TIES435
Radio Networks and Self-Organization

WCDMA physical layer and link performance

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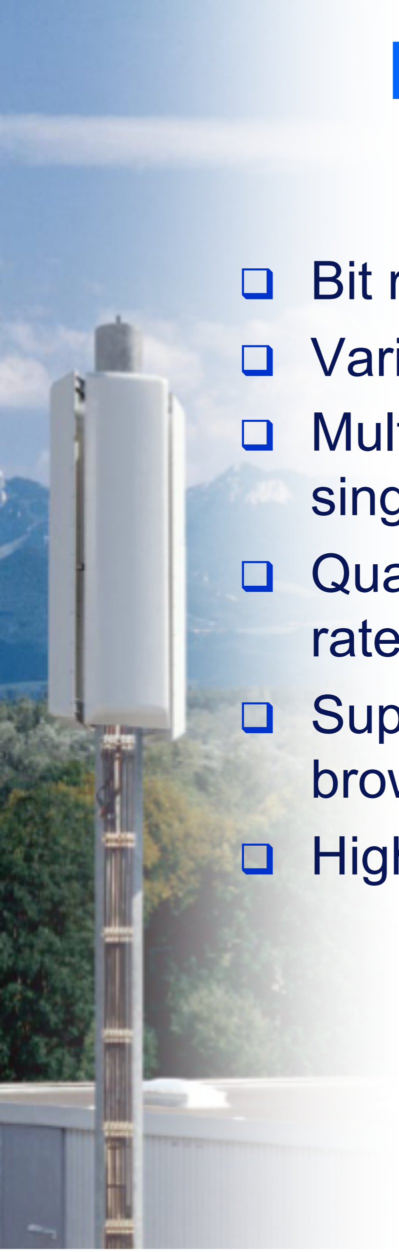
What is physical layer ?

- Physical layer defines how the data (control data and the user data = user traffic) has been structured for the transmission over the air interface
- In mobile cellular systems the effect of the physical layer is high because of the characteristics of the radio channel (=air interface)
- Defines the maximum capacity limits of the system (maximum allowed bit-rate, maximum number of simultaneous users)
- This is why the physical layer of the radio interface has been typically the main discussion topic when different cellular systems have been compared against each other.
- For the overall system performance the protocols in the other layers, such as handover and other RRM protocols, also have a great deal of impact.

Requirements for the physical layer



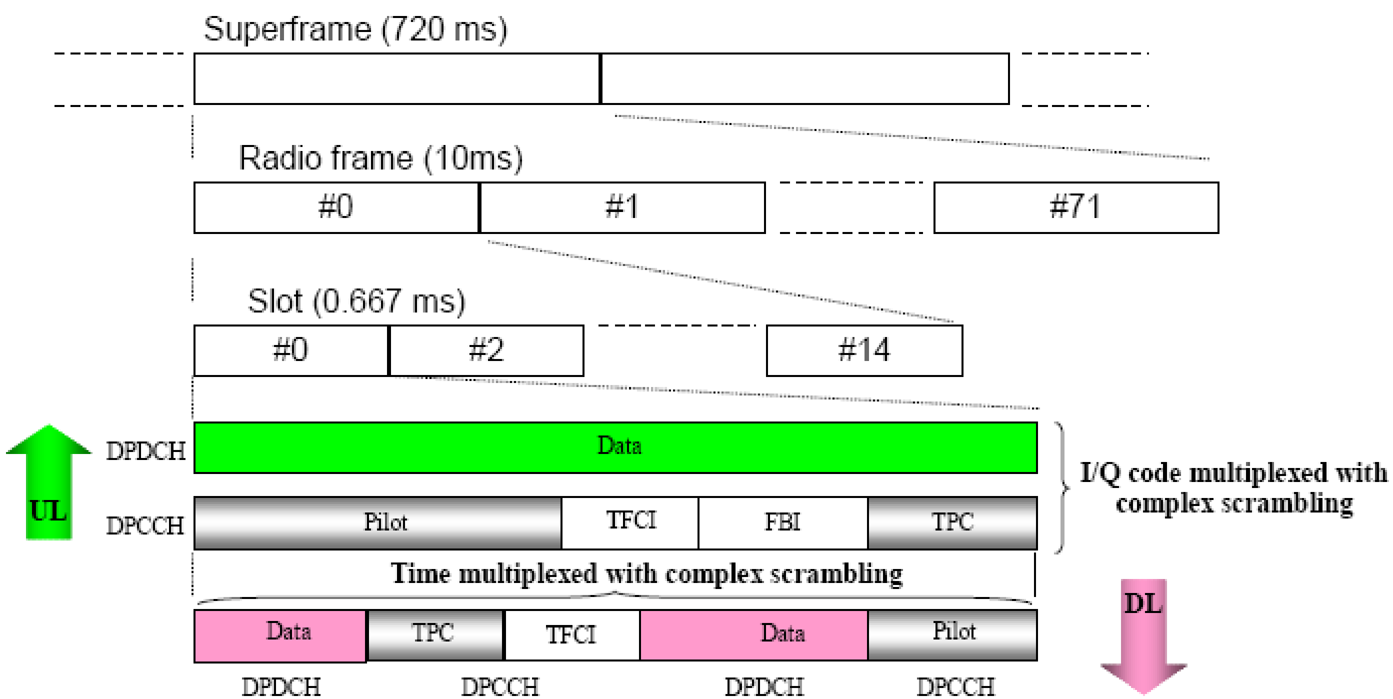
- Bit rates initially up to 2 Mbps
- Variable bit rate to offer bandwidth on demand
- Multiplexing of services with different quality requirements on a single connection, e.g. speech, video and packet data
- Quality requirements from 10 % frame error rate to 10^{-6} bit error rate
- Support of asymmetric uplink and downlink traffic, e.g. web browsing causes more loading to downlink than to uplink
- High spectrum efficiency

Main functions of the physical layer

- Error detection
- Channel coding, interleaving, rate matching
- Modulation, demodulation
- Spreading, despreading
- Combination of physical channels
- Closed loop power control
- Radio frequency processing (RF)
- Synchronization (chip, bit, slot, frame)
- Measurements
  - Bit-error ratio (BER), Signal-to-Interference ratio (SIR), Transmission power (TxP),
- Macrodiversity (soft(er)-handover)

Physical channels

- One radio frame (10 ms) includes 15 time slots (one slot equals to power control period, 1/(10ms/15)=1500 Hz).
- Chip-rate *W*=3.84 Mcps results in 2560 chips per one time slot.
- Physical channels either *dedicated* (for a single user only) or *common* (for all or for a group)
- UL: 1 bit for data **and** 1 bit for control (I/Q code multiplexed)
- DL: 2 bits for control **or** 2 bits for data (time multiplexed)

