High Speed Downlink Packet Access

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KTL FEI STU
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Data traffic characteristics

- Asymmetrical
- Bursty
- > 384 kbps needed
- Low latency
How to...

Reduce latency
- fast scheduling
- adaptive scheduling
- HARQ
- avoid protocol translation
- reduce signaling
- simple core architecture
- increase L1/L2 granularity

1) L2/L3 issues
2) small effect on L1
3) can be changed in already existing system

Increase throughput
- more bandwidth
- higher order modulation
- less FEC
- more power
- more MIMO

1) mostly L1 properties
2) set by the system design/regulation
3) harder to change in already existing system
What has bigger impact?

Sensitivity analysis - latency
cnn.com

Throughput increase

Latency decrease

16% 39% 72% 226% 329% 609% 4000%

10% 20% 30% 40% 50% 60% 70%
What about UMTS R99?

- Design changes
  - Channel
    - transport
    - physical
  - Scheduler
  - Frame format
  - Modulation
  - HARQ
  - Functionality move towards the Node B
  - Power control
Power control – R99

- Circuit switched services are guaranteed
- Packet switched services are best effort
Power control - revised

- No guarantee
- Best effort
- Maximize cell capacity
- Utilize all available power

Evaluate radio conditions
Accept throughput

Unused cell power

HSDPA
R99
Common Channels

Power

Time
HSDPA – 3GPP Rel.5

- 2 ms frame format
- 2 ms scheduler ATDMA/CDMA
  - CQI
- 16 QAM or QPSK
- HARQ (Chase, Incremental Redundancy)
  - on L1 (not RLC)
- Fixed SF = 16
- Turbo code only
- Fixed CRC (24 bit)
- No soft handover
Higher Order Modulation

- **16QAM**
  - Twice the data rate compared to QPSK (used in R99)
- **Making optimal use of good channel conditions (high C/I)**
  - Close to cell site
  - Low speed
  - Little or no dispersion
Short TTI
Transmission Time Interval

- Reduced air-interface delay
  - Improved end-user performance
- HSDPA features operate at 500 times per second
  - Fast Link Adaptation
  - Fast hybrid Automatic Repeat Request (ARQ) with soft combining
  - Fast Channel-dependent Scheduling

*Earlier releases*

- 2 ms
- 10 ms
- 20 ms
- 40 ms
- 80 ms
Code multiplexing
Fast Channel-dependent Scheduling

- Scheduling = which UE to transmit to at a given moment
- Basic idea: transmit at fading peaks
  - May lead to large variations in data rate between users
  - Tradeoff: fairness vs. cell throughput

![Graph showing data rate variation over time for two users.](Image)
Scheduling

• UEs send reports

• CQI = Channel Quality Indicator (0-30)

• Not explicit quality indicator, but the date rate supported by the UE
HSDPA Transport Channels

- one **High-Speed Downlink Shared Channel** (HS-DSCH), used for downlink data transmission, mapped to up to 15 HS-PDSCH, and is dynamically allocated every 2 msec
- up to **four High-Speed Shared Control Channels** (HS-SCCH), used for downlink control signaling, (e.g. - UE ID, HARQ, TFRC)
- one **Associated Dedicated Channel** (A-DCH) pair (UL & DL) per HSDPA user in connected state used for controlled signaling and uplink data transmission
**HS-PDSCH**

Data
\[ N_{data1} \text{ bits} \]

\[ T_{slot} = 2560 \text{ chips}, M \times 10 \times 2^k \text{ bits} \quad (k=4) \]

<table>
<thead>
<tr>
<th>Slot format ( i )</th>
<th>Channel Bit Rate (kbps)</th>
<th>Channel Symbol Rate (ksps)</th>
<th>SF</th>
<th>Bits/ HS-DSCCH subframe</th>
<th>Bits/ Slot</th>
<th>Ndata</th>
</tr>
</thead>
<tbody>
<tr>
<td>0(QPSK)</td>
<td>480</td>
<td>240</td>
<td>16</td>
<td>960</td>
<td>320</td>
<td>320</td>
</tr>
<tr>
<td>1(16QAM)</td>
<td>960</td>
<td>240</td>
<td>16</td>
<td>1920</td>
<td>640</td>
<td>640</td>
</tr>
</tbody>
</table>
Hybrid ARQ

