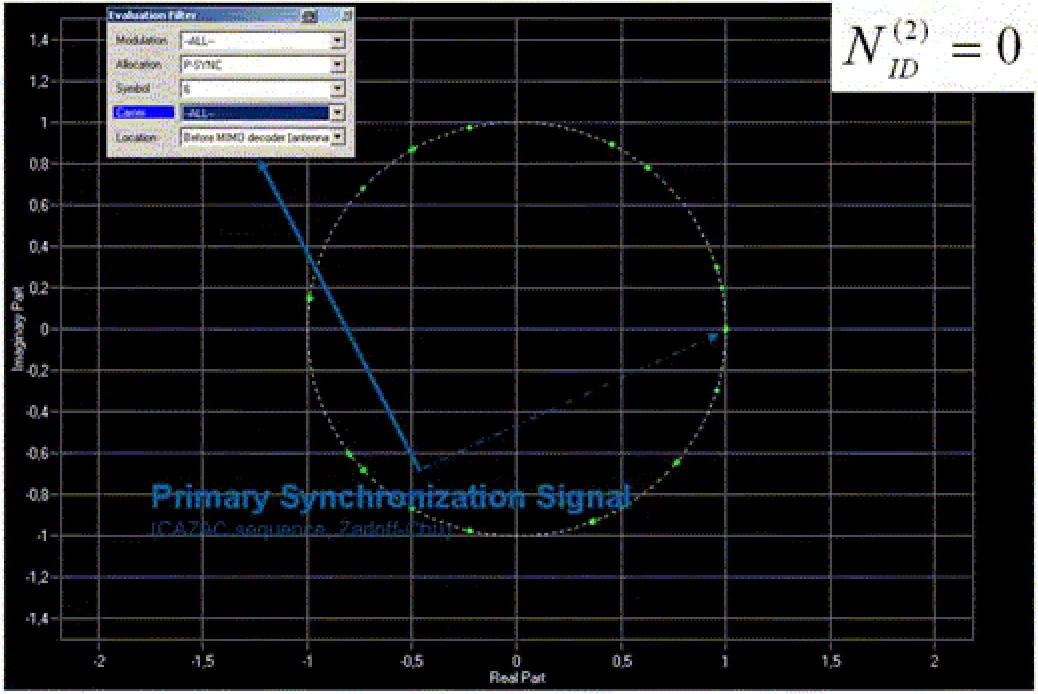
| LTE Downlink Physical Channels | |
|---|---|
| **Physical Broadcast Channel (PBCH)** | Provides essential system information e.g. system bandwidth |
| **Physical Control Format Indicator Channel (PCFICH)** | Indicates format of PDCCH (CFI) |
| **Physical Downlink Control Channel (PDCCH)** | Carries control information (DCI = Downlink Control Information) |
| **Physical Downlink Shared Channel (PDSCH)** | Carries data (user data, system information, ... ) |
| **Physical Hybrid ARQ Indicator Channel (PHICH)** | Carries ACK/NACK (HI = HARQ indicator) for uplink data packets |
| **Physical Multicast Channel (PMCH)** | Carries MBMS user data |

# Cell search in LTE




- Hierarchical cell search as in 3G; providing PSS and SSS for assistance,
  - PSS is carrying physical layer identity $N_{ID}^{(2)}$,
  - SSS is carrying physical layer cell identity group $N_{ID}^{(1)}$,
  - Cell Identity is computed as $N_{ID}^{cell} = 3N_{ID}^{(1)} + N_{ID}^{(2)}$, where $N_{ID}^{(1)} = 0,1,...,167$ and $N_{ID}^{(2)} = 0, 1, 2$

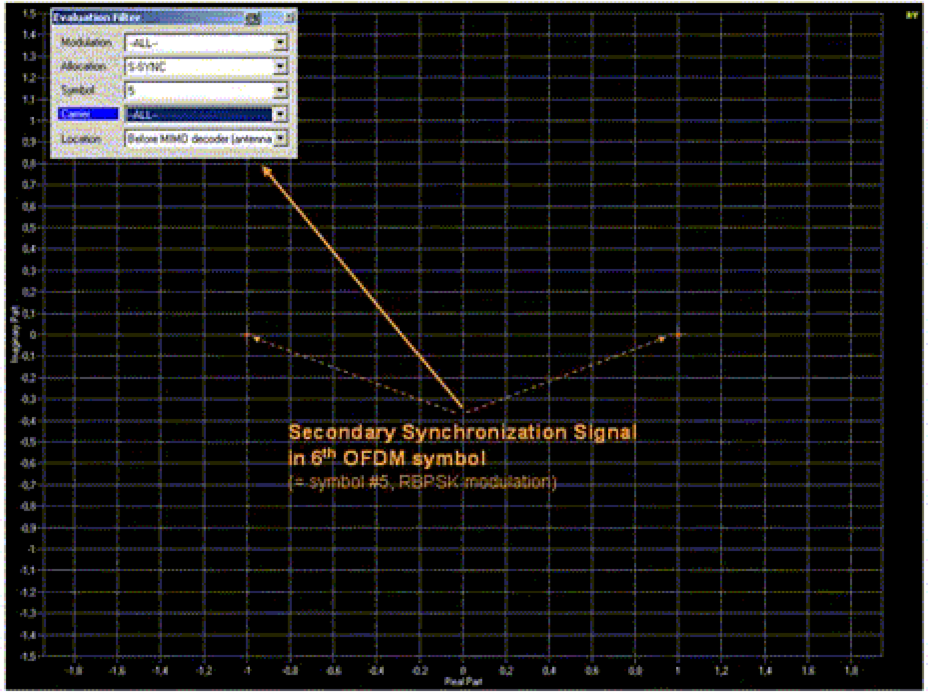
# Primary Synchronization Signal




$$N_{ID}^{(2)} = 0$$

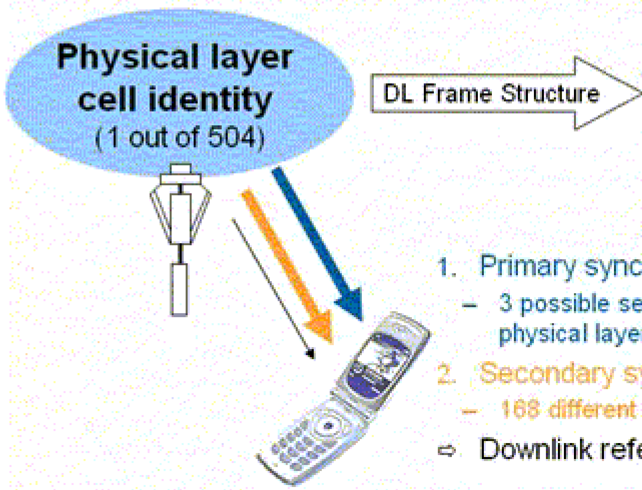
Screenshot taken from R&S® FSQ signal analyzer