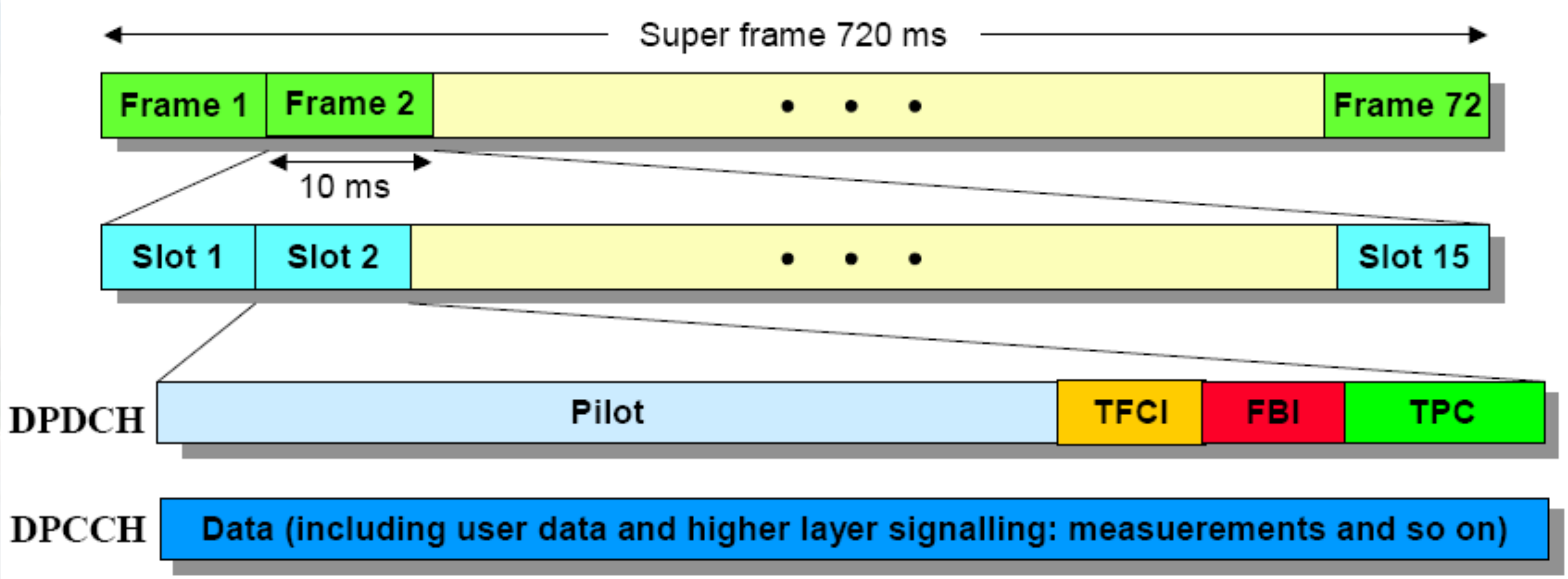


Dedicated physical channels

- **DPCCH** (Dedicated physical **control** channel) is *constant* bit rate channel and carries all the information in order to keep physical connection running, and carries:
  - uses reference symbols (pilot) for channel estimation in coherent detection and for SIR estimation in fast power control,
  - power control signalling bits (TPC),
  - transport format combination information (TFCI)=bit rate & interleaving information, and
  - feedback information (FBI) for advanced diversity techniques (CL Tansmit Diversity & Site Selection Diversity Techniques (SSDT))
- **DPDCH** (Dedicated physical **data** channel) is *variable* bit rate and carriers:
  - user data, and
  - higher layer signalling, e.g. mobile measurements, active set updates, packet allocations

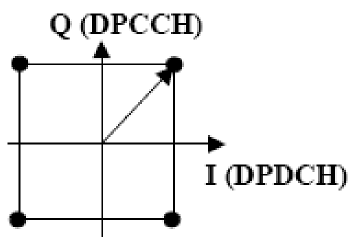
Uplink dedicated physical channels (1/2)

- Procedure in the base station:
  - Estimate the SIR from the known pilot symbols (used for UL PC & data detction)
  - Detect TPC and adjust DL transmit power.
  - Detect the used bit-rate and interleaving (TFCI).
  - Detect the data (Data): needs buffering of the Data field.



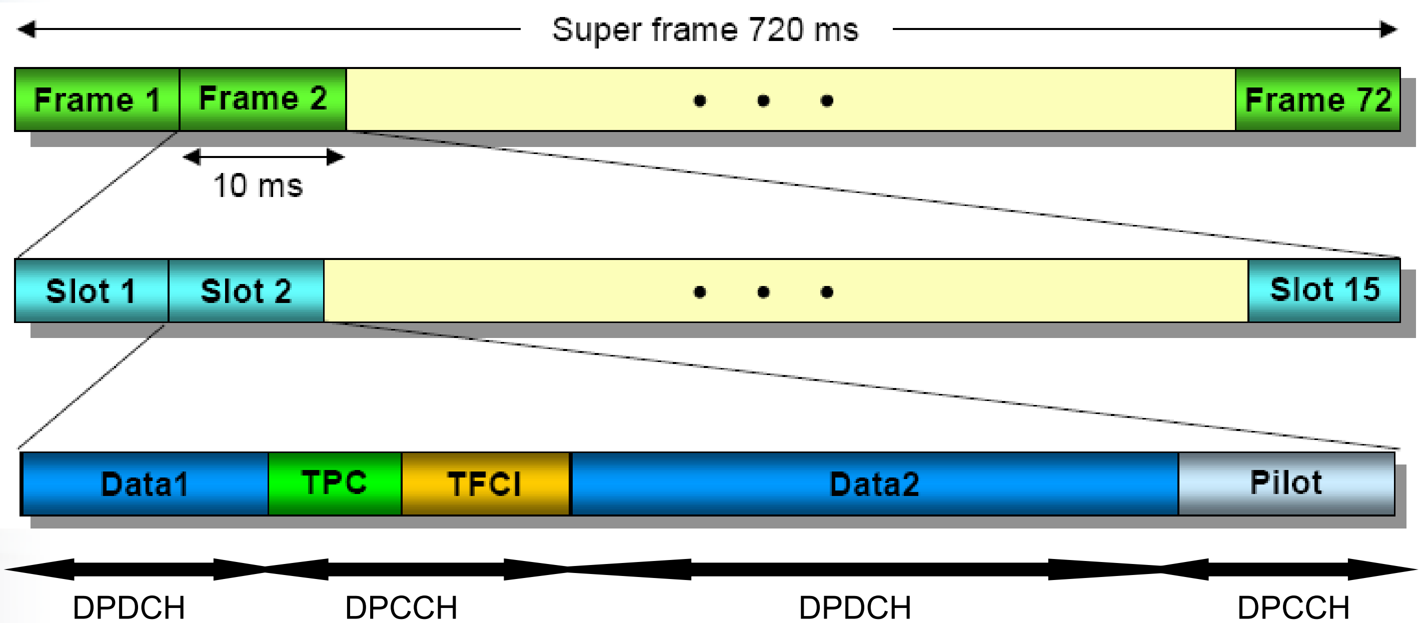
Uplink dedicated physical channels (2/2)

- There can be several uplink data channels (DPDCH) for one mobile but only one control channel (DPCCH).
- DPDCH spreading factor may range from 4 to 256
- DPCCH spreading factor is always 256
- Example:speech&data, what spreading factor to use ?
  - Speech (AMR codec) 12.2 kbps + 64 kbps packet data + control data 3.4 kbps
  - Without coding: 12.2 + 64 + 3.4 = 79.6 kbps
  - For example, 1/3 coding (that is, the coded bit stream is 3 times longer that the uncoded one) → 238.8 kbsp
  - This data rate can be realized by spreading factor SF = 16, because it equals to the bit rate of 240 kbps (3.84 Mcps / 16)



Downlink dedicated physical channels (1/3)

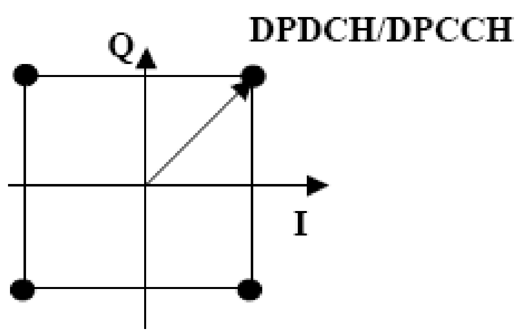
- DPDCH and DPCCH are now time multiplexed
- They have the same power and the same SF
- DPDCH spreading factor may vary from 4 to 512



