

Mobile Communications

Universal Mobile Telecommunication System

4. Universal Mobile Telecommunication System

4.1 New service paradigms for mobile communication

4.2 Bandwidth and Standard process for UMTS

 **4.3 Spread Spectrum Communications - principles**

4.4 UMTS Signalling and control functions

4.5 UMTS Core Network – IP integration issues

4 Universal Mobile Telecommunications System

4.3 Spread Spectrum Communication - principles

the access technique
orthogonal coding
spreading factor and processing gain
transmission technique
physical and logical channels

extensions:

e4.1 system acquisition

e4.2 power control

e4.4 packet communication

e4.3 handover

2



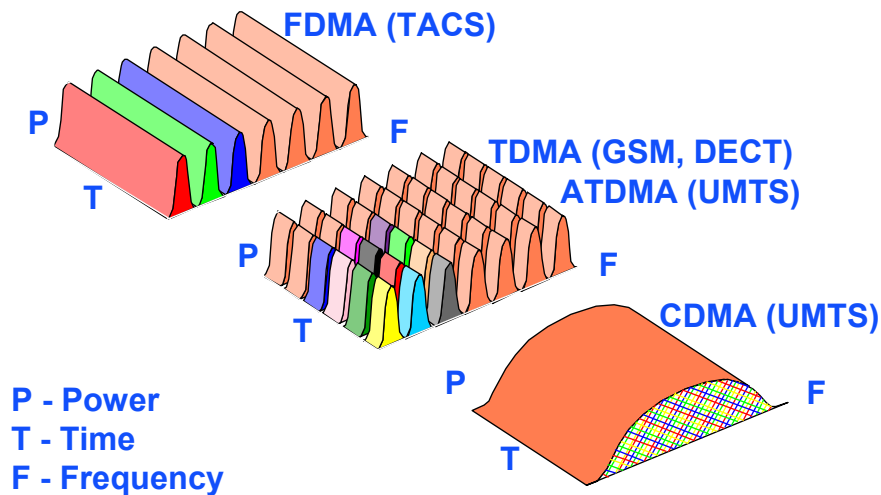
An important portion of functions, interfaces and architectural solutions adopted for the UMTS derive from the radio features.

This section considers the main radio principles embedded in UMTS.

A key question is the control of the radio resources and this issue is assigned particular attention.

The scheme is the one adopted at the Standard level.

Access techniques for mobile communications



3

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The most important families of radio access schemes are: FDMA (Frequency Division Multiple Access), TDMA (Time Division Multiple Access) e CDMA (Code Division Multiple Access).

For each, the related radio resource usage mechanisms are highlighted in the time, frequency and power domains.

In the light of the most recent developments, the most innovative access technique in the field of mobile services is the Code Division Multiple Access (CDMA) technique. In January 1998 ETSI took an important decision about the radio access technique to be used for UMTS:

- for the asymmetrical portion of the spectrum available for UMTS, a hybrid solution based on a TDMA + a CDMA scheme has been chosen
- for the symmetrical portion of the spectrum, a wide band CDMA W-CDMA) scheme has been adopted.

The former solution is thought mainly for in-door applications, the latter for public/outdoor/high mobility services.

The Code Division Multiple Access (CDMA) belongs to the family of Spread Spectrum techniques. The following figures are recalling just some of the basic concepts on which the CDMA technique is based; this is done to supply some background information to facilitate the comprehension of the subsequent considerations referred to radio and network subsystems.

Spread spectrum techniques

AWGN CAPACITY WITH LIMITED SPECTRUM

$$C = B \log_2 (1 + S/N)$$

[C]=bit/s

[B]=Hz

S/N=signal to noise ratio

A given bit rate R can
be obtained through

Narrow band and high S/N

Wide band and low S/N

4

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Spread spectrum systems are characterised by the use of a transmission bandwidth much greater than the bandwidth of the information signal.

A simple explanation of the basic idea of spread spectrum communications is provided by the band limited Additive White Gaussian Noise (AWGN) channel capacity formula (Shannon). The formula supplies the channel capacity in function of the used bandwidth and the signal to noise ratio when AWGN conditions arise.

By looking at the invoked variables, it can be said that a given capacity can be obtained:

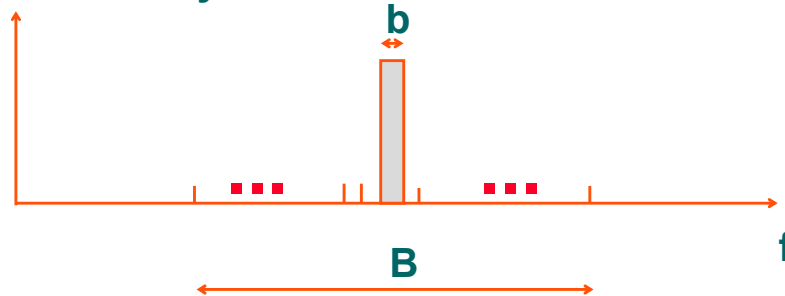
- by assigning the channel a narrow band, pursuing, at the same time, high value of Signal to Noise ratio (S/N), as it is typically done in FDMA/TDMA systems
- by using a much wider band, admitting much lower values of S/N.

The latter approach is the one corresponding to the spread spectrum techniques: all the users are transmitting and receiving on common frequencies and each connection perceives all the other as a noise.

The discrimination between different connections is performed through different codes which are associated to the different connections. Each code is used in the transmission phase to encode the original signal and on the receiving side, the same code in some way addressed in the decoding process.

Frequency Hopping

Power density



The information signal (with bandwidth “ b ”) is transmitted changing frequently the carrier (within a band $B \gg b$) according to a hopping pattern determined by the user code

5

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The code can be assigned by using various mechanisms corresponding to various CDMA implementation techniques:

- Direct Sequence (DS-CDMA)
- Frequency Hopping (FH-CDMA)
- Time Hopping (TH-CDMA)

The Direct Sequence CDMA technique has been adopted for the third generation mobile services.

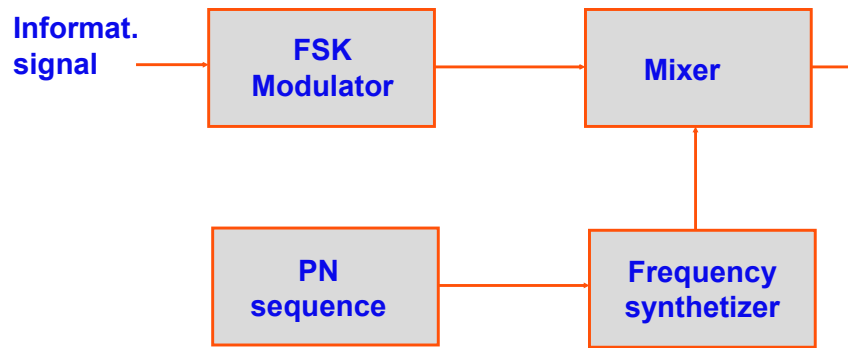
Spread spectrum transmission derives from military applications. In that context, it has appeared to be the best solution to guarantee the security and the availability of the communication in a hostile environment. Due to complexity and cost issues, such a kind of systems have not been considered for civil applications for a long time, even if their advantage in some situations were evident.

One of this situation is the case of cellular mobile systems: in cellular systems the low probability of interception can be seen as a low level of interference created toward other users and pre-existing systems. The robustness against jamming can be seen as a low sensitivity to the interference created by other users or systems.

During the second half of the seventies (when high performance hardware was starting to be available also for civil use), some researchers (Nettleton, Cooper) proposed the adoption of spread spectrum in the area of cellular systems.

Frequency hopping (figure) is a spread spectrum technique that belongs to the category of the so called “avoidance” systems; this means that the systems tries to avoid in some way the jamming source that can impair transmission quality. The bandwidth spreading is obtained changing the frequency carrier used for the transmission of a signal with bandwidth “ b ” in a frequency band having width $B \gg b$. A specific user code (PN sequence) drives the carrier changes. If a set of orthogonal codes is adopted (i.e., codes that do not allow the use of the same carrier in same instant) it is possible to perform multiple access.

Frequency hopping scheme



6

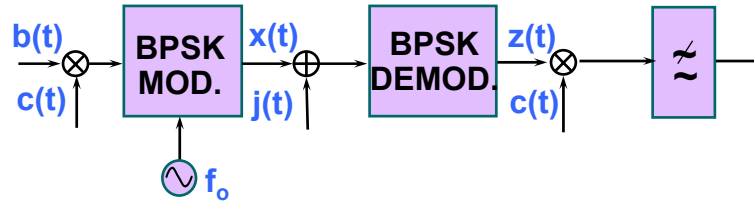
There are two kind of FH hopping techniques:

- the fast FH, where several hops are performed within a bit duration
- the slow FH, where the hops are performed just every a limited number of bits.

In the former case, the requirements for the local oscillator frequency are quite stringent: it is possible that several tens of Mhops/s are required.

The picture shows the basic scheme of a FH spread spectrum signal. The local oscillator frequency is changed every hopping time according to the values of a pseudo noise sequence. As a consequence, the RF carrier at the mixer output will change every hopping time.

Direct Sequence-CDMA



$$z(t) = b(t)c(t) + j(t)$$

$$z(t)c(t) = b(t)c^2(t) + j(t)c(t) = b(t) + j(t)c(t)$$

spread interferer

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7

In the area of spread spectrum techniques, Direct Sequence CDMA (DS-CDMA) represents the most important approach. Also the North American IS-95 standard, adopts a DS-CDMA technique. The same has been chosen as the access technique for UMTS.