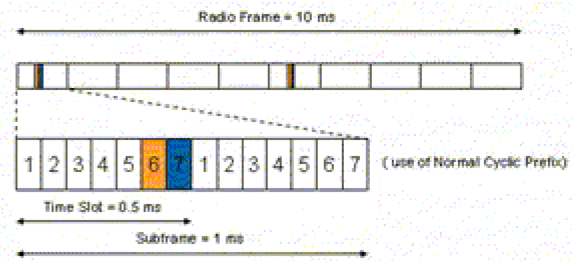
# Secondary Synchronization Signal




Screenshot taken from R&S® FSQ signal analyzer

# Cell search in LTE, reference signals



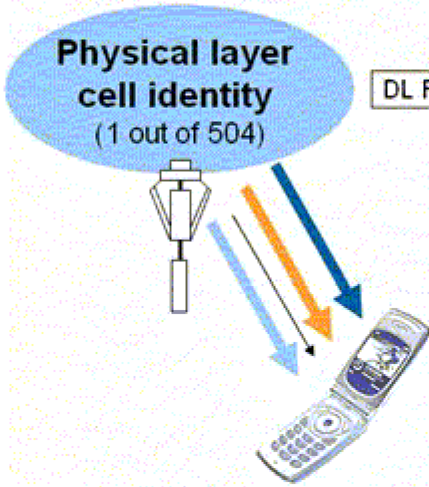



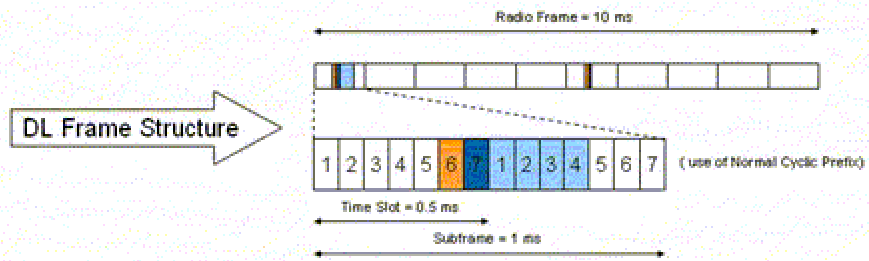

1. Primary synchronization signal (PSS)
   – 3 possible sequences to identify the cell's physical layer identity (0, 1, 2).
2. Secondary synchronization signal (SSS)
   – 168 different sequences to identity physical layer cell identity group.

⇨ Downlink reference signals.

- Cell-specific reference signals are used for…
  – … cell search and initial acquisition,
  – … downlink channel estimation for coherent demodulation/detection at the UE,
  – … downlink channel quality measurements.

# Cell search in LTE, essential system information

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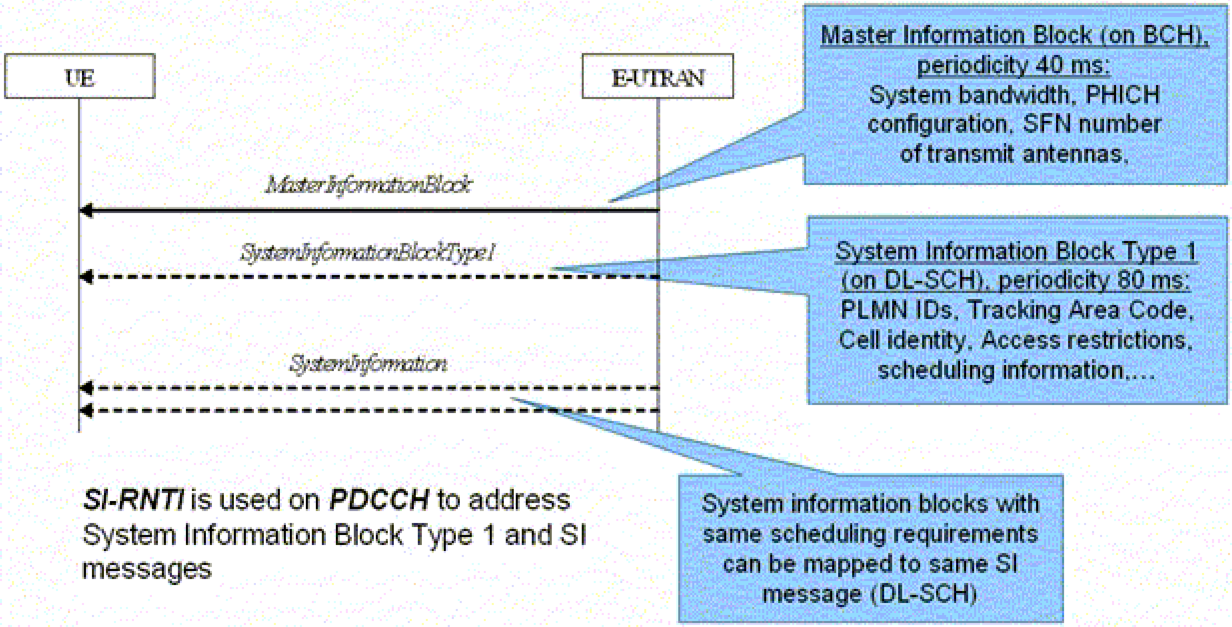
   - 168 different sequences to identity physical layer cell identity group.

⇨ Downlink reference signals.