Downlink dedicated physical channels (2/3)

- Due to time multiplexing, QPSK symbol carries two bits
- Example: speech and data again
  - Speech (AMR codec) 12.2 kbps + 384 kbps packet data + control data 3.4 kbps results in 12.2×3 + 384×3 + 3.4×3 = 1198.80 with 1/3 coding.
  - By puncturing, this can be lowered to 960 kbps
  - This can be handled by SF = 8, which now results in:

3.84 Mcps / 8 = 480 ksps = 960 kbps.



Downlink dedicated physical channels (3/3)

Slot Format #i	Channel Bit Rate (kbps)	Channel Symbol Rate (ksps)	SF	Bits/Frame			Bits/Slot	DPDCH Bits/Slot		DPCCH Bits/Slot		
				DPDCH	DPCCH	TOT		N_{Data1}	N_{Data2}	N_{TFCI}	N_{TPC}	N_{Pilot}
0	15	7.5	512	60	90	150	10	2	2	0	2	4
1	15	7.5	512	30	120	150	10	0	2	2	2	4
2	30	15	256	240	60	300	20	2	14	0	2	2
3	30	15	256	210	90	300	20	0	14	2	2	2
4	30	15	256	210	90	300	20	2	12	0	2	4
5	30	15	256	180	120	300	20	0	12	2	2	4
6	30	15	256	150	150	300	20	2	8	0	2	8
7	30	15	256	120	180	300	20	0	8	2	2	8
8	60	30	128	510	90	600	40	6	28	0	2	4
9	60	30	128	480	120	600	40	4	28	2	2	4
10	60	30	128	450	150	600	40	6	24	0	2	8
11	60	30	128	420	180	600	40	4	24	2	2	8
12	120	60	64	900	300	1200	80	4	56	8*	4	8
13	240	120	32	2100	300	2400	160	20	120	8*	4	8
14	480	240	16	4320	480	4800	320	48	240	8*	8	16
15	960	480	8	9120	480	9600	640	112	496	8*	8	16
16	1920	960	4	18720	480	19200	1280	240	1008	8*	8	16

Half rate speech

144 kbps

384 kbps

Uncoded bit-rate

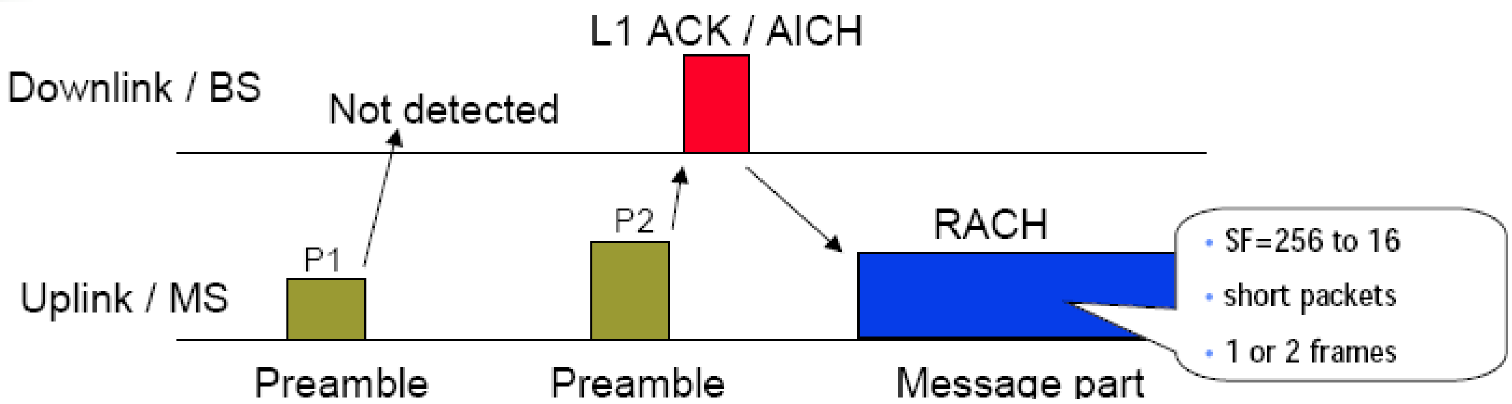
- In DL, the spreading factor = the number of orthogonal spreading codes
- With spreading factor of 4 and with 3 parallel code channels, 2 Mbps can be reached

Common physical channels

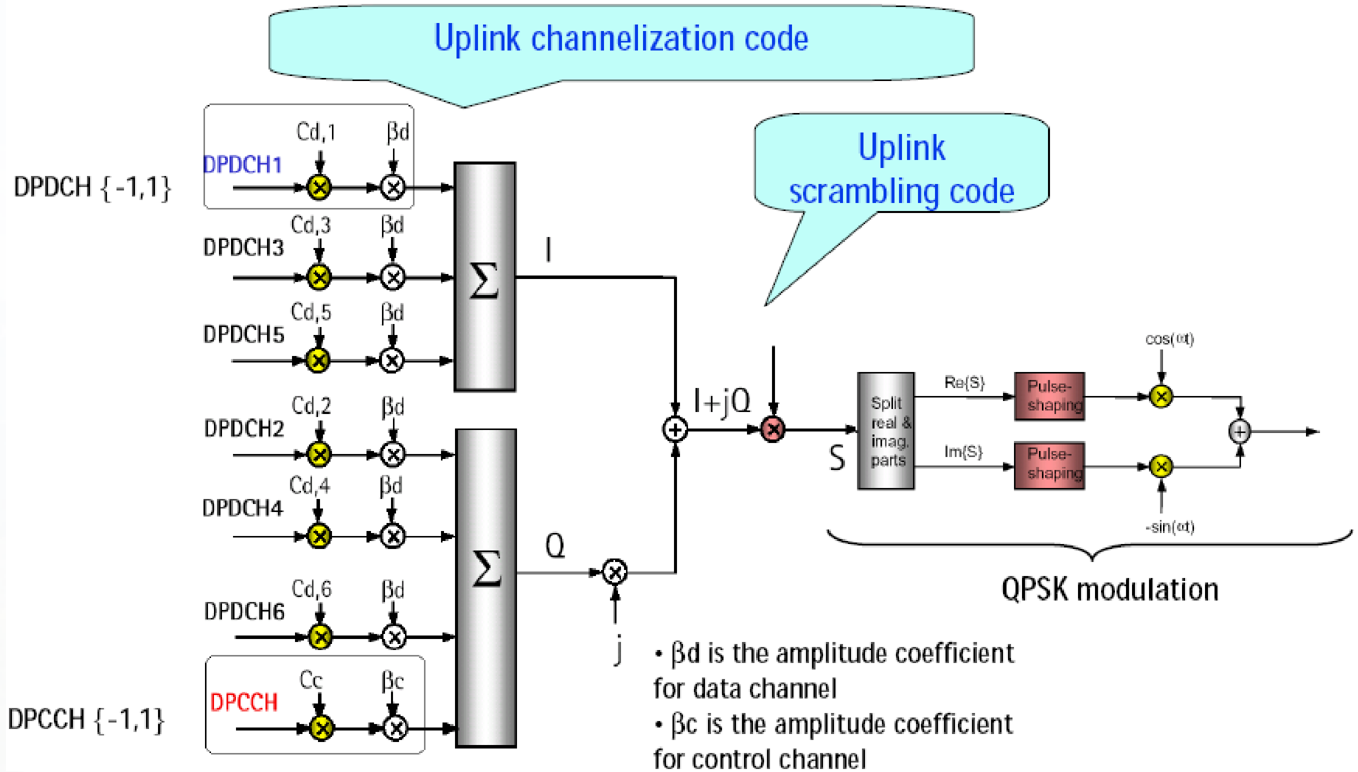
- Uplink
  - Physical Random Access Channel (PRACH)
  - Physical Common Packet Channel (CPCH)
- Downlink
  - Downlink Common Pilot Channel (CPICH)
  - Primary Common Control Physical Channel (P-CCPCH)
  - Synchronisation Channel (SCH)
  - Secondary Common Control Physical Channel (S-CCPCH)
  - Acqusistion Indicator Channel (AICH)
  - Paging Indicator Channel (PICH)