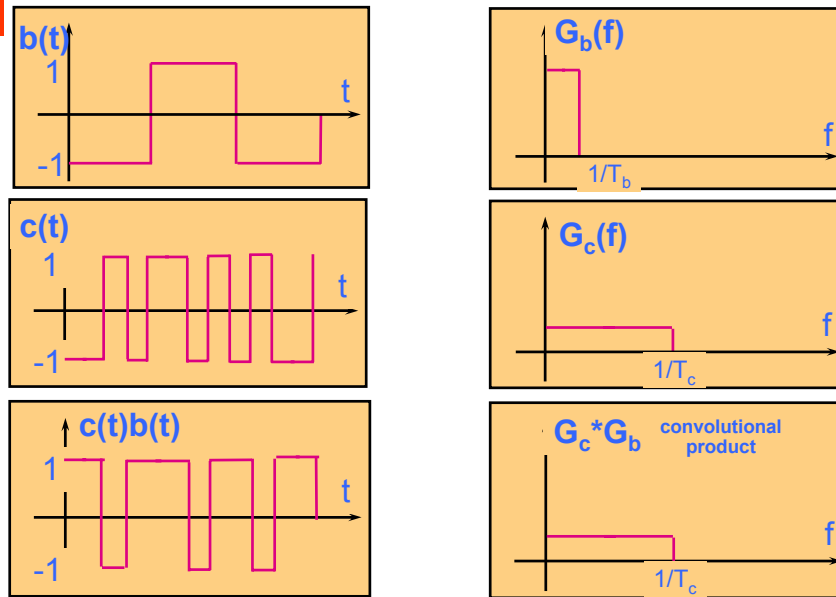
The Direct Sequence CDMA is based on the following functional principles.

- the original digital signal $b(t)$ is multiplied by a wide band digital signal $c(t)$ which represents the code assigned to that particular connection
- this spreads the original signal on the available spectrum
- the resulting signal is then modulated and transmitted.

On the receiving side, after demodulation, the resulting signal is multiplied by the same encoding code $c(t)$ to recover the original signal. A possible narrow band jammer arising on the radio channel is spread in spectrum on the receiving side, so that it can be easily extracted.

CDMA system are not characterised by and hard limitation of resources: given that the number of available codes is large enough, new calls can always be set up because there is no resource limit (a quality criteria will establish when new incoming calls are to be blocked). This concept assigns CDMA systems a “soft capacity” attitude, consisting in the ability to operate under capacity limits that are fixed by the overall system interference rather than being defined in a deterministic way, cell by cell as for TDMA and FDMA systems.

Direct Sequence-CDMA



8

Using both time and frequency domains, the sequence previously described can be represented as shown in the figure. The three steps are those preceding modulation and transmission.

The information signal $b(t)$, taking values from the set $[-1, +1]$ is a narrowband signal (the power spectrum $G_b(f)$ has bandwidth $\cong 1/T_b$); in the time domain the rectangular pulses have a duration $= T_b$.

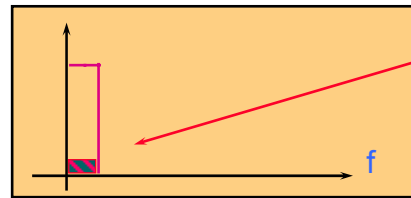
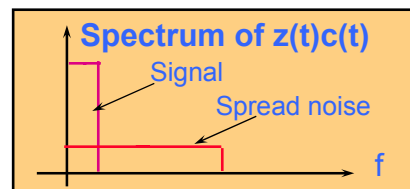
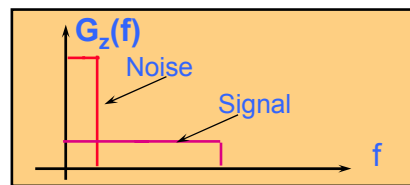
The code $c(t)$ takes also values from the set $[-1, +1]$ but, due to the very fast variation in the time domain ($T_c \ll T_b$), its power spectrum $G_c(f)$ is very wide (bandwidth $\cong 1/T_c$).

The product signal will be characterized by very fast variations as $c(t)$; as a consequence, its power spectrum, given by the convolution product of $G_b(f) * G_c(f)$, shows nearly the same bandwidth width as $c(t)$.

Sequences $c(t)$ must be orthogonal to each other. DS-CDMA adopts long and short codes.

- Short codes (e.g., Walsh codes) allow a better interference control but they typically require a complex code management.
- Long codes (long PN sequences) do not allow a precise mutual interference control but they do not need any code management because their number is extremely high.

Direct Sequence-CDMA



After the low pass filtering, only a fraction of the original interfering power is detected (reduction factor = R_c/R_b)

9

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After spreading and modulation, the signal is transmitted over the air interface. The radio channel can add both wideband and narrowband interference. In this example it is assumed that the transmitted signal is impaired by a narrowband interferer $j(t)$.

In order to recover the information signal $b(t)$, the demodulated signal $z(t)$ is multiplied by the spreading signal $c(t)$: since $c^2(t)=1$, the original signal $b(t)$ is obtained. In addition, on the receiving side, the narrowband interferer is spread over the entire bandwidth by the PN sequence $c(t)$.

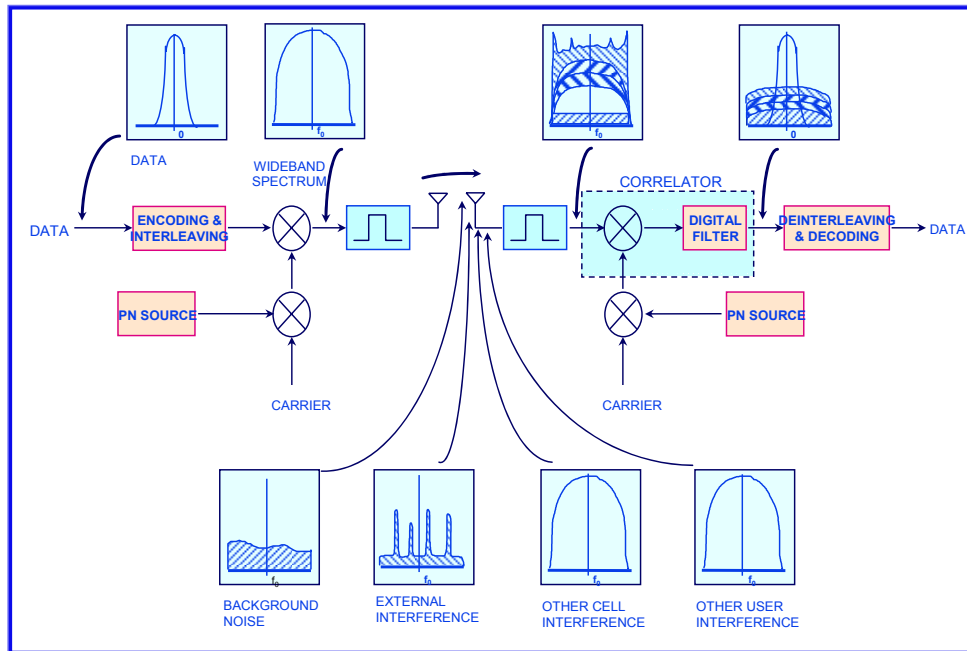
In this way, a low pass filter with band $1/T_b$ will recover the information signal intercepting only a portion of the jamming signal with a power density spectrum reduced by the factor R_c/R_b (R_c and R_b represent the chip rate (the rate of $c(t)$) and the rate of the original digital signal $b(t)$ respectively).

The term Spreading factor (SF) is defined as the number of chips used to represent a single coded bit before modulation. The term Processing gain (PG) is conversely used to represent the ratio between chip rate and user net bit rate ($PG \geq SF$) before the channel encoding.

Two typical aspects of a CDMA system are:

- the need of synchronising the spreading signal $c(t)$ between the receiving and the transmitting sides
- the interference - dependent behaviour: the simultaneous transmission of different signals over the same bandwidth, can take place as far as the interference level does not exceed a given threshold (the threshold which ensures a given quality).

CDMA system



The figure represents the overall process, from the original digital sequence generated by the source up to the reception.

The original signal can be extracted also from the wide band interfering signals. This is obtained by means of the correlation performed in the receiver. The correlation uses the spreading code as discrimination element among the different codes. This role is played in the rake receiver.

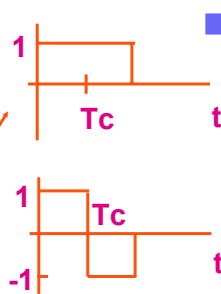
Walsh Codes

It is a set of orthogonal codes generated by the rows of a Hadamard matrix

The Hadamard matrix of order two is defined as:

$$H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Walsh functions



$$H_{2N} = \begin{bmatrix} H_N & H_N \\ H_N & -H_N \end{bmatrix}$$

11

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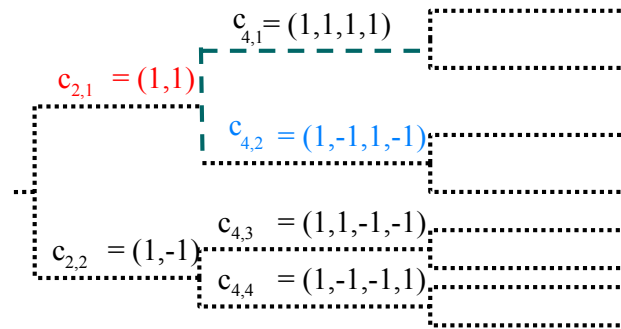
A family of orthogonal codes is derived through the *Walsh-Hadamard* function.

These codes are named channelisation or spreading codes and are used in the DS-CDMA technique. It is easy to verify that the scalar product of any couple of codes of the *Hadamard* matrix of a given order is equal to zero.

The *Hadamard* matrix of order $2N$ (hence the related codes, identified by its rows) is obtained through a recursion which is just using the N -order matrix:

$$H_{2N} = \begin{vmatrix} H_N & H_N \\ H_N & -H_N \end{vmatrix}$$

Orthogonal Variable Spreading factor Codes



12



The Orthogonal Variable Spreading Factor Codes (OVSFC) ensure the signals transmitted over different channels are orthogonal each other. The use of OVSF codes follows the binary tree scheme of the figure and the choice of the code depends on the bit rate of the connection to be spread.

The code sequence is repeated bit per bit of the original digital signal, hence the code depth is chosen accordingly. The choice of a given spreading code inhibits the use of all the codes it is subtending (or it is generated by) in the tree scheme.