(a) Chase combining

(b) Incremental redundancy
Hybrid ARQ

- **Send & Wait strategy**
  - Long delays

- Up to 12 parallel processes

- Buffer memory in the UE is important
ARQ Loops

End-to-end TCP ARQ loop

RLC ARQ loop

PHY HARQ loop

UE

Uu

Node B

Iub/ Iur

RNC
## UE classes

<table>
<thead>
<tr>
<th>HS-DSCH category</th>
<th>Maximum number of HS-DSCH codes received</th>
<th>Maximum L1 data rate (Mbps)</th>
<th>Maximum RLC data rate (Mbps)</th>
<th>QPSK / 16 QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 1</td>
<td>5</td>
<td>1.2</td>
<td>1.12</td>
<td>Both</td>
</tr>
<tr>
<td>Category 2</td>
<td>5</td>
<td>1.2</td>
<td>1.12</td>
<td>Both</td>
</tr>
<tr>
<td>Category 3</td>
<td>5</td>
<td>1.8</td>
<td>1.68</td>
<td>Both</td>
</tr>
<tr>
<td>Category 4</td>
<td>5</td>
<td>1.8</td>
<td>1.68</td>
<td>Both</td>
</tr>
<tr>
<td>Category 5</td>
<td>5</td>
<td>3.6</td>
<td>3.36</td>
<td>Both</td>
</tr>
<tr>
<td>Category 6</td>
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<td>3.36</td>
<td>Both</td>
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<tr>
<td>Category 7</td>
<td>10</td>
<td>7.3</td>
<td>6.72</td>
<td>Both</td>
</tr>
<tr>
<td>Category 8</td>
<td>10</td>
<td>7.3</td>
<td>6.72</td>
<td>Both</td>
</tr>
<tr>
<td>Category 9</td>
<td>15</td>
<td>10.2</td>
<td>9.6</td>
<td>Both</td>
</tr>
<tr>
<td>Category 10</td>
<td>15</td>
<td>14.0</td>
<td>13.44</td>
<td>Both</td>
</tr>
<tr>
<td>Category 11</td>
<td>5</td>
<td>0.9</td>
<td>0.8</td>
<td>QPSK only</td>
</tr>
<tr>
<td>Category 12</td>
<td>5</td>
<td>1.8</td>
<td>1.6</td>
<td>QPSK only</td>
</tr>
</tbody>
</table>
3G – voice or data?