Physical Random Access Channel (PRACH)

- This is used to carry control information from the terminal, such as requests to set up a connection.
- This channel is not power controlled. Therefore, *power ramping* is needed with preambles since the initial power level setting (by open loop PC) in the mobile is very coarse.
  - MS sends a preamble signature (1 preamble = 4096 chips)
  - MS increases the power every time the new preamble is sent
  - L1 acknowledgement: base station acknowledges the sequences received with high enough power level (AICH = Acquisition Indication CH)
  - RACH message of the MS follows the acknowledgement

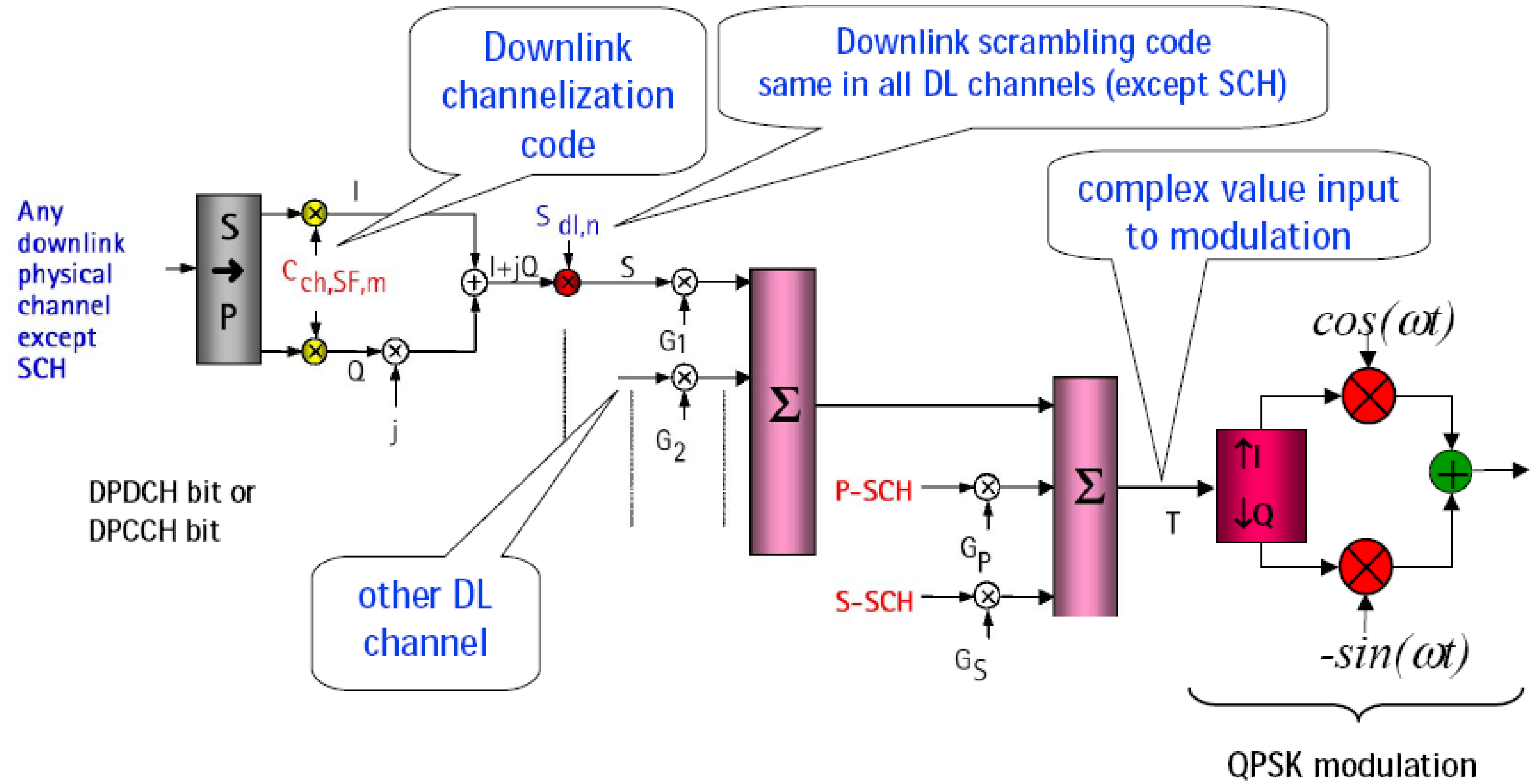


Uplink spreading on dedicated channels



- One DPCCH and up to 6 DPDCH channels can be transmit simultaneously.
- When only one DPDCH is to be transmitted the code has a required SF.
- When more than one DPDCH is to be transmitted the code has SF=4.
- Scrambling code and minimum SF are assigned by network in the beginning of connection.