Being the chip rate constant, the above allocation scheme implies that connections with different bit rates are transmitted with different spreading factors.

As said, a code can be used in a cell if and only if no other code on the path from the specific code to the root of the tree or in the sub-tree below the specific code is used in the same cell. As a consequence, the number of available spreading codes is not fixed but depends on the rate and spreading factor of each physical channel.

Walsh codes – channelization (example)

d1	1				-1				1			
d2	1				1				-1			
d3	-1				1				1			
w1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1
w2	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1
w3	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1
d1w1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
d2w2	-1	-1	1	1	-1	-1	1	1	1	1	-1	-1
d3w3	1	-1	-1	1	-1	1	1	-1	-1	1	1	-1
r(t) = d1w1+ d2w2+ d3w3	-1	-1	-1	3	-1	-1	3	-1	-1	3	-1	-1

13

The orthogonal codes are applied to each bit of the original digital flow. In the figure, three orthogonal codes w1, w2, w3, are applied to three different bit sequences d1, d2, d3 respectively. It is a case of *spreading factor 4* (rate between Tb and Tc).

Walsh codes – channelization (example)

To recover the information $d1$ multiply the composite signal $r(t)$ by the code $w1$ and then we sum up (integrate) over the bit time

$w1$	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1
$r(t)w1$	1	-1	1	3	1	-1	-3	-1	1	3	1	-1
$D1=\sum T_b$	4				-4				4			

$D1 > 0 \Rightarrow$ transmitted $d1 = 1$
 $D1 < 0 \Rightarrow$ transmitted $d1 = -1$

$\Rightarrow d1 = [1, -1, 1]$

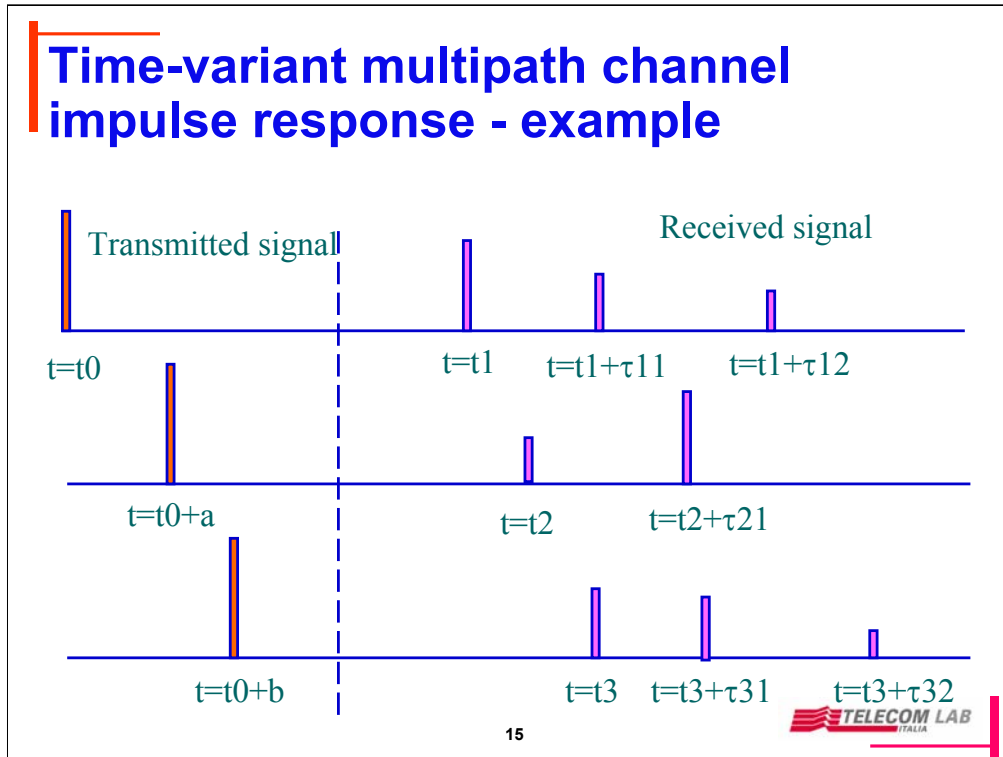
14



On the receiving side, to obtain for example the original sequence $d1$, the composite signal $r(t)$ is multiplied by the same code used in transmission.

The result is integrated over the bit time and the simple association of the figure delivers the original sequence $d1$.

On the receiving side, the correlation receiver sums exactly the result of the products (received signal) $\times$ (spreading code) chip per chip, over the entire bit length. The result 4 is correlated to the result of such an integration. All the other received signals, multiplied by the same spreading code and integrated over the same bit period, give rise to a *noise* signal whose power is close to zero.



However the transmission is affected by the *multipath* phenomenon. It is in function of this characteristic that the CDMA can take advantage from this propagation characteristic.

First, the transmission of an elementary information (e.g. a bit) takes place in times that are tied to the available bandwidth. For the UMTS, the transmission of a chip requires about $0.26 \mu\text{s}$ (at 3.84 Mchip/s).

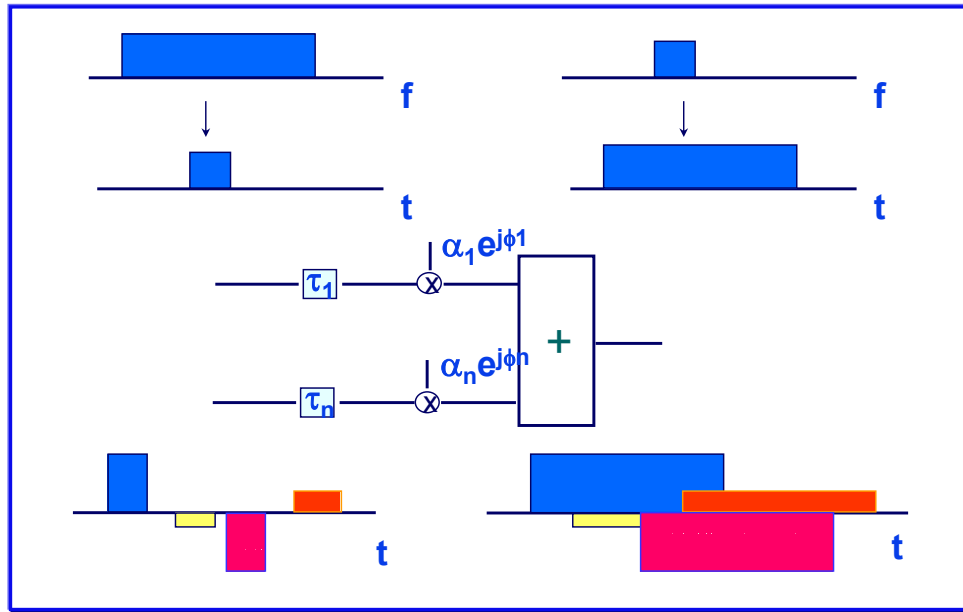
In a wide band system like the W-CDMA, the different replica of the same signal can be better take-apart on the receiving side. Not like that in a narrow band system.

In an urban environment, the delay arising between the different copies of the same signal is varying around $1\text{-}3 \mu\text{s}$. It is then very likely that different versions of the same signal (chip) arrive at the receiver in disjoint time intervals (at a distance greater than $0.26 \mu\text{s}$) then becoming easily to distinguish. This characteristic remains valid also for small cells (60-100m) thanks to the high bandwidth assigned to transmission.

The contribution to the received power given by a single signal replica, are determined by the Rayleigh fading. The fast fading effects are faced in the W-CDMA by means of:

- channel coding
- sophisticated de-modulation techniques
- interleaving techniques
- the increase of the received power through the constructive use of the rays received at the greater level (*rake receiver*)
- phase-alignment of the received rays *and fast power control*.

Propagation impairments due to multipath



Power control is performed through a *closed loop* mechanism with delays of the order of 1 ms.

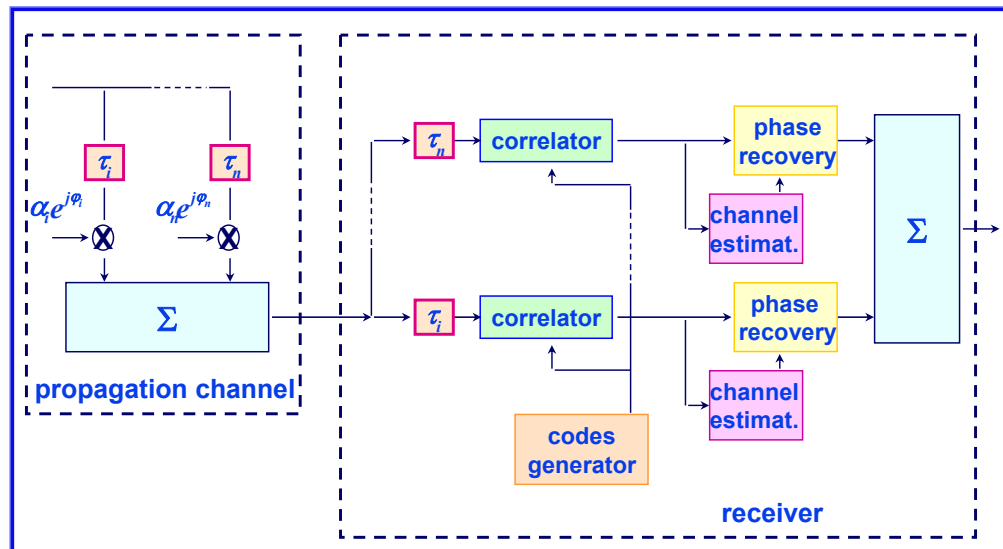
The granularity adopted to track the time shift of the high-power rays is of the order of a chip period.

It is then possible to use the so called *rake receiver*, able to reveal and demodulate independently each replica of the original signal (it exploits the *path diversity*). Each delayed version of the signal is phased and then summed in a constructive way with the other replica.