Data is surpassing voice on 3G since 2 years
HSPA+

- 64QAM (21 Mbps) alebo 2x2MIMO (28 Mbps)
- 64QAM a Dual-Cell (42 Mbps / 10 MHz)
- 64QAM a MIMO (42 Mbps / 5 MHz)
- MIMO a Dual-Cell (56 Mbps / 10 MHz)
- 64QAM a MIMO a Dual-Cell (84 Mbps / 10 MHz)
- 64QAM a MIMO a Q-Cell (168 Mbps / 10 MHz)
- 64QAM a 4x4MIMO a Q-Cell (336 Mbps / 10 MHz)
<table>
<thead>
<tr>
<th>Category</th>
<th>Max. number of HS-DSCH codes</th>
<th>Modulation</th>
<th>MIMO - Dual Carrier code rate required to achieve max. data rate</th>
<th>Max. data rate [Mbit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>QPSK and 16-QAM</td>
<td>.76</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>QPSK and 16-QAM</td>
<td>.76</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>QPSK and 16-QAM</td>
<td>.76</td>
<td>1.8</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>QPSK and 16-QAM</td>
<td>.76</td>
<td>1.8</td>
</tr>
<tr>
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<td>5</td>
<td>QPSK and 16-QAM</td>
<td>.76</td>
<td>3.6</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>QPSK and 16-QAM</td>
<td>.76</td>
<td>3.6</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>QPSK and 16-QAM</td>
<td>.75</td>
<td>7.2</td>
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<td>8</td>
<td>10</td>
<td>QPSK and 16-QAM</td>
<td>.76</td>
<td>7.2</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>QPSK and 16-QAM</td>
<td>.70</td>
<td>10.1</td>
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<tr>
<td>10</td>
<td>15</td>
<td>QPSK and 16-QAM</td>
<td>.97</td>
<td>14.4</td>
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<tr>
<td>11</td>
<td>5</td>
<td>QPSK only</td>
<td>.76</td>
<td>0.9</td>
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<td>12</td>
<td>5</td>
<td>QPSK only</td>
<td>.76</td>
<td>1.8</td>
</tr>
<tr>
<td>13</td>
<td>15</td>
<td>QPSK, 16-QAM and 64-QAM</td>
<td>.82</td>
<td>17.6</td>
</tr>
<tr>
<td>14</td>
<td>15</td>
<td>QPSK, 16-QAM and 64-QAM</td>
<td>.98</td>
<td>21.1</td>
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<tr>
<td>15</td>
<td>15</td>
<td>QPSK, 16-QAM</td>
<td>MIMO</td>
<td>23.4</td>
</tr>
<tr>
<td>16</td>
<td>15</td>
<td>QPSK, 16-QAM</td>
<td>MIMO</td>
<td>27.9</td>
</tr>
<tr>
<td>19</td>
<td>15</td>
<td>QPSK, 16-QAM</td>
<td>MIMO</td>
<td>35.3</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
<td>QPSK, 16-QAM, 64-QAM</td>
<td>MIMO</td>
<td>42.2</td>
</tr>
<tr>
<td>21</td>
<td>15</td>
<td>QPSK, 16-QAM</td>
<td>DC</td>
<td>23.4</td>
</tr>
<tr>
<td>22</td>
<td>15</td>
<td>QPSK, 16-QAM</td>
<td>DC</td>
<td>27.9</td>
</tr>
<tr>
<td>23</td>
<td>15</td>
<td>QPSK, 16-QAM, 64-QAM</td>
<td>DC</td>
<td>35.3</td>
</tr>
<tr>
<td>24</td>
<td>15</td>
<td>QPSK, 16-QAM, 64-QAM</td>
<td>DC</td>
<td>42.2</td>
</tr>
<tr>
<td>25</td>
<td>15</td>
<td>QPSK, 16-QAM</td>
<td>DC + MIMO</td>
<td>46.8</td>
</tr>
<tr>
<td>26</td>
<td>15</td>
<td>QPSK, 16-QAM</td>
<td>DC + MIMO</td>
<td>55.9</td>
</tr>
<tr>
<td>27</td>
<td>15</td>
<td>QPSK, 16-QAM, 64-QAM</td>
<td>DC + MIMO</td>
<td>70.6</td>
</tr>
<tr>
<td>28</td>
<td>15</td>
<td>QPSK, 16-QAM, 64-QAM</td>
<td>DC + MIMO</td>
<td>84.4</td>
</tr>
</tbody>
</table>
Enhanced Uplink
Resource usage

- Inter cell Interference
- R99 Intra cell Interference
- Inter cell Interference
Design principles

- Multi code transmission
- HARQ
- TTI 2/10 ms
- Scheduling
EUL – Physical Layer

- QPSK is used both in DL & UL, but:
  - in DL, QPSK for each data channel
  - in UL, every data channel is BPSK modulated
    - UL uses 2 separate OVSF code trees!
    - so EUL can use for example 2x SF2 & 2x SF4

\[ \text{I branch} \]

\[ \text{Q branch} \]

occupied by E-DPDCHs

left for control channels
EUL channels
Enhanced Uplink Channels

- **E-DCH Dedicated Physical Data Channel (E-DPDCH)**
  - is the data transport channel. The power of the E-DPDCH is set dynamically as an offset to the DPCCH, a so called gain or beta factor, signaled with the grant messages delivered by the scheduler.