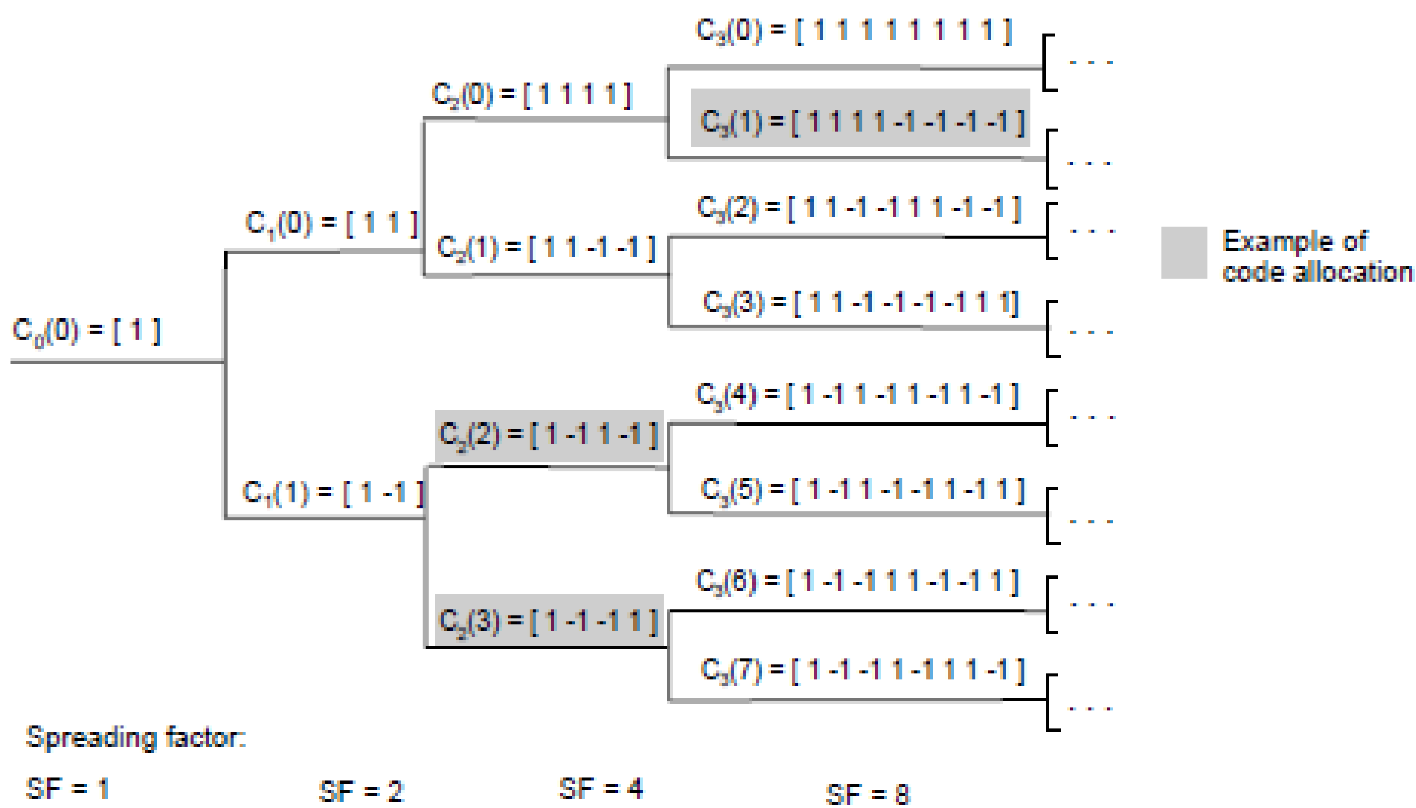
Downlink spreading and modulation

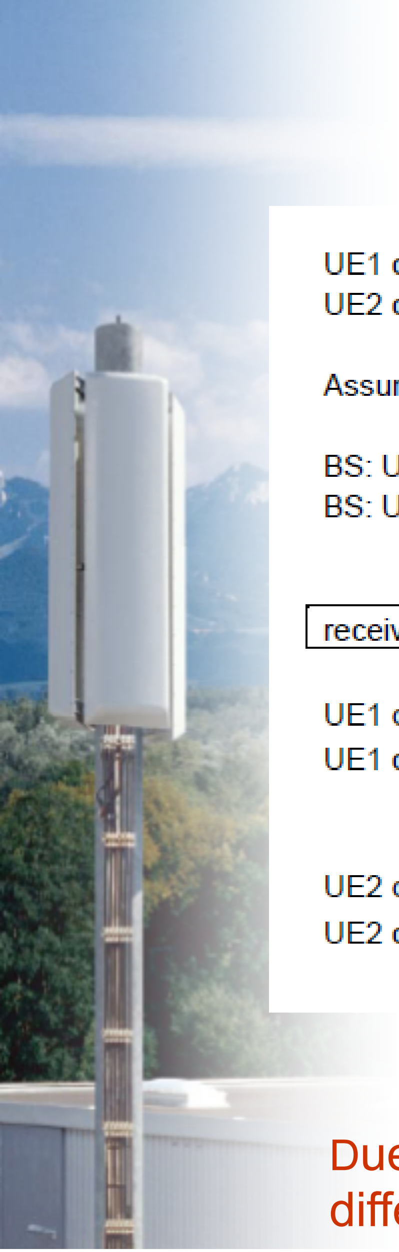


• Same channelization code (=short code=spreading code) as in uplink (OVSF code)
• Typically one code tree per cell, i.e. the code tree shared between all downlink users.

Orthogonal channelization codes

- Hierarchical selection of short codes from a "code tree" to maintain orthogonality
- OVSF (Orthogonal Variable Spreading Factor) codes





Example: Two UEs with different datarate and ideal channel

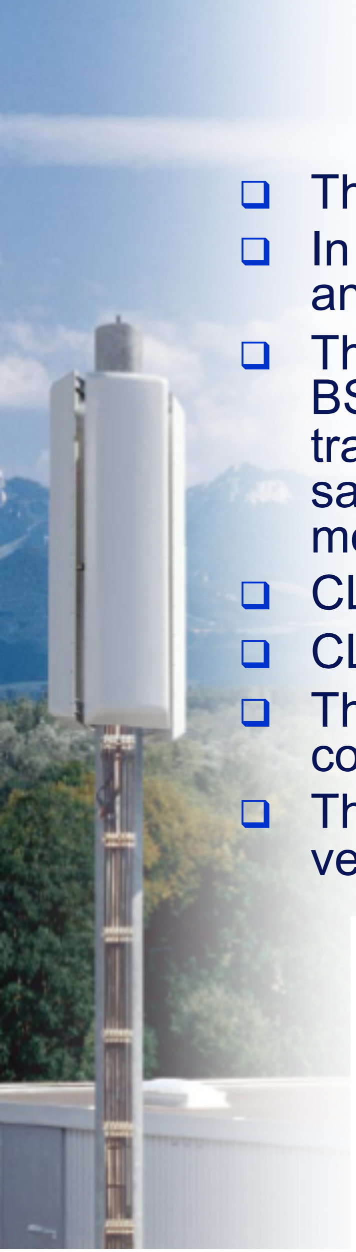
UE1 code (SF=8)	1	1	1	1	-1	-1	-1	-1	
UE2 code (SF=4)	1	-1	1	-1					
Assume: BS sends UE1 a bit +1, and for UE2 bits 1 and -1									
BS: UE1 chips	1	1	1	1	-1	-1	-1	-1	UE1 symbol
BS: UE2 chips	1	-1	1	-1	-1	1	-1	1	UE2 1st symbol
									UE2 2nd symbol
received chips by UEs	2	0	2	0	-2	0	-2	0	
UE1 despread chips	2	0	2	0	2	0	2	0	
UE1 chip integrator	2	2	4	4	6	6	8	8	"--> UE1 decides +1"
UE2 despread chips	2	0	2	0	-2	0	-2	0	
UE2 chip integrator	2	2	4	4	-2	-2	-4	-4	"--> UE2 decides +1 and -1"

Due to OVSF-codes, the orthogonality of UEs remains even if different data rates are used.

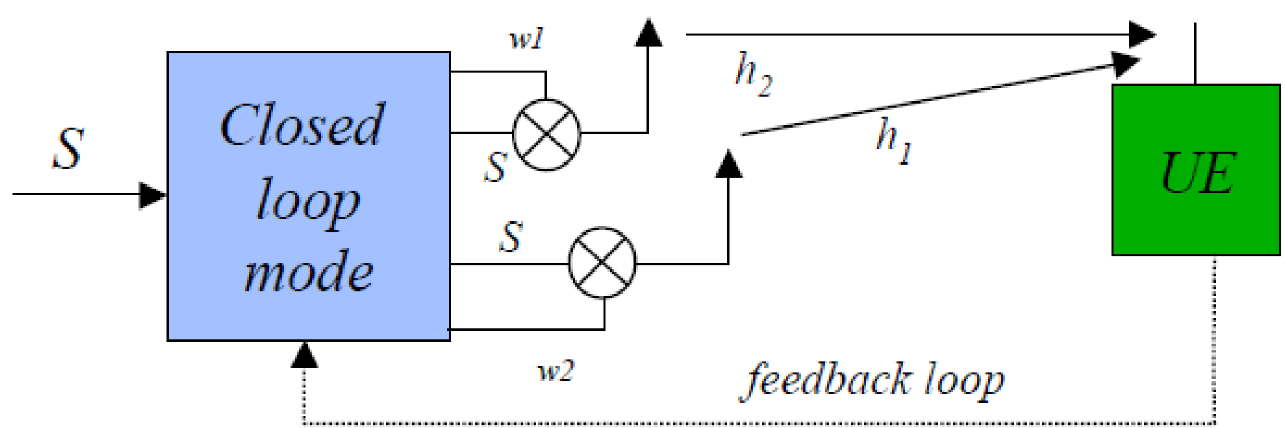
Tx Diversity: PHY operations

- 3GGP has defined transmit (Tx) diversity in BS. This has to be supported also in UEs.
- The problem with Tx diversity is the channel estimation !
- Two possible solutions
  - Closed loop (CL) mode: UE informs the BS about the channel conditions
  - Open loop (OL) mode: the space time coding scheme is applied.
- Tx diversity is based on the UE ability to separate the signal from two antennas