A Combining of the phased replica is performed to obtain a much greater quality compared to the case of a single demodulation of the highest-power ray.

In case of narrow-band transmission (GSM) the *multipath* effect requires that complex equalization techniques are used to erase the inter symbol interference.

The rake receiver



17

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The *rake receiver* refers to the various rays related to a single signal. The figure refers to the *up-link*. However, the general principles briefly reported here are also valid for the *down-link* functions realised in the mobile terminal.

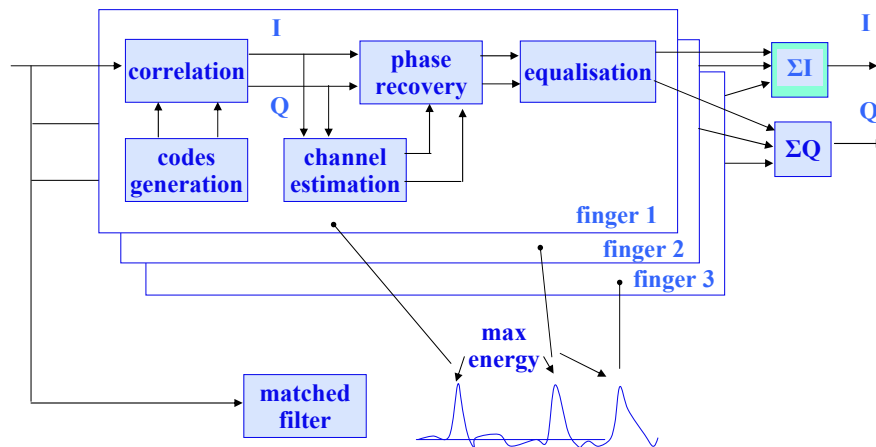
On the receiving side, first of all the delays accumulated by any single replica of the signal must be identified.

Only the replicas (fingers) showing the highest energy are considered. The power control is in charge of maintaining this energy more or less constant, in spite of the fast fading effects.

The granularity according to which the rays are identified is of the order of the *chip* period ($0.26 \mu\text{s}$). The estimate of the energy peaks is done by a match filter which chose the rays to be assigned to the specific connection.

The correlation function performs the *de-spreading* of any single replica. The various contribution phases are then aligned by making use of the channel estimate of the pilot channel.

Rake receiver, fingers, correlation



18

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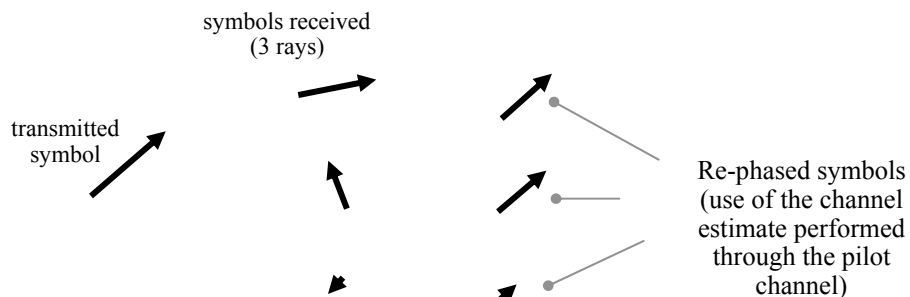
On the receiving side, the pilot symbols generated on the transmission side and allocated over the associated control channel are used. The channel estimate uses exactly these symbols. It recovers the right phase of the symbols. The delay between the various fingers is compensated by making use of the time difference arising between the various replica of the signal (the *highest energy* replica). Each ray is then summed-up constructively (maximum ratio combining).

The combiner acts on the two original flows I and Q respectively.

It can be noted how, after the demodulation, the matched filter, identifies the replicas showing the maximum energy. The most significant *paths* are assigned to the pool of correlation chains in such a way.

Filter, correlation device and codes generator operates at the chip level; channel estimate and phase recovery act instead at the symbol level.

All the scheme refers to a single connection. We'll see how each source is identified by a scrambling code while the single connection is associated a single spreading code.



UTRAN - the ETSI decision

- **W-CDMA access, FDD duplexing in the paired band**
- **TD-CDMA access, TDD duplexing in the unpaired band**
- **Parameters should be optimised so as to guarantee:**
 - **Low cost terminals**
 - **armonisation with GSM**
 - **Dual mode TDD/FDD terminals**
- **The system has to work with a minimum bandwidth assignment of 2x5 MHz (FDD component)**

The decision about the radio access scheme has been taken by ETSI in January 1998 after one-year evaluation performed by ad hoc groups which investigated different techniques (Wideband CDMA, Wideband TDMA, Orthogonal frequency division Multiple Access, Time Division CDMA, Opportunity driven Multiple Access).

The two UMTS Transmission Radio Access (UTRA) components are based on different access techniques. The Frequency Division Duplex (FDD) scheme is used in the paired band of the available spectrum, while the Time Division Duplex (TDD) scheme is defined for the unpaired band. A full compatibility between the two systems will be guaranteed.

At the same time another compatibility requirement has been considered: the harmonisation with GSM. This leads to the possibility to have multi mode terminals UTRA FDD, UTRA TDD, GSM900, GSM1800 and maybe others.

Main parameters

	UTRA/FDD	UTRA/TDD
Access technique	WCDMA	Hybrid WCDMA+TDMA
Chip rate	3.84 Mcps (SF FDD:4-256, TDD 1-16)	
Carrier spacing	4.4-5 MHz (200 kHz carrier raster)	
Frame duration	10 ms	
N. slot per frame	15	
BTS synchronization	Not required	Not required (advisable)
Modulation	DL: QPSK UL: Dual-code BPSK	DL: QPSK UL: QPSK
Coherent receiver	Uplink e downlink	
Multi-rate	Variable SF + Multi-code + Multi-slot (TDD only)	

20



The ETSI decision to harmonise the two UTRA components had an impact on the related parameters:

- chip rate,
- slot and frame duration
- modulation and filtering functions

This does not solve the problems of having two different access techniques, but it is a good way forward to reduce the complexity and cost of dual mode terminals and equipment.

The TDD and the FDD mode differs mainly on the access technique.

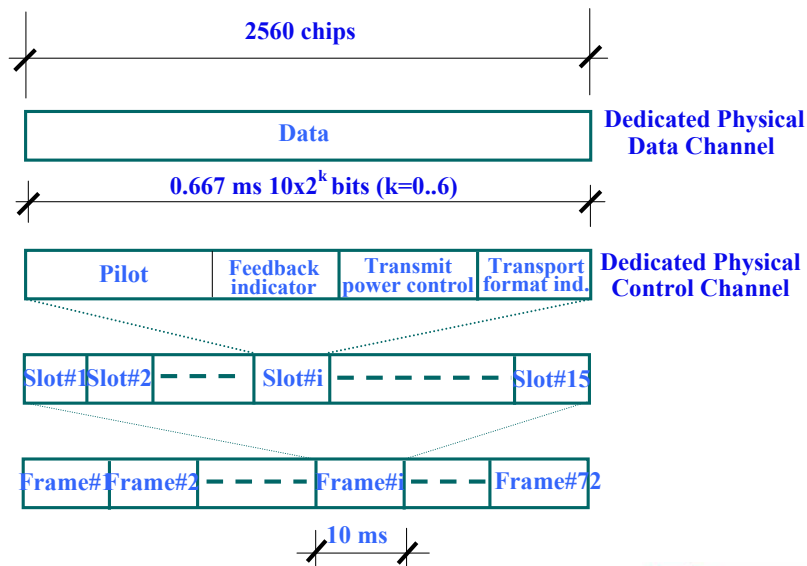
Of course there are other differences, but they are more related to the resource management and to some procedures like power control and handover.

Both FDD and TDD modes are based on a wideband CDMA technology, whose basic chip rate is 3.84 Mchip/s. Spreading widths of 2x3.84 and 4x3.84 Mchip/s are also foreseen.

Multi-layer structure (pico, micro and macro cells) can be realised by assigning different CDMA carriers to the different layers.

Within the same layer, the same frequency is reused within all the cells.

Layer 1 - up link physical channels



21

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Layer 1 services refer typically to the transport role; a transport channel is specified by the way (e.g. bit rate and delays) adopted to transport the data offered by the upper layers; this role is played by making use of physical channels, directly defined on the physical structure of the radio interface.

The figure represents the up link physical channels specified in ETSI for the W-CDMA scheme.

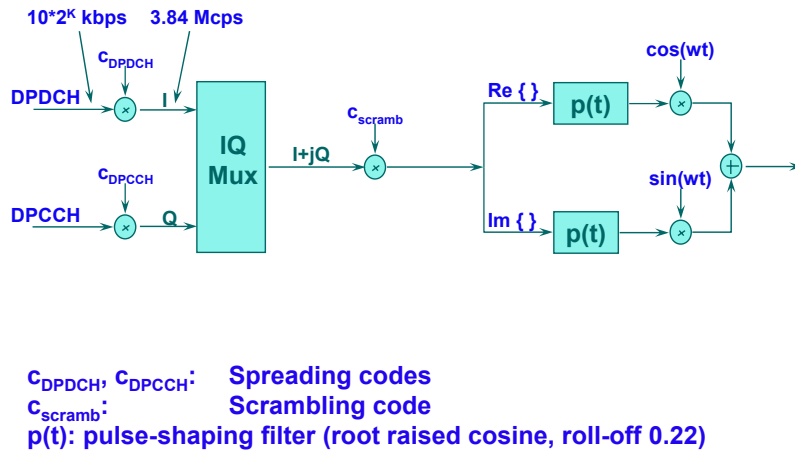
On the up link, two type of physical channels are identified, namely dedicated physical channels and common channels. The dedicated channels are:

- the Dedicated Physical Data Channel (DPDCH) used to carry the data (user or control data) generated by the MAC and upper layers
- the Dedicated Physical Control Channel (DPCCH) used to carry control information generated at Layer 1; specifically:
 - pilot symbols for the channel estimate;
 - transmission power control information
 - the transport format indicator (which specifies the configuration of encoding, interleaving, bit rate and physical channel mapping applied to the transport channels);
 - the feedback information channel, controlling the transmission diversity of the base station.