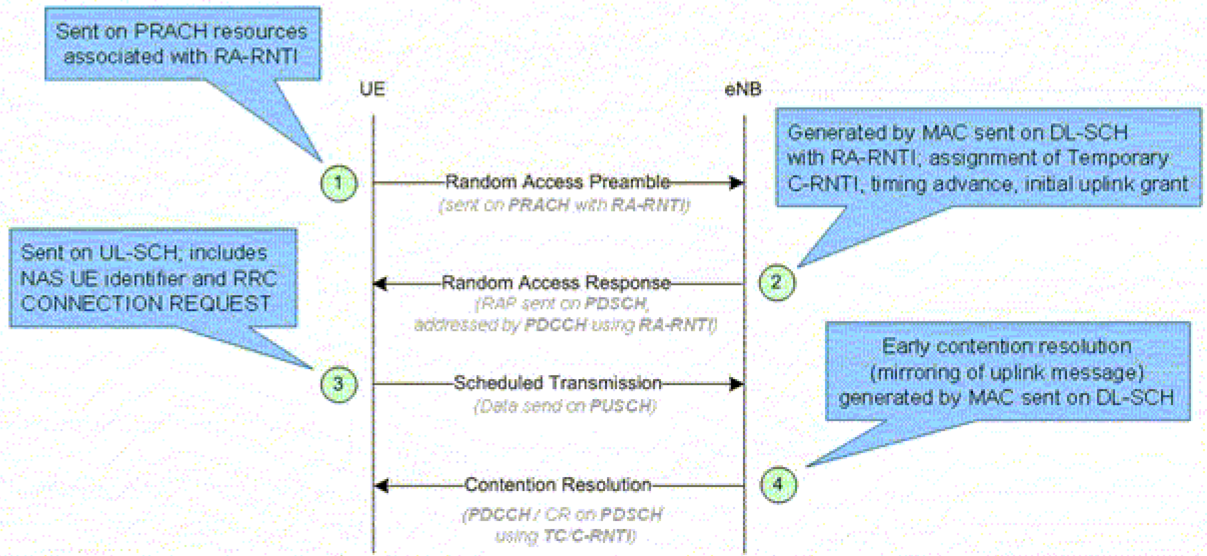
3. Physical Broadcast Channel (PBCH)
   - Carrying broadcast channel (BCH) with Master Information Block (MIB) System bandwidth [4 bit], PHICH configuration [Duration: 1 bit, Resource: 2 bit], System Frame Number [SFN, 8 bit] and indirect about the used Tx antennas.
   - QPSK modulated, cell-specific scrambling
   - Transmitted on 72 subcarriers around the carrier frequency.

# System information broadcast in LTE



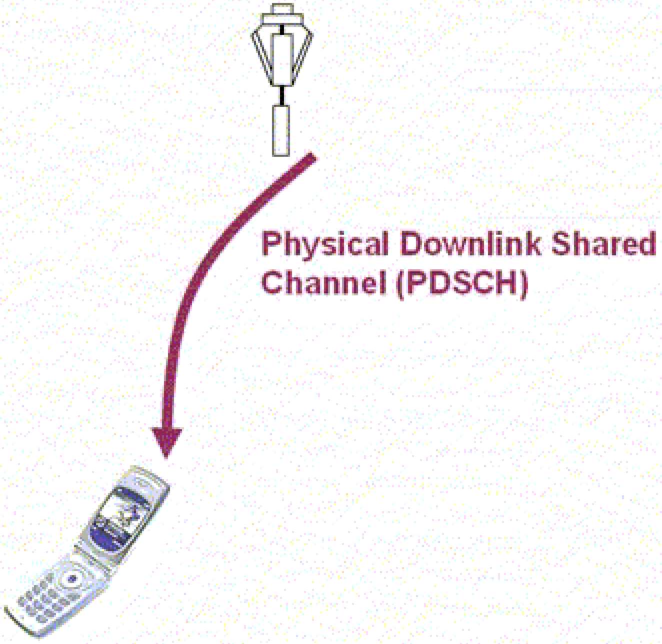

***SI-RNTI*** is used on ***PDCCH*** to address System Information Block Type 1 and SI messages

# Random Access Procedure

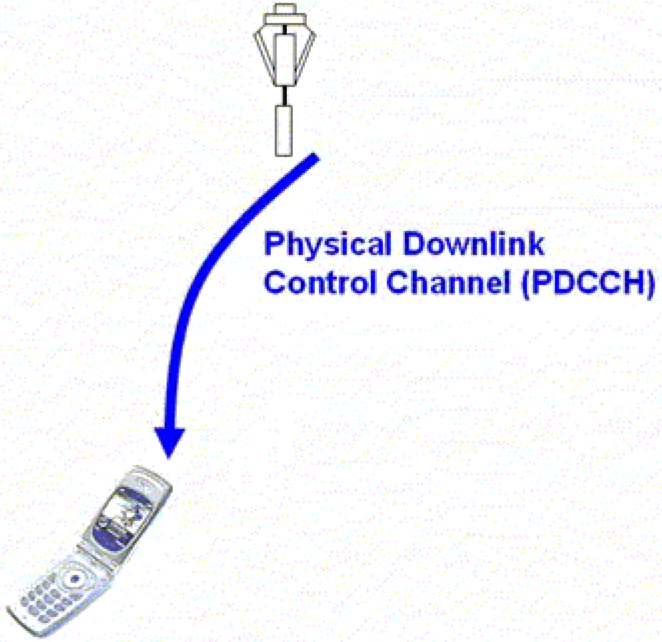



| | | | |
|---|---|---|---|
| PRACH | Physical Random Access Channel | C-RNTI | Cellular RNTI |
| RA-RNTI | Random Access Radio Network Temporary Identity | UL-SCH | Uplink Shared Channel |
| MAC | Medium Access Control (Layer) | CR | Contention Resolution |
| DL-SCH | Downlink Shared Channel | TC-RNTI | Temporary Cellular RNTI |