Tx Diversity: Closed loop modes



- There exists two Closed loop modes
- In both methods the UE measures the received signals from both BS antennas, and tries to estimate the phase difference of the two channel.
- The target of UE is to inform BS about this phase difference so that the BS could make an appropriate phase-correction already in the transmission → then the received symbols would arrive at the UE with the same phase, i.e. they get combined in the UE receive antenna in the most optimal way.
- CL Mode 1: the phase of antenna 1 will be adjusted relative to antenna 2.
- CL Mode 2: both phases *and* amplitudes of two antennas are adjusted.
- The performance of the CL is better than the open loop but it is more complex to implement.
- The performance of the Tx Div can further increase with antenna verification which tries to find potential errors of the feedback channel.

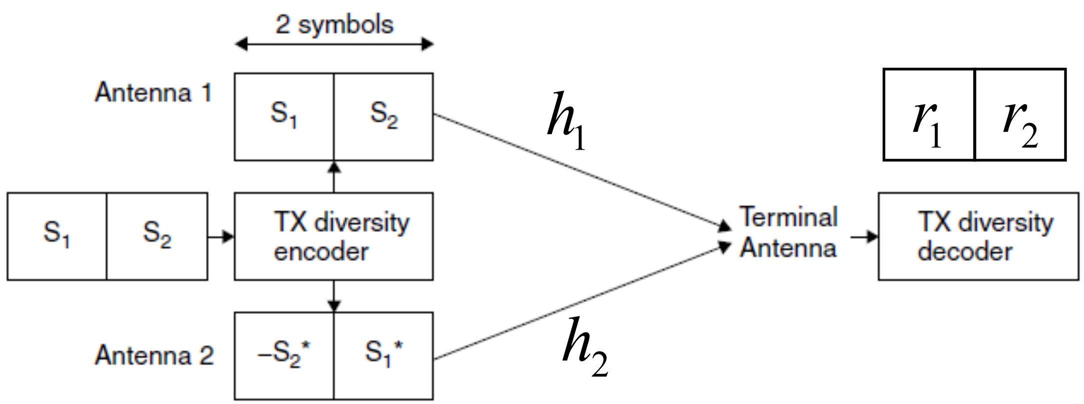


Tx Diversity: Open loop mode

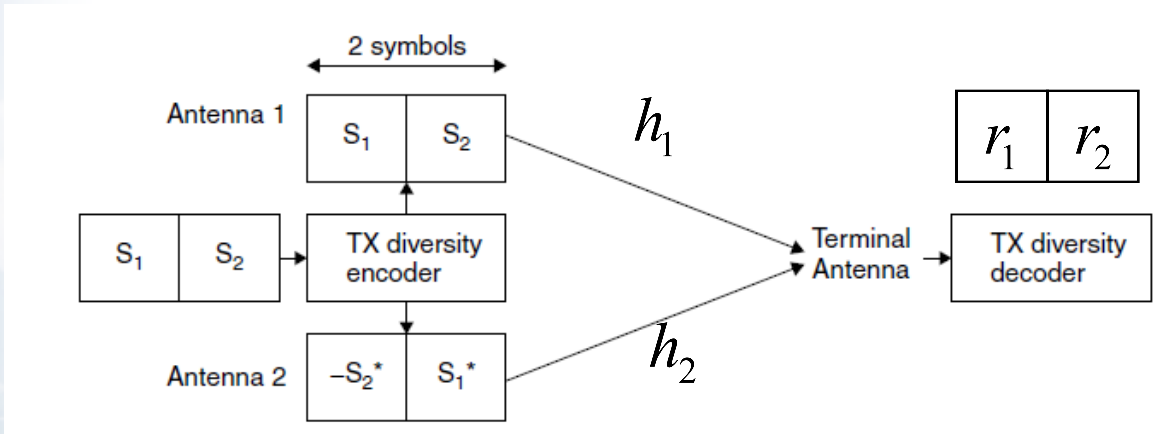
- OL mode is based on the Space-Time Transmit Diversity (STTD)
- The encoding technique makes the two transmit signals orthogonal to one another.
- For example, we have two adjacent symbols, S_1 and S_2, coming to the Tx diversity encoder.
- The channels from two antennas are h_1 and h_2.
- The two received encoded signals from antenna during two symbols period are then:

$$r_1 = h_1 S_1 - h_2 S_2^*$$

$$r_2 = h_1 S_2 + h_2 S_1^*$$



Tx Diversity: Open loop mode (cont'd)



$$S_1 = ?$$
$$S_2 = ?$$
$$h_1 = ?$$
$$h_2 = ?$$

- The mobile tries to estimate the symbols as:

$$\hat{S}_1 = \hat{h}_1^{\ *} r_1 + \hat{h}_2 r_2^{\ *}$$
$$\hat{S}_2 = \hat{h}_1^{\ *} r_2 - \hat{h}_2 r_1^{\ *}$$

- For simplicity, let us assume that UE is able to perform **perfect** channel estimation, i.e.

$$\hat{h}_1 = h_1, \hat{h}_2 = h_2$$

Tx Diversity: Open loop mode (cont'd)

Recall:

$$r_1 = h_1 S_1 - h_2 S_2^*$$

$$r_2 = h_1 S_2 + h_2 S_1^*$$

- Then, for S_1 estimation we have:

$$\begin{aligned}
\hat{S}_1 &= h_1^* r_1 + h_2 r_2^* \\
&= h_1^* \left(h_1 S_1 - h_2 S_2^*\right) + h_2 \left(h_1 S_2 + h_2 S_1^*\right)^* \\
&= h_1^* h_1 S_1 - h_1^* h_2 S_2^* + h_2 h_1^* S_2^* + h_2 h_2^* S_1 \\
&= \left(\left|h_1\right|^2 + \left|h_2\right|^2\right) S_1
\end{aligned}$$

- We see that the estimate of S_1 **is not interfered by S_2** ! Similarly (exercise), the estimate of S_2 is not interfered by S_1.