A single common channel is defined on the up link, namely the Physical Random Access Channel (PRACH), offering the early access capabilities to the MSs. The PRACH is based on a Slotted Aloha concept; the access slots are defined on the depicted frame structure and the broadcast channel reports the needed information about the PRACH that can be accessed in that particular cell.

Both DPDCH and DPCCH obey the frame structure depicted in figure; the frame is a 10 ms frame, split in 15 slots, each one lasting 0.667 ms, corresponding to a power-control period. The spreading factor can vary from 4 to 256.

Modulation and Spreading - Uplink



22



Physical Data and Physical control channels undergo two kinds of coding in both the up and down link.

Orthogonal Spreading Factor Codes are used as Channel Codes for both Data and Control Channels on the up link (*channel* and *spreading* are used as synonymous). They identify the single channel and can be assigned without any co-ordination between the MSs and may be re-used for different mobiles. Different codes are used for Data and Control Channels.

Scrambling codes allow to identify any single source of information (the MS and the BTS respectively). Scrambling codes may be either short or long codes (the latter can be used whenever interference cancellation is not used on the receiving side).

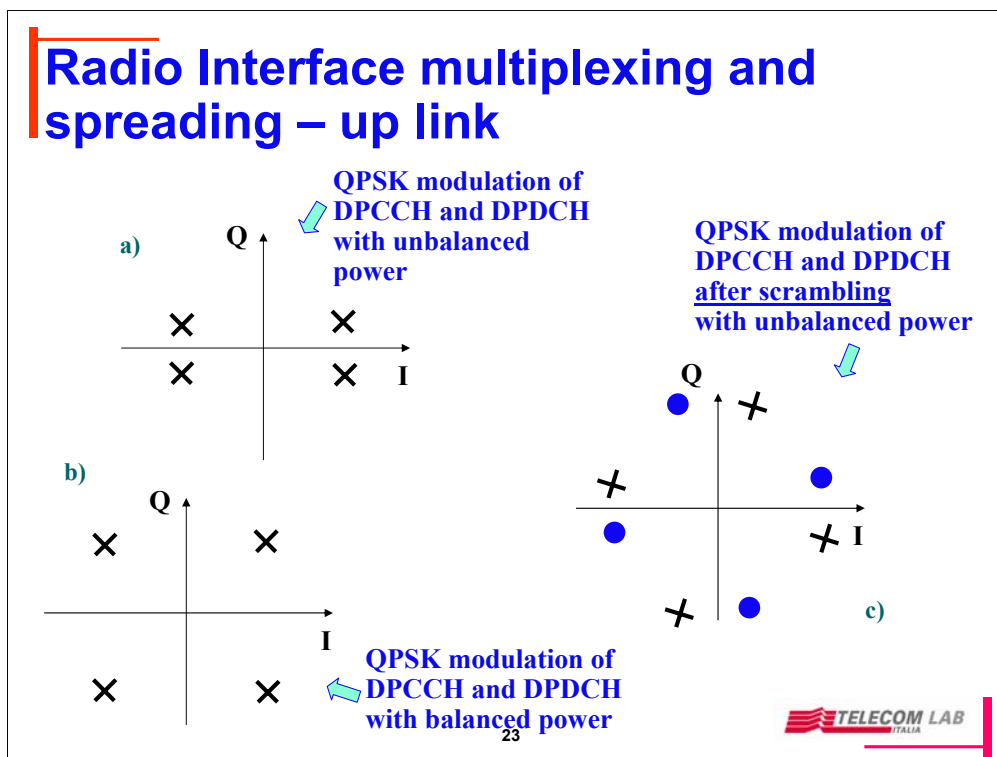
It is in fact possible to spread the information signal by means of a channel code e.g a spreading factor 128 and then to improve the correlation properties of the signal performing a scrambling (i.e., multiplying the spread signal with a PN sequence). In such a way, the PN sequence gives to the original coded signal the appearance of nearly white noise.

The modulation is as 2 dual channel QPSK” where DPDCH and DPCCH are mapped to the I and Q branch respectively. The I and Q branch are then spread to the chip rate with two different spreading codes c_D and c_C and subsequently complex scrambled by a mobile station specific complex scrambling code c_{Scramb} .

For multi-code transmission, each additional uplink DPDCH may be transmitted on either the I or the Q branch. For each branch, each additional uplink DPDCH should be assigned its own channel code.

The spreading factor of the DPCCH is 256. A single DPCCH may control one or more dedicated channels (DPDCH) belonging to the same up-link connection. The DPDCH uses spreading factors that can be varied with a frame pace (10ms).

The dedicated channel supports *soft handover* features and requires a fast power control. Conversely, the common control channels *soft handover* mechanisms are not implemented, but some of them adopt the fast power control.



On the *up link* the terminal amplifier must have a high efficiency. For this reason, a continuous transmission has been chosen, which multiplexes *in code* (not in time) data and control channels. This choice avoids the transmission in the low frequency band (with the relevant problems caused in the GSM system).

In addition, it indirectly allows to reduce the *peak-to-average* ratio under which the amplifier has to work.

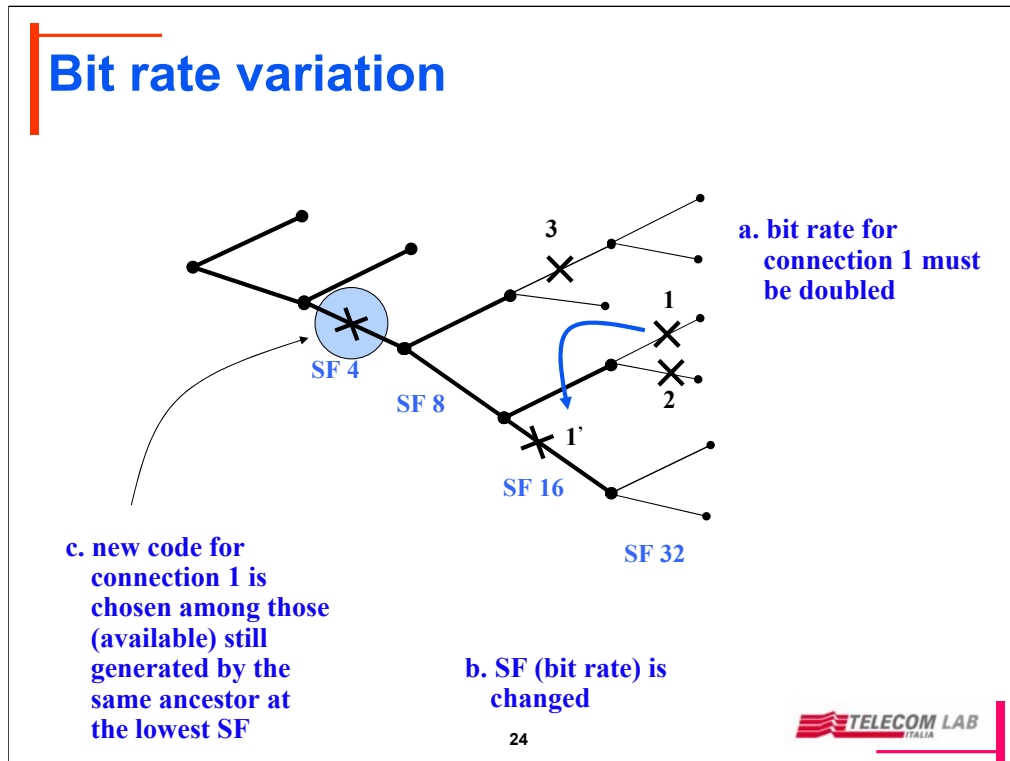
The data channel DPDCH (In phase) and the control channel DPCCH (in Quadrature) are then assigned 2 spreading codes and multiplexed by using the two In phase and Quadrature components.

Figures a) e b) show how, using a canonical QPSK modulation, a great power un-balance would contribute to increase the transmission *peak-to-average* ratio.

The complex scrambling codes improve the situation. First, the *scrambling* sequence is chosen in such a way that rotations of $\pm\pi$ in the symbol period are avoided (only $\pm\pi/2$ rotations are generated). Moreover, the *complex spreading* leads even with an unbalanced power, to a limited *peak-to-average* ratio in the amplifier input. In fact, the possible constellation points used for the transmission belong to either if the two rotated QPSK constellations of figure c). This happens even if the power is not balanced.

With balanced powers the two constellations would become a single one.

The *scrambling* codes may either be long or short codes. They do not need to be planned on the *up link* direction.



A signal that has been assigned a scrambling code inducing a given *spreading factor* may be de-spread through 2 phases:

- in the first phase, a channel code with a low *spreading factor* is used, provided that it is an ancestor of the assigned code
- in the second phase the correct *spreading factor* is applied, to obtain the original signal.

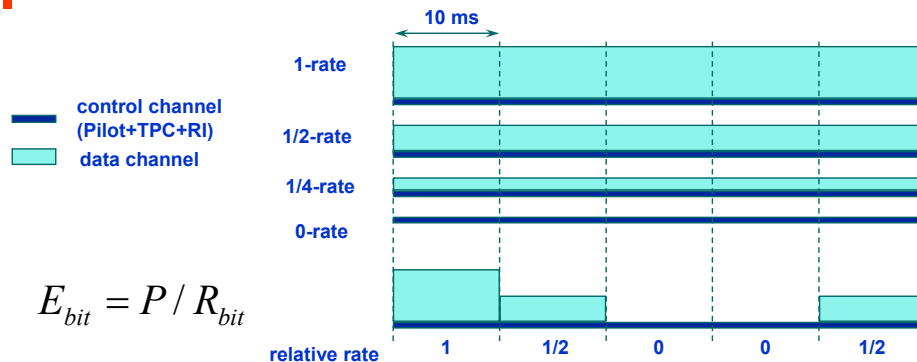
This feature is used in the rake receiver to manage the bit rate modifications arising along the same connection in a simpler way.