# How to derive information in LTE?

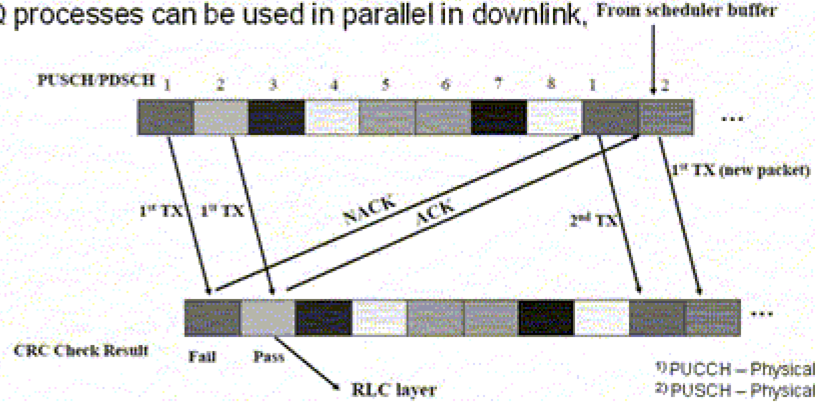


# Indicating PDCCH format



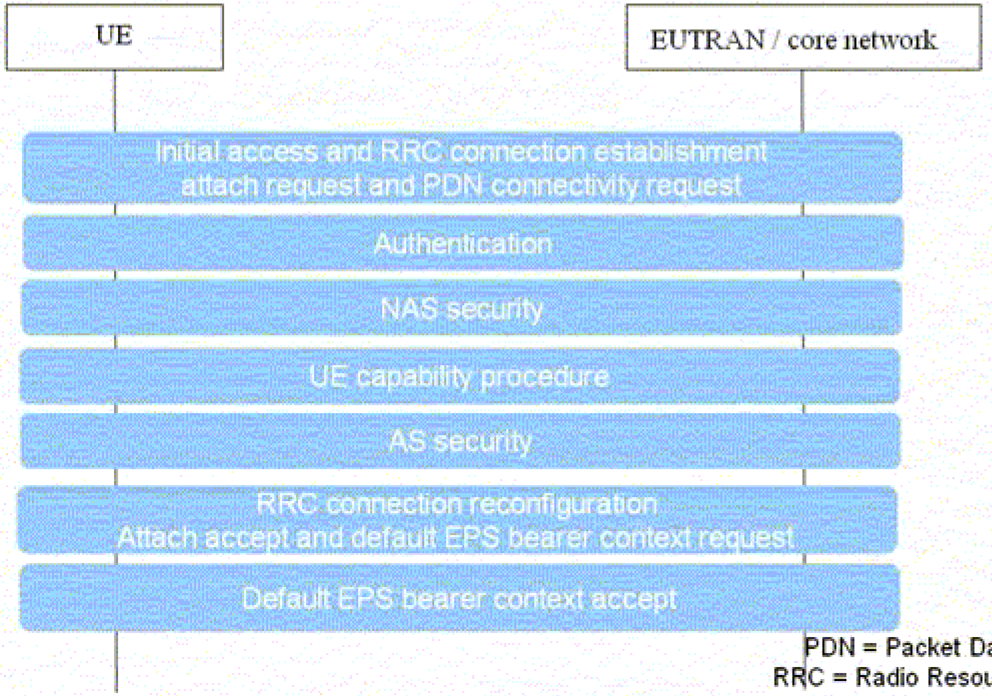
# Hybrid ARQ in the downlink

- ACK/NACK for data packets transmitted in the downlink is the same as for HSDPA, where the UE is able to request retransmission of incorrectly received data packets,
  - ACK/NACK is transmitted in UL, either on PUCCH[1] or multiplexed within PUSCH[2] (see description of those UL channels for details),
  - ACK/NACK transmission refers to the data packet received four sub-frames (= 4 ms) before,
  - 8 HARQ processes can be used in parallel in downlink,




[1] PUCCH – Physical Uplink Control Channel
[2] PUSCH – Physical Uplink Shared Channel

# Default EPS (Evolved Packet System) bearer setup



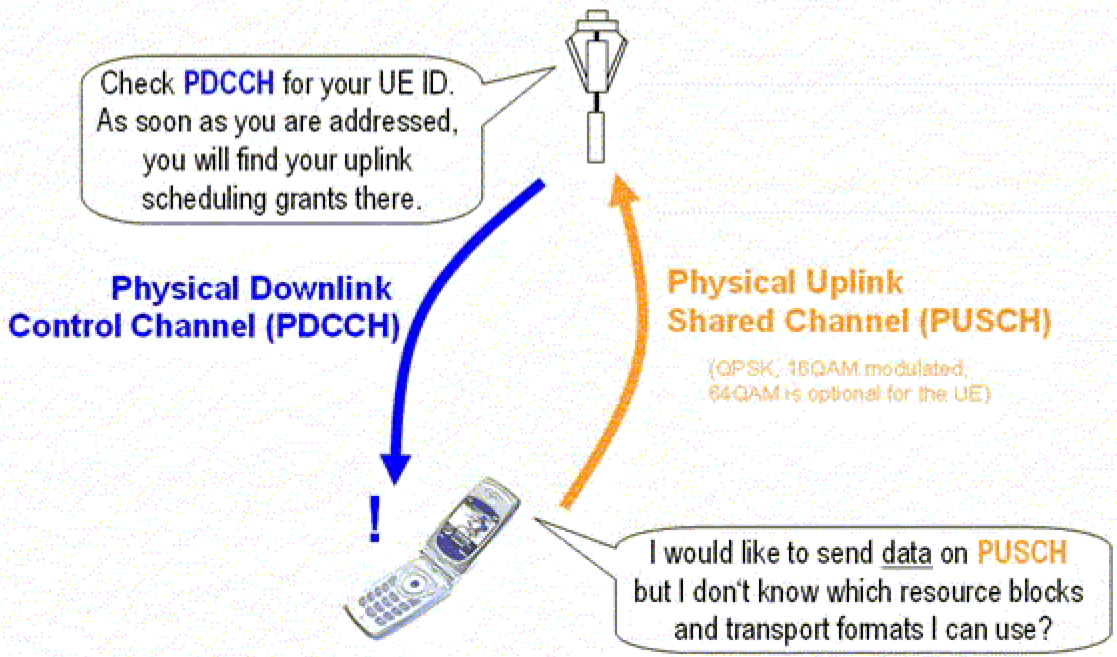

PDN = Packet Data Network
RRC = Radio Resource Control
NAS = Non-Access Stratum
AS = Access Stratum