Tx Diversity: Benefits in WCDMA

- Reduction in SIR requirements relative to the case of single antenna transmission:

Diversity Mode	Modified Vehicular A			Pedestrian A
	3 km/h	50 km/h	120 km/h	3 km/h
Open-loop mode	1.0 dB	0.5 dB	0.5 dB	3.0 dB
Closed-loop mode 1	1.5 dB	1.0 dB	0.0 dB	3.5 dB

- Capacity gains:

Diversity Mode	Macrocell Capacity Gain	Microcell Capacity gain
Open-loop mode	25%	50%
Closed-loop mode 1	35%	70%

Radio link performance definitions (1/5)

- BLER
  - Block Error Rate, a long term average calculated from the received data blocks.
  - e.g. 10^5 blocks with 1 erroneous block (at least one bit error in the block)→ BLER= 10^{-5}
- BER
  - Bit Error Rate *after decoding*. The channel BER (*raw BER,* i.e. BER before decoding) is a always higher than BER
- Bit Rate, *R*
  - Rate of user information bits = bit rate before L1 processing (CRC, coding, etc)
- E_b/N_0
  - bit-energy over noise spectral density
  - It relates to respective quality target (e.g. BER/BLER)
  - In WCDMA, the E_b/N_0 is generally defined as:

$$E_b / N_0 = \frac{\frac{W}{R} p_{rx}}{I}$$

where p_{rx} is the received power, *I* is the received interference power and the *W* is the bandwidth

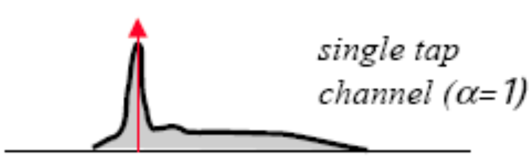
  - Target of the power control is to keep E_b/N_0 as close to the target as possible

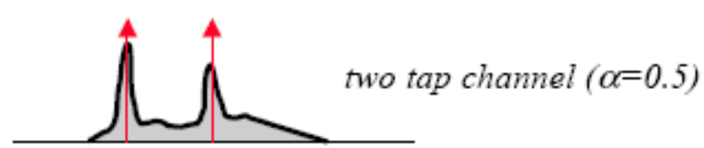
Definitions (2/5)

- Orthogonality, α, $0 \le \alpha \le 1$
  - It measures the level of interference that the *own* base station causes to the mobile receiver. It is *modelled* as

$$I_{own} = p_{rx}(1-\alpha)$$

  - In the case of single path channel the interference from the own base station is small, because short codes in WCDMA are orthogonal. Hence, $I_{own} = 0$, that is, $\alpha=1$.
  - In the case of multipath channel the received replica of the codes are no longer orthogonal with each other. Hence, the interference from the own base station is non-zero. $0 < \alpha < 1$.
  - The orthogonality is highly varying and only the average value is used in the radio network planning.





Example

- OVSF code with multipaths:

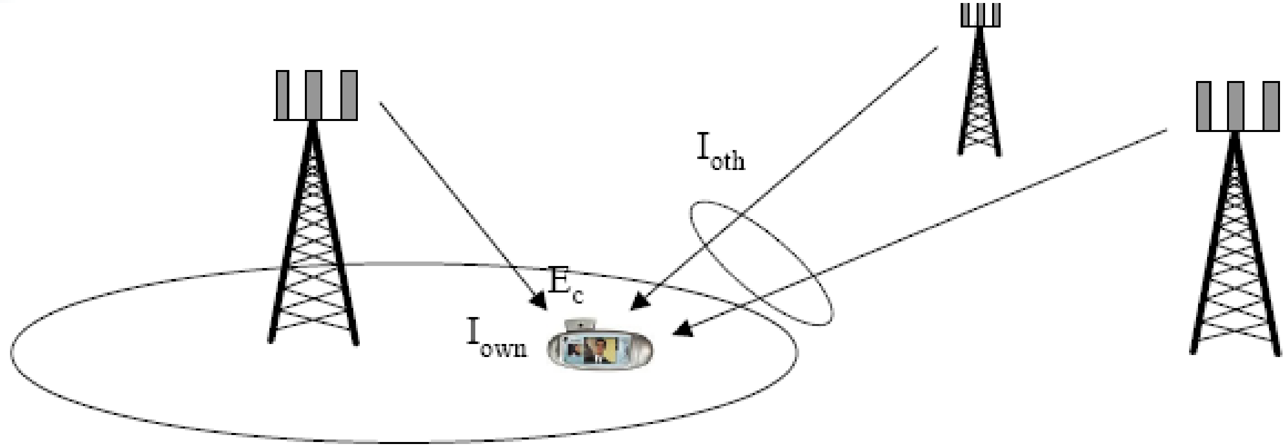
UE1 code (OVSF)	1	-1	-1	1						
Assume 2 bit are sent (+1 +1) :										
transmitted chips	1	-1	-1	1	1	-1	-1	1		
Assume 2 paths with delay differerence equal to 2 chip, and that the second path is a bit srtronger than the other:										
path 1 chips	1	-1	-1	1	1	-1	-1	1		
path 2 chips			1,2	-1,2	-1,2	1,2	1,2	-1,2	-1,2	1,2
reveived chips	1,0	-1,0	0,2	-0,2	-0,2	0,2	0,2	-0,2		
path 1 despread chips	1,0	1,0	-0,2	-0,2	-0,2	-0,2	-0,2	-0,2		
path 1 integrator	1,0	2,0	1,8	$\boxed{1,6}$	-0,2	-0,4	-0,6	$\boxed{-0,8}$		

- In optimal case, path1 integrator should end up with +4 for both symbols.
- We see that due to multipaths, strong IPI (inter-path interference) will exist. Similarly, two different users interfere with each other due to multipaths, even if their codes are orthogonal with each other.

Definitions (3/5)

- E_b / N_0 (again, now in the WCDMA downlink)
  - In the downlink the E_b/N_0 can be evaluated in more detail, because the synchronised orthogonal codes reduce the interference from the serving cell. In the following N equals to the thermal noise power:

$$E_b / N_0 = \frac{W}{R} \frac{p_{rx}}{I_{own}(1-\alpha) + I_{oth} + N}$$

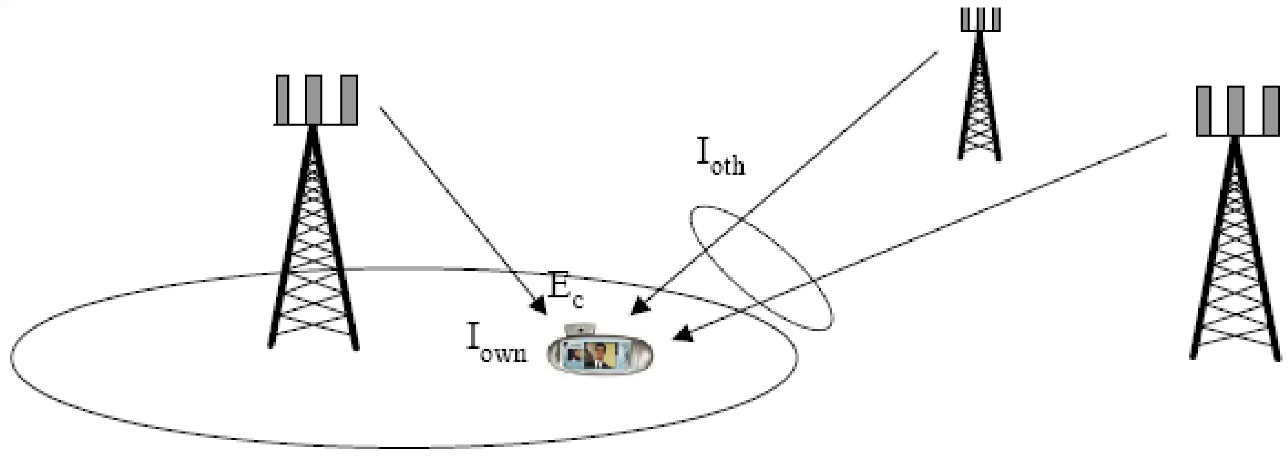


Definitions (4/5)

- E_c / I_o
  - Received *chip* energy relative to total power spectral density.
  - Uplink: $E_c/I_0 = E_b/N_0 / (W/R)$
  - Downlink: I_0 is the total received *wideband* (i.e. chip level) power

$$E_c / I_0 = \frac{p_{rx}}{I_{own} + I_{oth} + N}$$

Notice: orthogonality is not taken into account !