The *bit rate* on the *up link frame* is activated through the SF with a maximum pace that coincide with the frame period.

To simplify the *de-spreading* operation, the code change is typically performed by keeping unchanged the minimum SF (SF=4). In fact, under this condition, the correlation phases in the *rake receiver* don't have to be updated since they are performed in two phases, as described (sequence a, b, c in the figure).

Long spreading codes are applied to receivers of the kind described. They are obtained by high degree generator polynomials but they are anyway truncated at 38400 *chips*, equivalent to a frame interval (38400 *chip* every 10 ms).

Up Link Variable Rate



Lower connection bit rates admit (require) higher spreading factors:

- target E/N_0 maintained by reducing accordingly the transmitted power
- bit rate can change every 10 ms (frame)
- transmission continuity granted by the dedicated channel

25

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In CDMA systems the interference reduction leads automatically to a capacity increase. It is then very important to exploit every opportunity that allows a transmitted power reduction, as the information source silences.

The WCDMA component adopts two different techniques for up and downlink.

On the uplink, in order to avoid synchronisation recovery problems, a signal is always transmitted, without any silence.

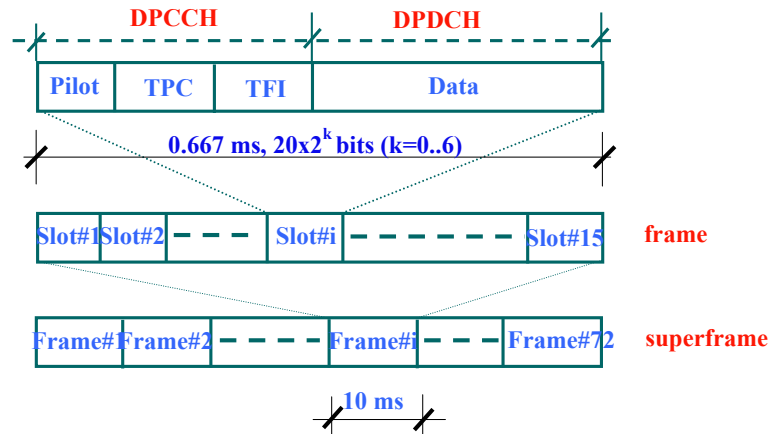
In case of low bit rates, a higher Spreading Factor is used, reducing the needed power to a level lower than the one used in case of full rate transmission. In fact, in order to meet the same E_b/N_0 target, if we reduce R_b , we have to reduce also the transmitted power P ($E_b = P/R_b$).

When source is completely silent (no information to be transmitted), the transmission continuity is guaranteed by the transmission of the DPCCH, owing to the information it is carrying.

The minimum granularity of the variable bit rate is equal to the CDMA frame length (i.e., 10 ms)

Different connections can then use different rates and the rate of a connection can be changed along the connection itself. The change of bit rate may also imply the modification of the mapping between transport and physical channels, whose configuration is controlled through the Transport Format Indicator.

Layer 1 - down link physical channels



26

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Also for the down link, dedicated and common physical channels are foreseen. Common physical channels are not represented in the figure. In the dedicated channels, data information generated at Layer 2 or above, are time-multiplexed with the control information generated at Layer 1 (pilot, power control and transport format indication).

The frame structure is the same as for the up link. Whenever the total bit rate of a connection exceeds the maximum allowed bit rate for a single DPCH, a multi-code transmission is adopted, employing more than one DPCH for that connection; if a single spreading factor is used for each DPCH, the Layer 1 control information is associated to one only of the physical channels: the other does not transmit in the corresponding slot period.

The common physical channels defined on the down link are:

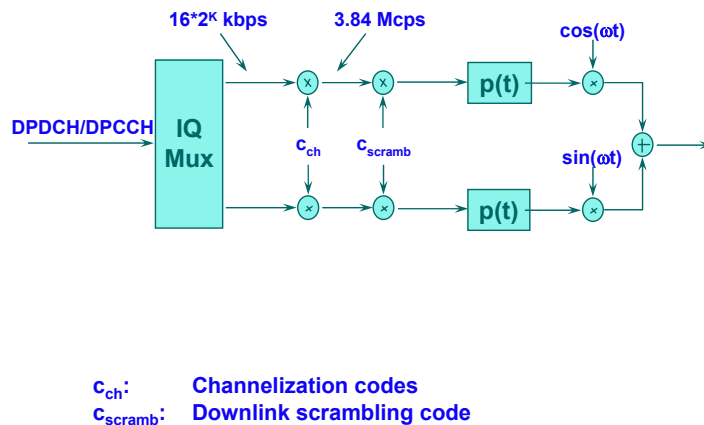
- the primary Common Control Physical Channel used to carry the Broadcast Channel (BCH)
- the secondary Common Control Physical Channels, used to carry the Forward Access Channel (FACH) and the Paging Channel (PCH); FACH is used to transmit mobile specific control information and short packets.

Both primary and secondary common channels obey the frame structure described for the dedicated channels; the only difference is that for the Common Channels, the single slot includes only two data fields, containing the pilot and the data information respectively; both primary and secondary control channels adopts a fixed bit rate, which is defined at system level for the former and at a cell level for the latter (the cell BCCH informs the roaming mobiles about the secondary channel bit rate).

A primary and a secondary synchronisation channels are defined on the down link and transmitted with specific codes synchronously with each BCH slot; the former is unique for all the system, the latter identifies the scrambling code associated to the specific station.

The Downlink Shared Channel (DSCH) is used to transmit packet traffic scheduled by the base station according to the traffic originated by the users. A dedicated channel used to carry the physical layer control information is always associated to DSCH.

Modulation and Spreading - Downlink



27

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Each pair of two bits are serial to parallel converted and mapped to the I and Q branch respectively. The I and Q branches are then spread to the chip rate with the same channel code c_{ch} and then scrambled by the same cell specific scrambling code C_{scramb} .

On the down link, different scrambling codes identify different base station. In general, however, more than one scrambling code can be assigned to the same base station. This is done whenever there are limitations due to the limited availability of the channel codes. The assignment of scrambling codes to the stations may induce code management problems between the various base stations.

The use of the channel codes on the down link is similar to that already described for the up link. However in this case, the entire set of orthogonal codes is shared between the entire set of mobiles belonging to the same cell.

An allocation policy is then needed within the cell. It could involve in general the level of the assigned code (spreading factor) with respect to the connection bit rate and, possibly the adoption of multi-code connections.

On the *down link* a QPSK modulation is used. Being the data channel and the control channel multiplexed in time, to limit the interference, a *discontinuous transmission* technique is used.

On the *down link* the *spreading factor* is not changed. It is instead used the bit rate adaptation mechanisms (*rate matching*) associated to the discontinuous transmission.

Radio Interface multiplexing and spreading – down link

same SF changing mechanism (as for the up link) applied to the shared channel

code-planning in the down link

scrambling code re-use (512 codes available)

28

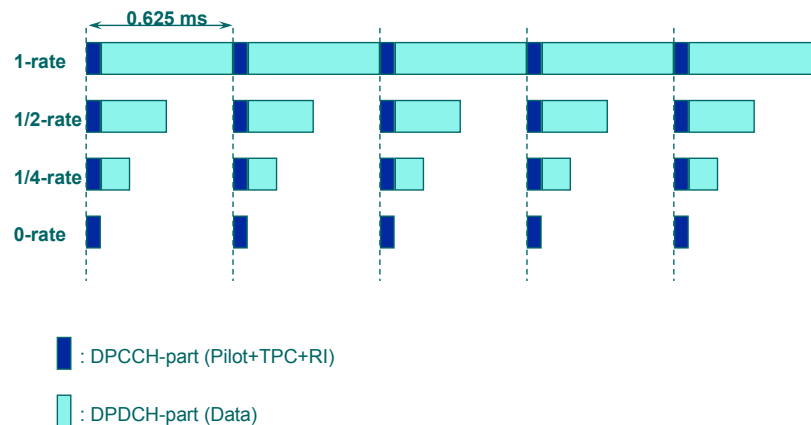
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- being the source a single one, there are no critical conditions for the *peak-to-average ratio* encountered for the up link
- the spreading codes are a scarce resource in the down link, where in principle, a single orthogonal code tree is available for all the connections in progress within that cell (sector): employing an orthogonal code for the dedicated control channel would be a useless waste of resources.

Each connection can use more than one transport channel, where more than one channel codes are used. The same SF is used per each transport channel, however different transport channels can use different SFs.

On the down link, secondary scrambling codes may be used. Each identifies a single dedicated channel. These codes do not impact on the planning of the primary scrambling codes (512).

Downlink Variable Rate (DTX based)



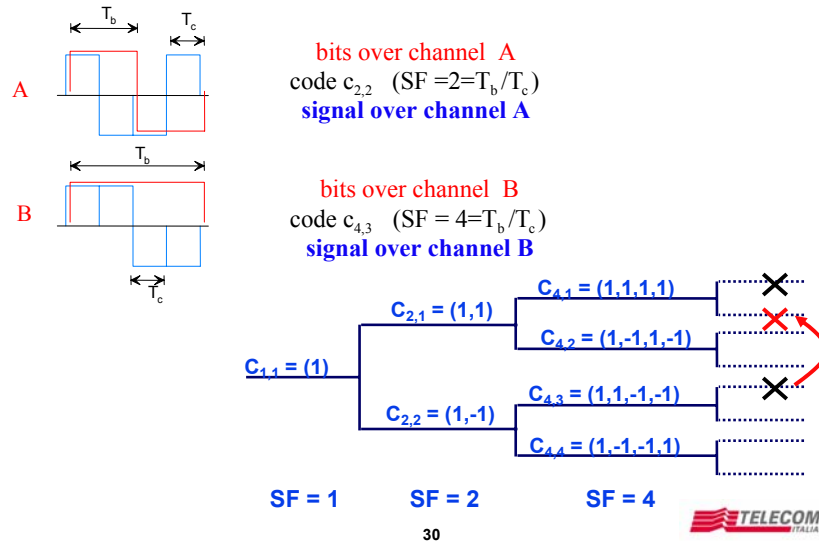
29

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As said, on the down link, Data and Control channels are time multiplexed. With the same spreading factor, variable bit rate within the same Physical Channel is managed through a discontinuous transmission mechanism, as depicted in the figure.