# Uplink physical channels and signals

| LTE Uplink Physical Channels | |
|---|---|
| **Physical Uplink Shared Channel (PUSCH)** | Carries user data |
| **Physical Uplink Control Channel (PUCCH)** | Carries control information (UCI = Uplink Control Information) |
| **Physical Random Access Channel (PRACH)** | Preamble transmission for initial access |

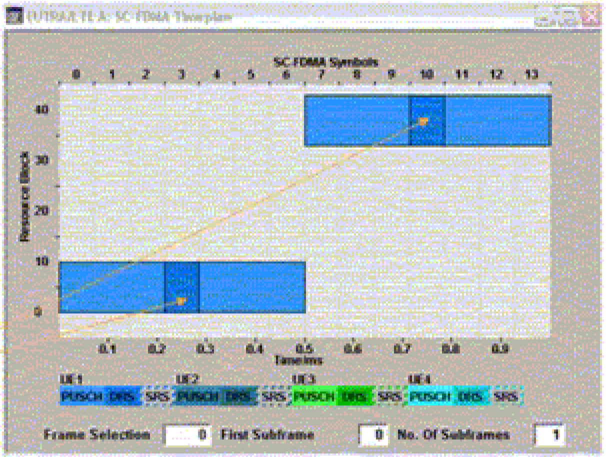
| LTE Uplink Physical Signals | |
|---|---|
| **Demodulation Reference Signal (DRS)** | Enables channel estimation and data demodulation |
| **Sounding Reference Signal (SRS)** | Enables uplink channel quality evaluation |

# Scheduling of uplink data



# Demodulation Reference Signal (DRS) in the UL

- **DRS are used for channel estimation in the eNodeB receiver in order to demodulate data (PUSCH) and control (PUCCH) channels,**
  - **PUSCH.** Located in the 4th SC-FDMA symbol in each slot (symbol #3, #10 for normal CP), spanning the same BW as allocated for user data,
  - **PUCCH.** Different symbols, depending on format (see one of the following slides),

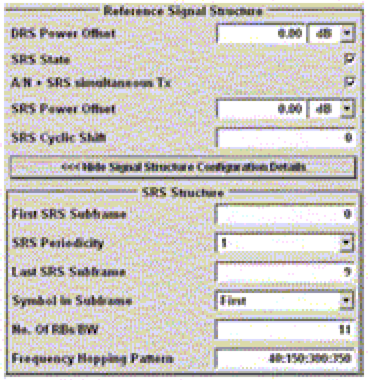


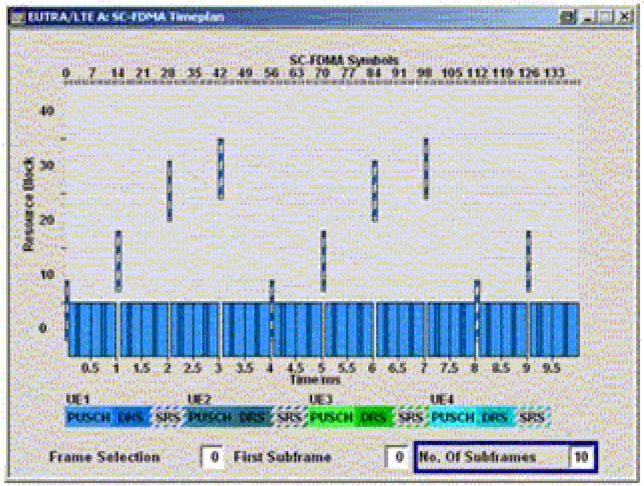

Demodulation Reference Signal (DRS)

Screenshot of R&S® SMU200A Vector Signal Generator

# Sounding Reference Signal (SRS) in the UL

- SRS are used to estimate uplink channel quality in other frequency areas as a basis for scheduling decisions,
  - Transmitted in areas, where no user data is transmitted, first or last symbol of subframe is used for transmission,
  - Configuration (e.g. BW, power offset, cyclic shift, duration, periodicity, hopping pattern) is signaled by higher layers,




Screenshot of R&S® SMU200A Vector Signal Generator

# PUSCH power control & timing relation

- Power level in dBm to be used for PUSCH transmission is derived using the following formula:

Maximum allowed UE power

Combination of cell-[1] and UE-specific[2] component configured by RRC

PUSCH transport format

$$P_{\mathrm{PUSCH}}(i) = \min\{P_{\mathrm{MAX}}, 10\log_{10}(M_{\mathrm{PUSCH}}(i)) + P_{\mathrm{O\_PUSCH}}(j) + \alpha \cdot PL + \Delta_{\mathrm{TF}}(TF(i)) + f(i)\}$$