- **E-DCH Dedicated Physical Control Channel (E-DPCCH)**
  - is used to transmit to the scheduler information about the channel conditions as seen from the UE.

- **E-DCH Absolute Grant Channel E-AGCH**
  - a shared downlink channel that carries absolute grants. The absolute grant is sent by the scheduler to the UE giving it the information it needs to select a rate and the transmission power.

- **E-DCH Relative Grant Channel E-RGCH**
  - is the channel carrying relative grants. Relative grants are transmitted from non-serving cells only, at the rate of one relative grant per 10 ms from each cell in the active set.

- **E-DCH HARQ Acknowledgement Indicator Channel E-HICH**
  - a dedicated channel, carrying the binary hybrid ARQ (HARQ) acknowledgements. One E-HICH is set up to each EUL user from each cell in its active set.
Scheduling

• Node B decides at which power UE can transmit

• **Absolute Grant** – from serving cell

• **Relative Grant** – both from serving/non-serving cell(s)
  
  – Serving cell (UP, DOWN, HOLD) – dedicated to 1 UE

  – Non-serving cell(s) (DTX, DOWN) – to all UEs
    (overload indicator)
Scheduling

- Scheduling request (UL)
  - Used by the UE to request more resources
- Absolute grant (DL)
  - Used for large absolute changes of the data rate
- Relative grant (DL)
  - UP/HOLD/DOWN
EUL UE classes

<table>
<thead>
<tr>
<th>Category</th>
<th>Max codes</th>
<th>Min spreading factor</th>
<th>Support for 2 ms TTI</th>
<th>Max L1 data rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1 x SF4</td>
<td>No</td>
<td>0.74 Mbps</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2 x SF4</td>
<td>Yes</td>
<td>1.46 Mbps</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2 x SF4</td>
<td>No</td>
<td>1.46 Mbps</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2 x SF2</td>
<td>Yes</td>
<td>2.92 Mbps</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2 x SF2</td>
<td>No</td>
<td>2.00 Mbps</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>2 x SF4 + 2 x SF2</td>
<td>Yes</td>
<td>5.76 Mbps</td>
</tr>
</tbody>
</table>

cat7 – 16QAM = 11,5 Mbps
New Radio interface protocol entities

- **UE**
  - MAC -es/
  - PHY
- **Node B**
  - MAC -e
  - E-DCH
- **lub**
  - PHY
  - TNL
- **DRNC**
  - TNL
- **lur**
  - TNL
- **SRNC**
  - DTCH
  - DCCH
HSDPA / EUL peak rates

**Downlink**
- 3.6 Mbps
- 14 Mbps
- 21 Mbps
- 28 Mbps
- 42 Mbps
- 84-336 Mbps

- 15 codes
- 64QAM
- 2x2 MIMO
- Multi-carrier
- 4x4 MIMO
- Higher Modulation Combinations

**Uplink**
- 20-40 Mbps
- 12 Mbps
- 5.8 Mbps
- 2 Mbps
- 0.384 Mbps

- Multi-carrier
- 16QAM
- 2 ms TTI
Multi-antenna systems
MIMO principle

- **Array gain**: Increased coverage.
- **Diversity gain**: Improved quality.
- **Spatial multiplexing**: Increased spectral efficiency.
- **Additional transmission pipe**: Increased data rates.
MIMO principle

MIMO works well, when:

1) conditions are bad:
   - no LOS signal component (or polarization separation)
   - lot of scatteres

2) antennas have sufficient spacing
   - uncorrelated antennas
   - independent CIRs
Capacity

\[ C_{SISO}^D = \log_2(1 + \rho h^2) \text{ bps/Hz} \]

\[ C_{MISO}^D = \log_2(1 + \frac{\rho}{M} \sum_{i=1}^{M} h_i^2) \text{ bps/Hz} \]

\[ C_{SIMO}^D = \log_2(1 + \rho \sum_{i=1}^{N} h_i^2) \text{ bps/Hz} \]

\[ C_{MIMO}^D = \sum_{i=1}^{r} \log_2(1 + \frac{\rho}{M} \lambda_i) \text{ bps/Hz} \]