High bit-rate connections require a multi-code transmission, making use of more than a single spreading code per user. The multi-code transmission is normally adopting a single spreading factor.

OVSF Codes conditions and re-arrangement (code handover)

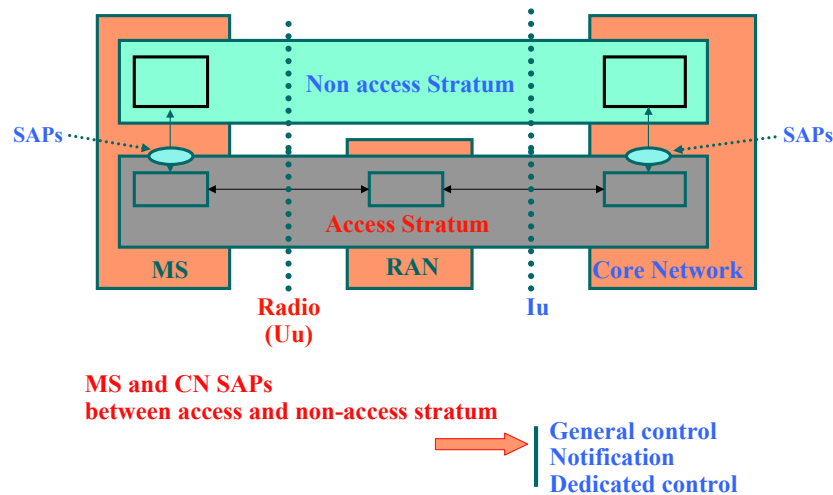


A single source may use at the same time different channel codes showing a different spreading factor. This is true provided that the codes belong to different branches of the tree (see the example built-up on the channels A and B).

The inefficient use of the spreading codes may cause the shortage of the code *resource*. In many cases code handover procedures can be activated to improve the code accessibility.

The code rearrangement shown in figure enlarges the possibility of using for the subsequent connections codes with a *spreading factor* 4 and 2.

Radio Interface - reference architecture



31

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It is useful at this stage to introduce the radio sub-system choices that have been performed in the context of UMTS Standardisation.

The radio interface is normally embedded in a framework where access functions are logically separated from the non-access functions.

The latter are played typically in a direct relation between the mobile and the Core Network.

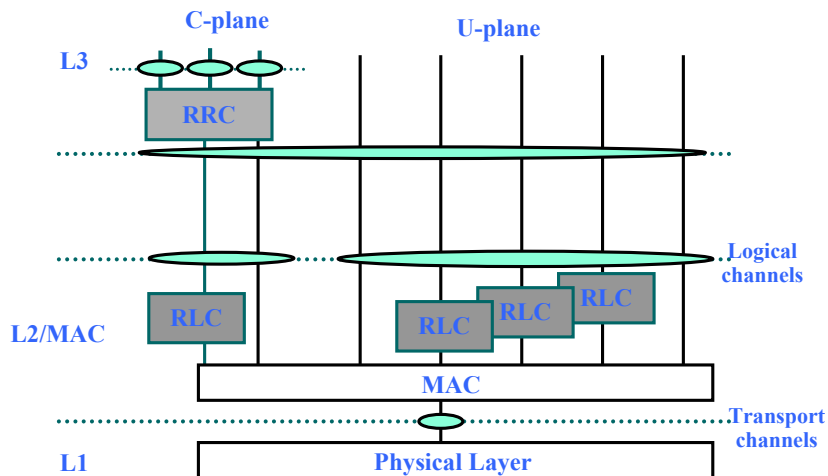
The very general scheme is shown in the figure; the access stratum supplies a defined set of services to the non-access stratum; this is done through appropriate Service Access Points (SAPs).

The scheme anticipates some typical issues arising in the third generation network architecture definition, specifically the definition of the radio dependent/independent part of the architecture.

Functions and signalling relations arising between the Mobile Station (MS) and the Radio Access Network (RAN) in the Access Stratum tend to be radio technology dependent, while those arising between MS and the Core Network (CN) should be radio technology independent in the sense that they should remain unchanged, whatever the radio access technique is.

The uniqueness of the Iu interface between the radio access network and the core network reflects the ITU position about the Basic IMT2000 System Model, aiming at the compatibility between different radio access systems.

Radio Interface - protocol architecture



32

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The relationship between the mobile and the network is normally seen through the radio interface. It specifies how the information that has to be exchanged between those two entities (both user data and signalling information) has to be organised in a layered framework.

Note that the radio interface is not directly specifying the end points of each protocol layer in the network: the allocation of the protocol end-points termination obeys network efficiency and performance criteria that will be discussed.

The physical layer implements all the services and functions needed for the transfer of signalling and data information; from a radio resource viewpoint, the basic role of L1 is to map the transport channels to the radio physical channels.

The MAC layer offers the transport service to the upper layers, in line with the defined attributes.

The Radio Link Control Protocol (RLC) offers services and functions that are ensuring the correctness of the data transfer (ARQ functions) and performs the data segmenting/re-assembling features. This protocol could in principle be embedded in the MAC protocol.

The upper layer 2 consists in supplying retransmission features mainly in relation to handover and macro-diversity requirements.

Layer 3 contains, at least in the radio access segment on the C-Plane, services and functions related to the control of the radio resources.

Mapping transport channels onto physical channels

<u>Transport Channels</u>	<u>Physical Channels</u>
DCH	Dedicated Physical Data Channel (DPDCH) Dedicated Physical Control Channel (DPCCH)
RACH	Physical Random Access Channel (PRACH)
CPCH	Physical Common Packet Channel (PCPCH) Common Pilot Channel (CPICH)
BCH	Primary Common Control Physical Channel (P-CCPCH)
FACH	Secondary Common Control Physical Channel (S-CCPCH)
PCH	Synchronisation Channel (SCH)
DSCH	Physical Downlink Shared Channel (PDSCH) Acquisition Indicator Channel (AICH) Access Preamble Acquisition Indicator Channel (AP-AICH) Paging Indicator Channel (PICH) CPCH Status Indicator Channel (CSICH) Collision-Detection/Channel-Assignment Indicator Channel (CD/CA-ICH)

33

The figure represents the allocation of the transport channels over physical channels. This is performed at the MAC layer as specified.

Many physical channel exhaust their role at this level, hence they do not have equivalent channels at the transport layer.

The physical channels CSICH and CD/CA-ICH are necessary just when the *Up link Common Packet Channel* (CPCH) is present.

Transport channels (example)

- **Dedicated Channel (DCH):** fast change of bit rate (10ms)
fast power control
inherent MS addressing
- **Random Access Channel (RACH) - up link:** collision
open loop power control
explicit MS addressing
- **Broadcast Control Channel (BCH) - down link**
- **Forward Access Channel (FACH) - down link:** slow power control
explicit MS addressing
- **Paging Channel (PCH) - down link:** use of sleep modes

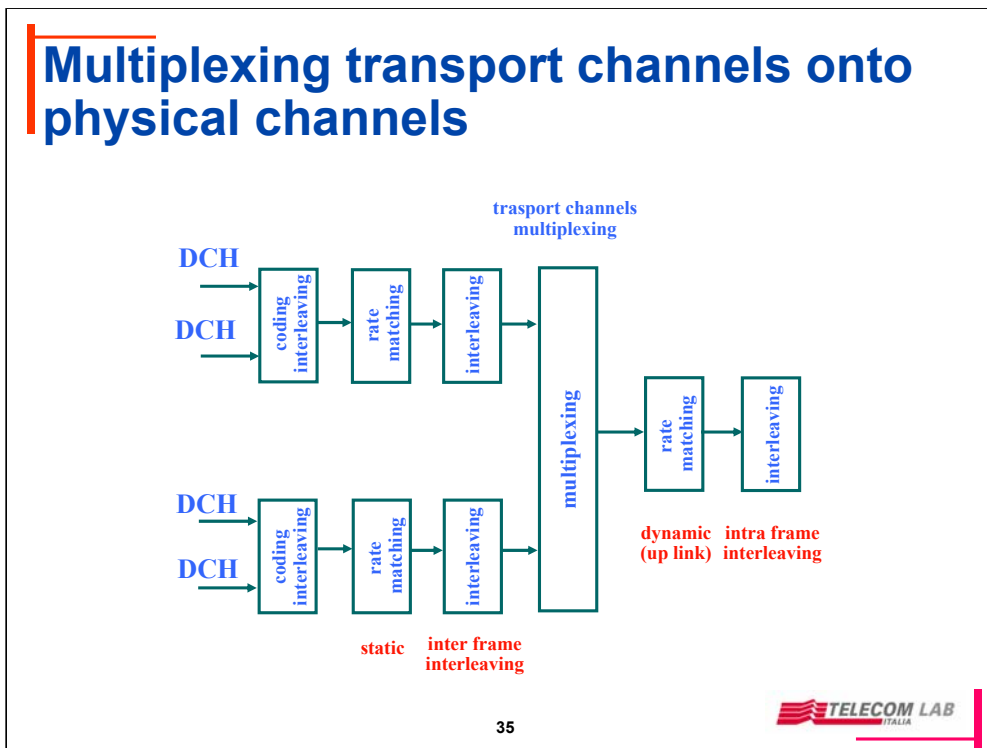
34



The transport channels of the UMTS associated to the physical channels previously introduced are listed in this figure.

Each transport channel has its own transport format specified by the *Transport Format Indicator*.

The transport format belongs to a family of possible formats that cover a wide set of possibilities.



At Layer 1, the Dedicated Transport Channel, in general undergoes some processing before being mapped to physical channels and transmitted (after spreading); the basic process steps are shown in the figure.