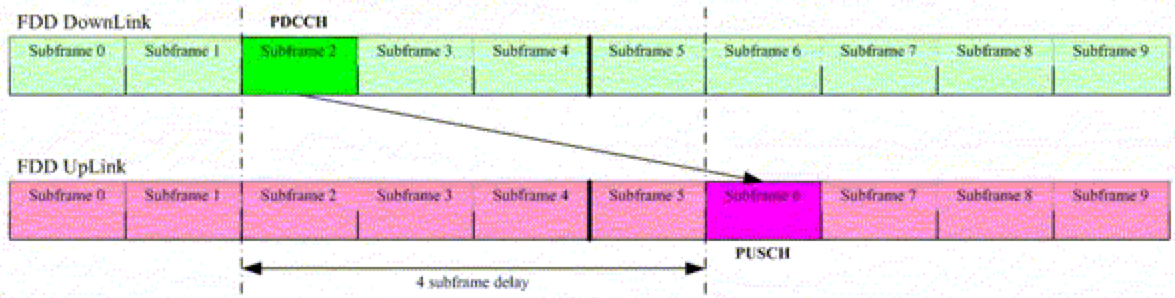
UE PUSCH transmit power in subframe i

Number of PUSCH resource blocks

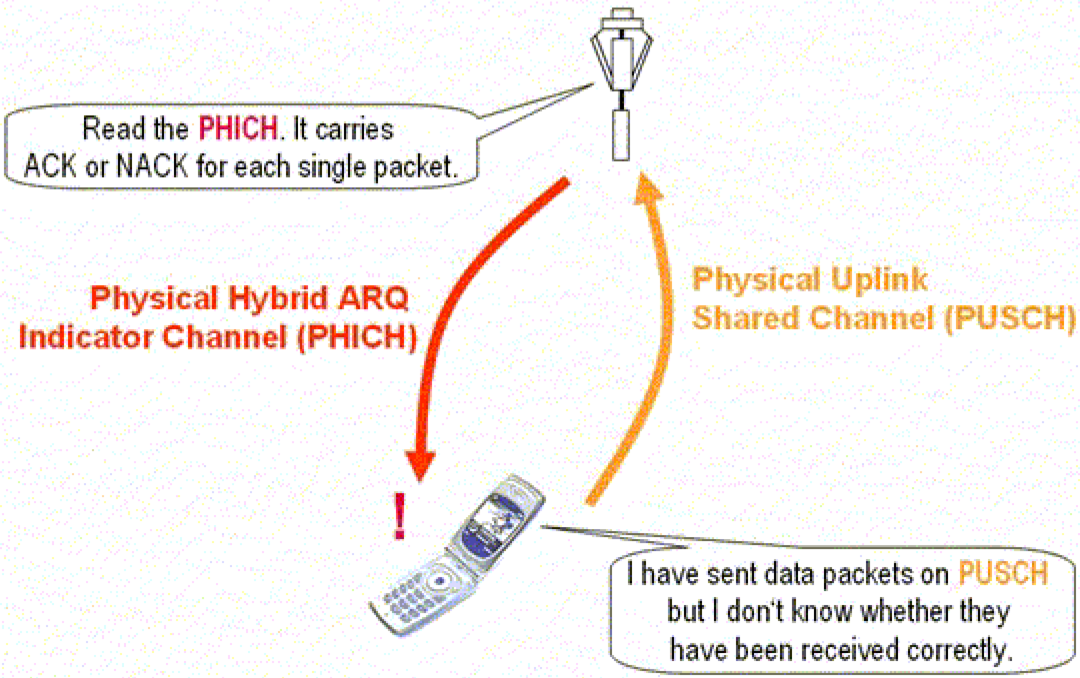
Cell-specific Parameter configured by RRC

Downlink path loss estimate

Power control adjustment derived from TPC command received via DCI format subframe (i-4)



# Acknowledging UL data packets on PHICH



# Physical Uplink Control Channel

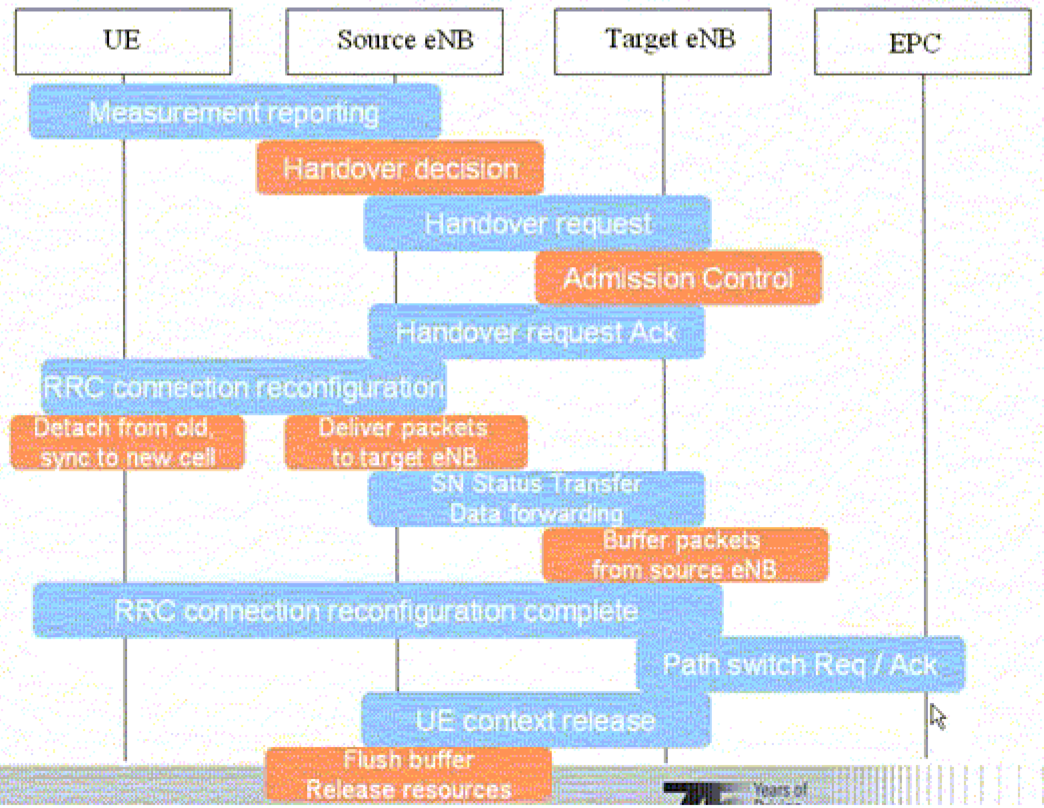
- PUCCH carries Uplink Control Information (UCI), when no PUSCH is available,
  - If PUSCH is available, means resources have been allocated to the UE for data transmission, UCI are multiplexed with user data,
- UCI are Scheduling Requests (SR), ACK/NACK information related to DL data packets, CQI, Pre-coding Matrix Information (PMI) and Rank Indication (RI) for MIMO,
- PUCCH is transmitted on reserved frequency regions, configured by higher layers, which are located at the edge of the available bandwidth
  - Minimizing effects of a possible frequency-selective fading affecting the radio channel,
  - Inter-slot hopping is used on PUCCH,
  - A RB can be configured to support a mix of PUCCH formats (2/2a/2b and 1/1a/1b) or exclusively 2/2a/2b,

| PUCCH format | Bits per subframe | Modulation | Contents |
|---|---|---|---|
| 1 | On/Off | N/A | Scheduling Request (SR) |
| 1a | 1 | BPSK | ACK/NACK, ACK/NACK+SR |
| 1b | 2 | QPSK | ACK/NACK, ACK/NACK+SR |
| 2 | 20 | QPSK | CQI/PMI or RI (any CP), (CQI/PMI or RI)+ACK/NACK (ext. CP only) |
| 2a | 21 | QPSK+BPSK | (CQI/PMI or RI)+ACK/NACK (normal CP only) |
| 2b | 22 | QPSK+BPSK | (CQI/PMI or RI)+ACK/NACK (normal CP only) |