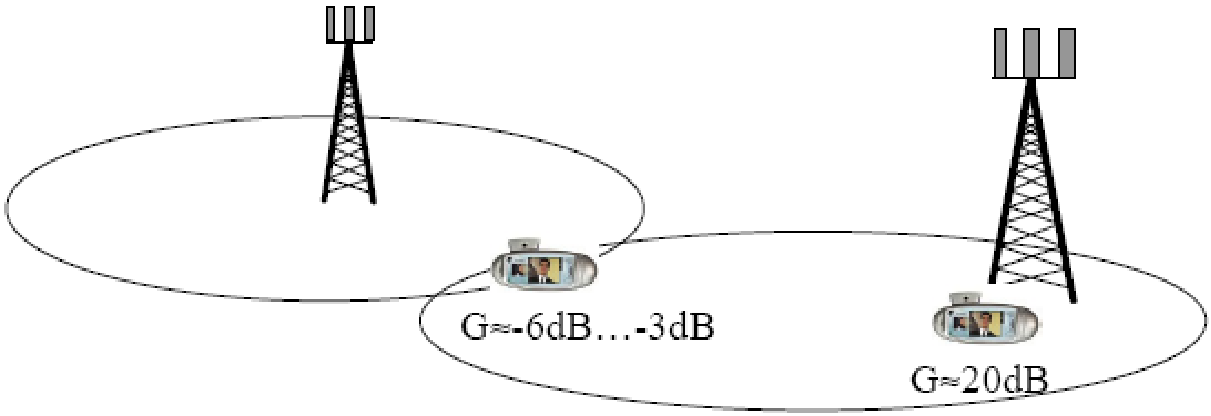


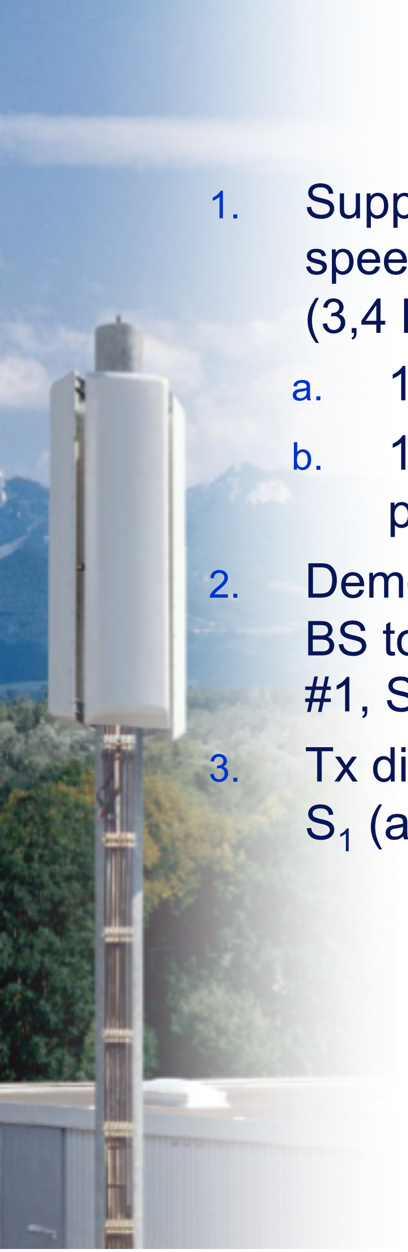
Definitions (5/5)

- Geometry Factor
  - Used in downlink performance evaluation:

$$G = \frac{I_{own}}{I_{oth} + N}$$

  - When the network is interference limited ($I_{oth} >> N$), then $G \approx 1/i$
  - Typically –3 dB for the cell edge and 20 dB close to the BS





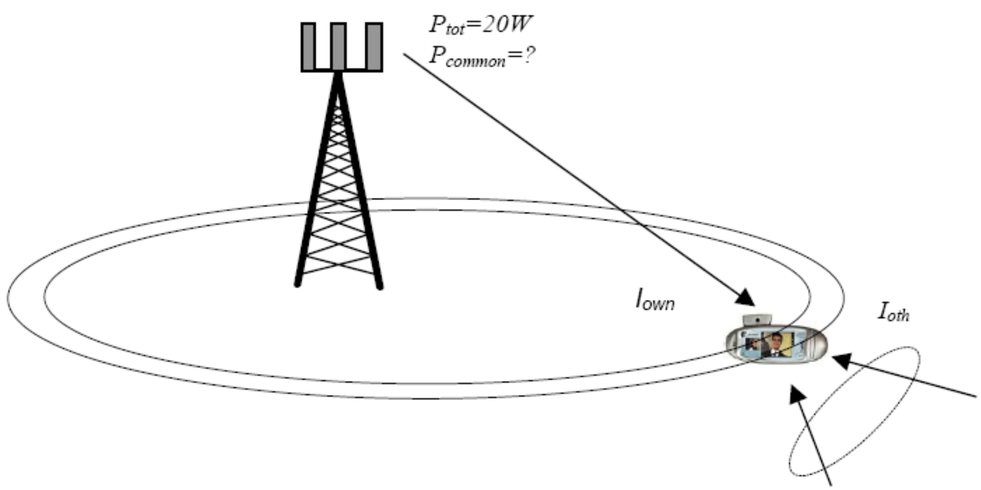
Exercises (1/3)

1. Suppose the dedicated physical channel should carry simultaneous speech (12,2 kbps) and data (128 kbps) with higher layer signalling data (3,4 kbps). What spreading factor could be used in uplink and downlink if
   a. 1/3 coding is used ?
   b. 1/2 coding and puncturing is used ? In this case, how much (in percentage) should ne punctured ?
2. Demonstrate by an example (like in the slide 26) that it is possible for a BS to serve 3 users with different spreading factors, like SF=2 for user #1, SF=4 for user #2, SF=8 for user #3.
3. Tx diversity (slide 22): show that the estimate of S_2 is not interfered by S_1 (assuming a perfect channel estimation).

Exercises (2/3)

4. Suppose that the target E_c/I_0 for the BS control channel equals -18dB. How much transmit power should be reserved for this channel (P_{common} in the figure), when the total transmit power of a BS is 20W, the geometry factor G=-3dB and the background noise is ignored (that is, N=0).

Hint: The power *ratio* (P_{common}/P_{tot}) remains the same at the reception. In the reception the power ratio can be written as (p_{rx} / I_{own}), where p_{rx} is the received power from a common channel and I_{own} is the total received power from your own BS.



Exercises (3/3)

5. Suppose that control channel power equals P_{common}=0,5W and that the total BS transmit power is 20W. What would be the E_c/I_0 value of the control channel near the BS, that is, assuming for example that G=20dB ?
6. Let's consider WCDMA downlink. Suppose first that there is no multipaths and suppose A_1 equals the E_b/N_0 in this case. Suppose A_α equls E_b/N_0 in the case when multipaths, and their existence is characterized by the channel orthogonality α.
   a. Derive the ratio A_α / A_1 assuming that there is no background noise (N=0). This ratio tells how much the E_b/N_0 value will reduce in the presence of multipaths.
   b. Calculate how much the E_b/N_0 value will reduce near the BS (G=20dB) and at the cell border (G=-3dB) if the channel orthogonality is α=0,5. Why the E_b/N_0 is reduced much less at the cell border?