- \( \rho = \text{SNR} \)
- \( h = \text{channel impulse response} \)
- \( H = \text{channel impulse response MxN (input, output antennas) matrix} \)
- \( r = \text{matrix rank} \)
Rx diversity (SIMO)

\[ \hat{s} = \begin{bmatrix} w_1^* & \ldots & w_{NR}^* \end{bmatrix} \begin{bmatrix} r_1^T \end{bmatrix} = \bar{w}^T \bar{r} \]

\[ \bar{r} = \bar{h} \cdot \bar{s} + \bar{n} \]
Tx diversity (MISO)
Tx Diversity (open loop), Rel. 6 (MISO)

- 2 Tx antennas
- improved quality & coverage
- support is mandatory for all Rel.6 compliant UEs

Node B → UE

…for QPSK
Closed loop Tx diversity

DPCCH

DPDCH

DPCH

Spread/scramble

CPICH\textsubscript{1}

\[ \sum \]

\[ \sum \]

\[ \sum \]

CPICH\textsubscript{2}

Ant\textsubscript{1}

Ant\textsubscript{2}

Weight Generation

Determine FBI message from Uplink DPCCH

UE

3G EMS
\[
\begin{bmatrix}
\hat{s}_1 \\
\hat{s}_2
\end{bmatrix} = H^{-1} \cdot \bar{r} = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + H^{-1} \cdot \bar{n}
\]

\[
\bar{r} = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{bmatrix} \cdot \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}
\]
max MIMO capacity

\[
\frac{C}{W} = \min\{N_T, N_R\} \cdot \log_2 (1 + \frac{N_R}{\min\{N_T, N_R\}} \cdot \frac{S}{N})
\]

\[
C_{MIMO}^D = \sum_{i=1}^{r} \log_2 (1 + \frac{\rho}{M} \lambda_i) \text{ bps/Hz}
\]
MIMO & HOM relation

- MIMO can be considered as a form of HOM
- 2 streams of 4QAM = 1 stream of 16QAM
So many antennas...
So many antennas...
So many antennas...
MIMO introduction into 3GPP

- **3GPP Rel. 5**
  - HSDPA
  - EUL
  - TxD

- **3GPP Rel. 6**
  - MIMO for HSDPA
  - MIMO for R99

- **3GPP Rel. 7 & 8**
  - LTE

**UL**
- SC-FDMA
- OFDMA
- MC-WCDMA

**DL**
- OFDMA
- MC-WCDMA

- MIMO mandatory

**FDD only**
HSDPA MIMO

• Where it’s hot:
  – higher isolation between cells and/or non-uniform load distribution: **URBAN MICRO**
  – **PICO & INDOOR**

• Where it’s not:
  – uniform load distribution, frequency reuse of one, high load and little isolation between cells: **URBAN MACRO**
HSDPA + MIMO

- 3GPP Release 7 – still open (LTE is also part of Rel. 7)
- 11 proposals
- MIMO up to 4x4
- achievable data rate < 45 Mbps *
  (channel capacity < 80 Mbps *)
HSDPA + MIMO

1. Per-antenna rate control
2. Rate-Control Multi-Paths diversity
3. Double Space Time Transmit Diversity with Sub-Group Rate Control
4. Single Stream Closed loop MIMO with 4 Tx and L Rx antennas
5. Per-User Unitary Rate Control
6. TPRC for CD-SIC MIMO
7. Selective Per Antenna Rate Control
8. Double Transmit antenna array (D-TxAA)
9. Spatial Temporal Turbo Channel Coding
10. Double Adaptive Space Time Transmit Diversity with Sub-Group Rate Control
11. Single & Multiple Code Word MIMO with Virtual Antenna mapping
Selective per-antenna rate control (S-PARC)

separately encoded data streams are transmitted from each antenna with equal power but with different data rates

adaptively selects the number of antennas
And the winner is…

Double Transmit antenna array (D-TxAA)
LG Electronics