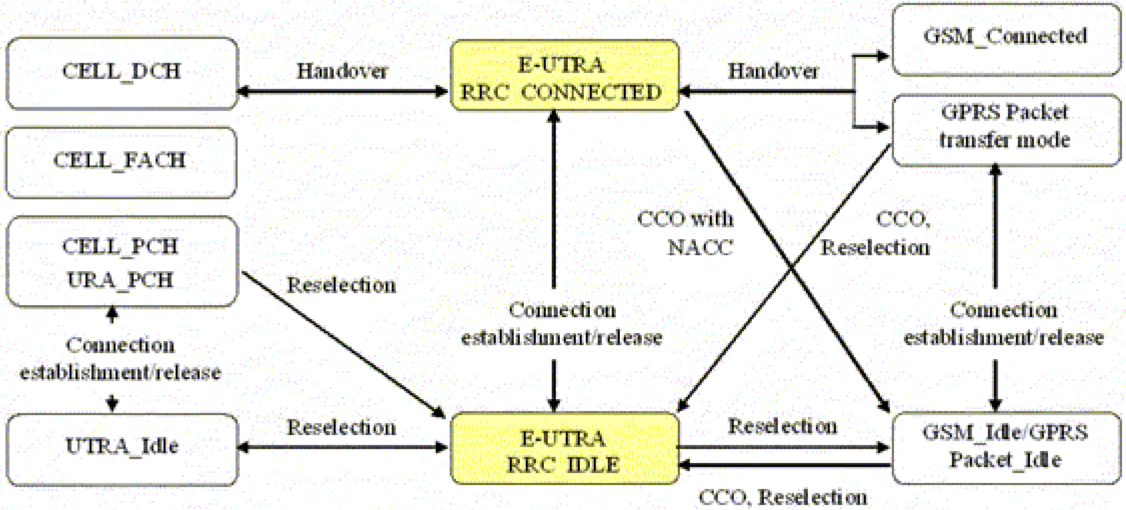
CQI/PMI/RI are only signaled via PUCCH when periodic reporting is requested, scheduled and aperiodic reporting is only done via PUSCH

# LTE mobility

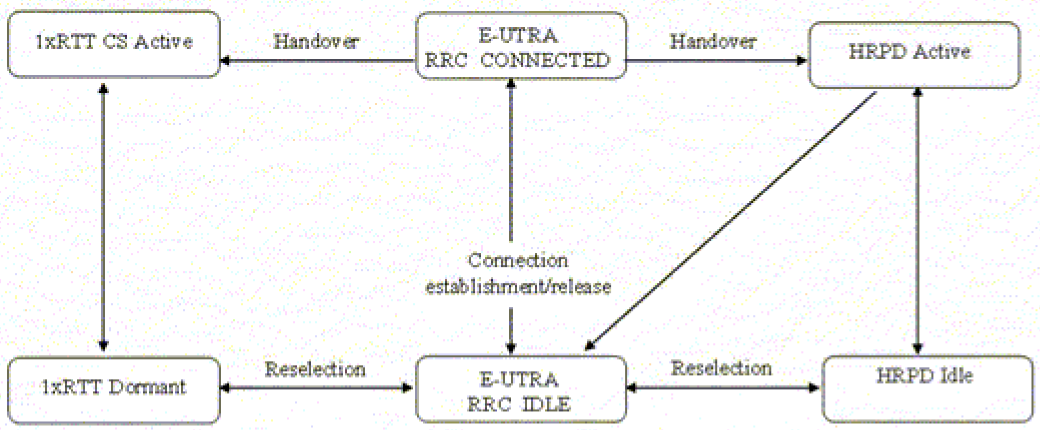
# Handover (Intra-MME/Serving Gateway)



# LTE Interworking with 2G/3G
# Two RRC states: CONNECTED & IDLE



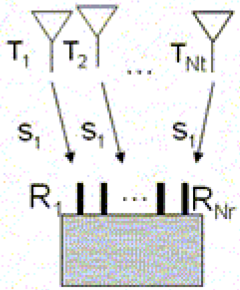
# LTE Interworking with CDMA2000 1xRTT and HRPD (High Rate Packet Data)



# MIMO

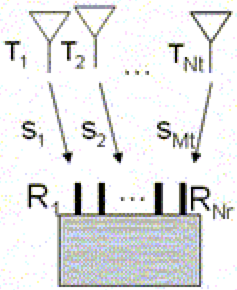
## Introduction to MIMO

# gains to exploit from multiple antenna usage




- **Transmit diversity (TxD)**
  - Combat fading
  - Replicas of the same signal sent on several Tx antennas
  - Get a higher SNR at the Rx
- **Spatial multiplexing (SM)**
  - Different data streams sent simultaneously on different antennas
  - Higher data rate
  - No diversity gain
  - Limitation due to path correlation
- **Beamforming**

# Introduction to MIMO
## gains to exploit from multiple antenna usage

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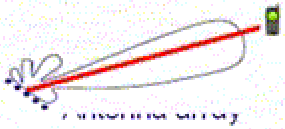

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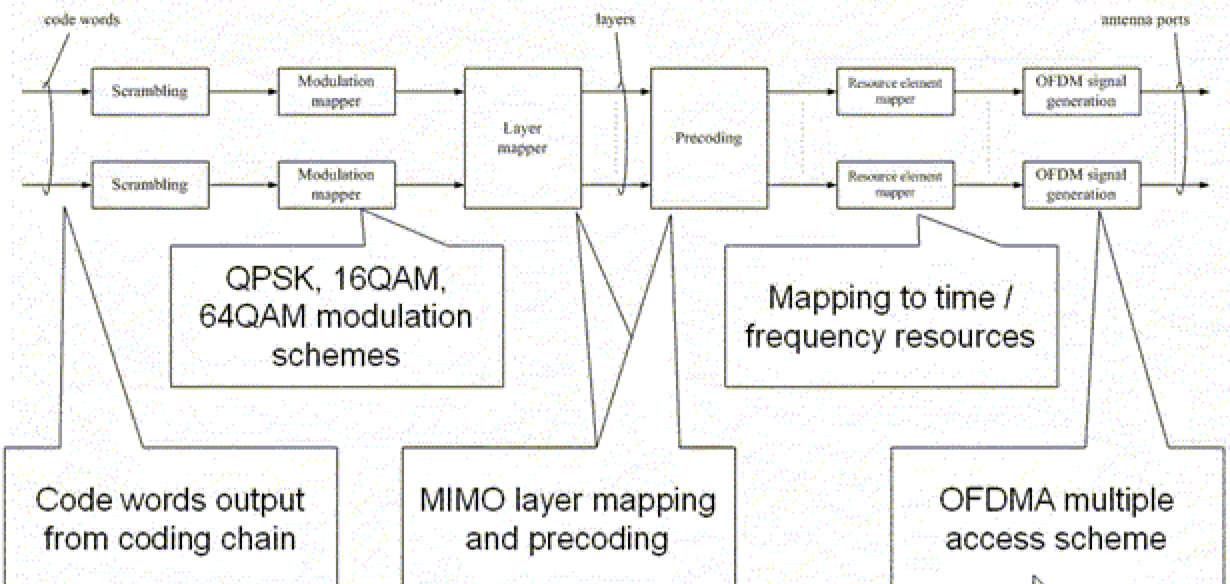
# LTE MIMO
## downlink modes

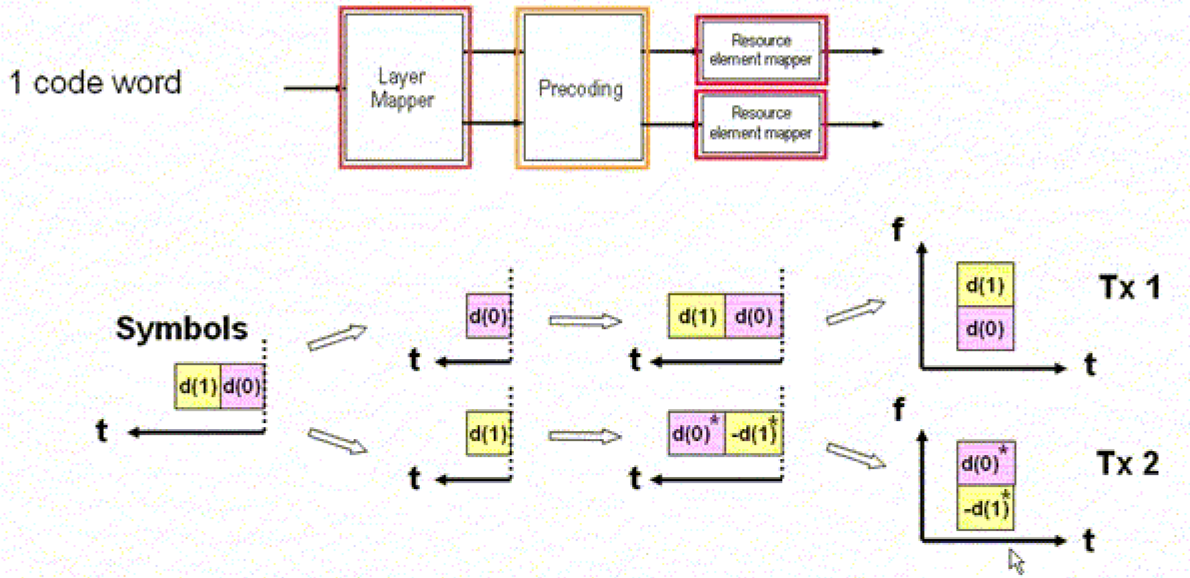
- **Transmit diversity:**
  - Space Frequency Block Coding (SFBC)
  - Increasing robustness of transmission
- **Spatial multiplexing:**
  - Transmission of different data streams simultaneously over multiple spatial layers
  - Codebook based precoding
  - Open loop mode for high mobile speeds possible
- **Cyclic delay diversity (CDD):**
  - Addition of antenna specific cyclic shifts
  - Results in additional multipath / increased frequency diversity
- **Beamforming**

# LTE downlink transmitter chain



# Downlink transmit diversity

## Space-Frequency Block Coding (2 Tx antenna case)

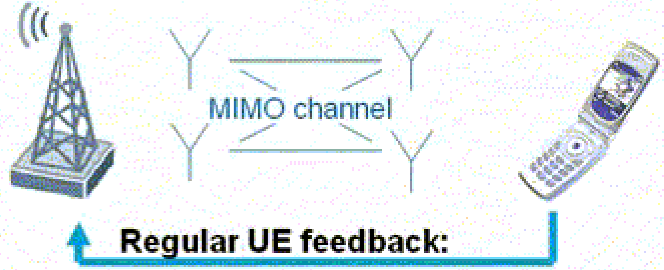


# Downlink spatial multiplexing
## codebook based precoding

- **The signal is "pre-coded" (i.e. multiplied with a precoding matrix) at eNodeB side before transmission**

Codebook of precoding matrices for 2x2 MIMO:

| Codebook index | Number of layers υ | |
|---|---|---|
| | 1 | 2 |
| 0 | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$ | $\frac{1}{\sqrt{2}}\begin{bmatrix}1&0\\0&1\end{bmatrix}$ |
| 1 | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1&1\\1&-1\end{bmatrix}$ |
| 2 | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1&1\\j&-j\end{bmatrix}$ |
| 3 | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$ | - |




**Regular UE feedback:**

PMI = Precoding Matrix Indicator

RI = Rank Indication

CQI = Channel Quality Indication

- **Optimum precoding matrix is selected from predefined "codebook" known at eNode B and UE side**
- **Selection is based on UE feedback**

# LTE MIMO
## uplink schemes

- Uplink transmit antenna selection:
  - 1 RF chain, 2 TX antennas at UE side
  - Closed loop selection of transmit antenna
  - eNodeB signals antenna selection to UE
  - Optional for UE to support

- Multi-user MIMO / collaborative MIMO:
  - Simultaneous transmission from 2 UEs on same time/frequency resource
  - Each UE with single transmit antenna
  - eNodeB selects UEs with close-to orthogonal radio channels