Several transport channels can be multiplexed before being mapped to one or more physical channels.

Channel coding is performed in general per each transport channel independently; several options are available for the coding algorithm (convolutional, Reed-Solomon, turbo coding) that can possibly be use in conjunction.

Different transport channels can possibly be interleaved. The static rate matching is performed at a slow pace, typically when a transport channel is added or removed from the pool of jointly transmitted transport channels. This process is done in order to fulfil the transmission quality requirements of each transport channel, by maintaining at the same time a uniform bit energy per each channel.

Another role of the static rate matching is to adjust the (coded) channel bit rate in accordance with the available bit rate of the dedicated physical channels.

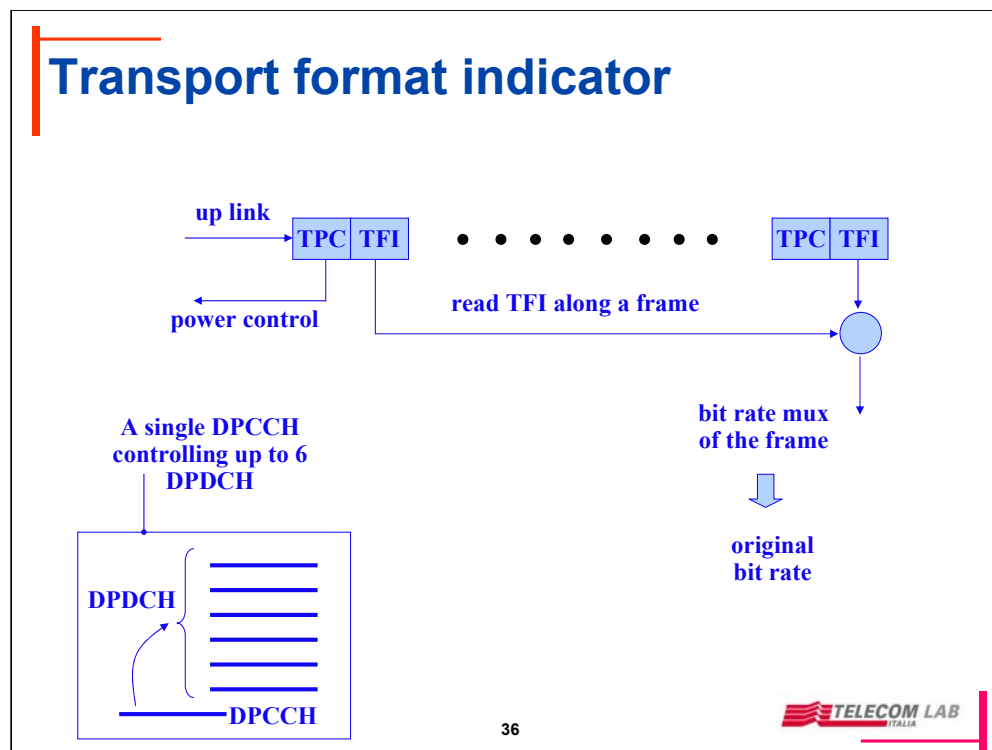
The dynamic rate matching is performed on the up link, after multiplexing, to adapt the instantaneous bit rate of the multiplexed transport channels to the bit rate of the dedicated physical channel (s); on the down link, DTX is used to cope with bit rate misalignments; both static and dynamic rate matching use unequal repetition techniques.

The transport channel multiplexing is performed on a time-division basis, within a radio frame.

Inter frame interleaving is performed within a single transport channel over more than one frame for those services that require this kind of mechanism.

An inter-frame *interleaving* (over more than one frame) is used for those services that require this *time spreading* mechanism for protection purposes. The intra-frame *interleaving* is applied instead to the transport channels before multiplexing.

Transport format indicator



It is the *Transport Format Indicator* that informs the receiving side (BS) about the *bit rate* (SF) used on the dedicated channel. TFI is particularly protected at the coding level: its loss would imply the loss of the data transmitted along an entire frame.

The use of multiple channels on the *up link* can admit up to 6 channels (codes) associated to the same communication. The minimum *spreading* is equal to 4 (960 Kbit/s). 6 channels can then transport up to 6Mbit/s.

On the receiving side (BS) the DPDCH is de-coded (*de-spreading*) with the minimum *spreading* factor (as if a maximum bit rate signal had transported on the DPDCH). The result of the de-coding is stored for 10 ms, to allow the receiver to interpret consistently the TFI.

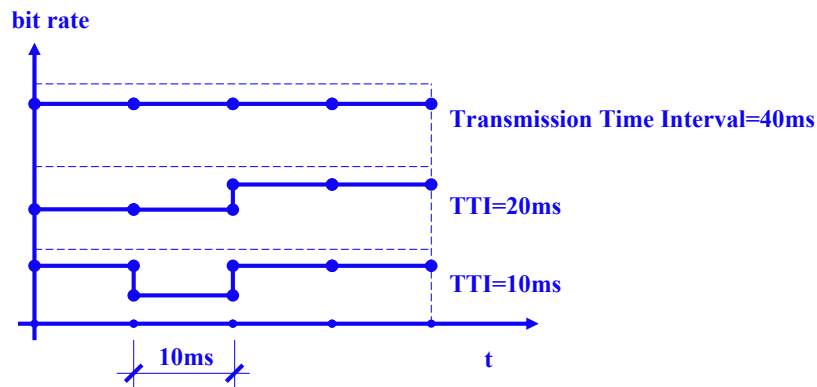
At the end of the frame (10 ms) the receiver is able to decode the DPDCH according to the effective SF and it can also understand all the data concerning the transmission configuration used on the *up link*.

These operations are performed frame by frame provided that the interleaving depth coincides with the frame length. The system can use greater *interleaving* depths, corresponding to 2, 4, 8 frames. In these cases the DPDCH re-construction induces a greater latency. The *interleaving* depth corresponds to the *Transmission Time Interval* namely to the period of time that has to elapse so that all the bits are stored to be transmitted over the physical layer.

The power control data are used slot per slot (see the extension about the power control).

For the *down link* channels the same sequences at the slot level hold. On the *down link* however, the *bit rate* is constant.

An example



37

On the *up link* all the services related to the same connection are transmitted at the same power. It is needed to balance the bit rate of each service on the power level by acting on two parameters:

- *interleaving*
- *rate matching*.

The former is typically used in two phases. First the inter frame period is tuned (10, 20, 40, 80 ms). Different services can use different depths in function of the error and latency constraints. An interleaving synchronisation is anyway needed between the different flows (services). In the figure, 3 services are using different *interleaving* depths, corresponding to different *Transmission Time Interval*.

The *rate matching* function is used to ensure that the transmission is as far as possible uniform along the frame. This is useful for the transmission efficiency (reduction of the *peak-to-average* ratio): the PDPCH is dropped just when the source has nothing more to transmit (just the control channel remains active).

The rate matching typically acts through the repetition of the information content.

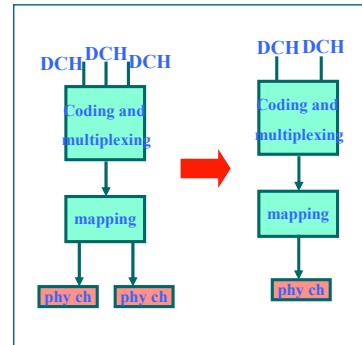
After the second *interleaving*, performed with frame depth, the frame uses all the bits that can be used in function of the SF assigned.

MAC Services and Functions

- set-up, release of logical channels
- data transfer service on logical channels
- allocation/re-allocation of radio resources
- measurement report

Functions ↓

- Selection of the transport format
- Handling of priority within one user/between users
- Scheduling of control messages (broadcast, paging, notification)
- Multiplexing/de-multiplexing of higher layers PDUs on/from common or dedicated transport channels
- Contention control on the random access channel



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38

The MAC layer manages the mapping of the logical channels to the transport channels by controlling the mapping/multiplexing mechanisms previously introduced.

The transport format is chosen within the set of available transport formats.

Priorities are handled by choosing the appropriate transport formats; for instance, data with high priority can use a high bit rate format; the same solution can be adopted for data which have accumulated a high delay in the upper layer queues.

On the down link, still the transport formats can be used to fulfil different priority requirements arising between different users.

Most of the functions listed in the figure may require an exchange of signalling information between MAC layers belonging to MS and the relevant end point in the access network.

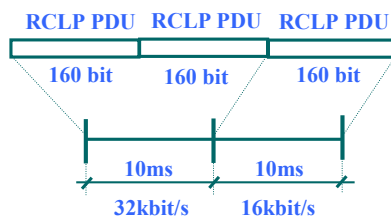
Contention control is related to the collision event that may arise on the random access channel. Contention is detected by Layer 1 and possibly resolved by Layer 3.

Retransmission Protocol - services and functions

- Layer 2 connection set-up and release
- transparent data transfer
- unacknowledged data transfer
- acknowledged data transfer

Services of RLC

Functions



- connection control
- segmentation and re-assembly
- error detection/recovery and in-sequence delivery
- transfer of user data
- flow control
- duplicate detection
- QoS adaptation

39

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The layer 2 functions residing above the MAC layer, take the role of controlling the data transfer of any connection; to do so they supply error correction, retransmission, combining and multi-casting when needed.

These roles are performed by the Radio Link Control (RLC) functions.

RLC controls the transfer of user data; in sequence delivery; segmentation and re-assembly mechanisms; Automatic Repeat Request (ARQ) functions.

Through the above mechanisms, RLC supports upper layers with:

- acknowledged mode operation (ARQ and variable bit rate)
- unacknowledged mode operation (variable bit rate)
- transparent mode operation (no RLC service)

An example of segmentation function is reported in the figure; in this case the RCL service allows to transmit with different rates, RCL data PDUs, according to the need of the traffic source; the bit rate can be changed every frame period (10 ms).

The above services are used to supply assured, not-assured and transparent transport services to layer 3 PDUs.

Radio Resource control - services and functions

- Broadcast of information | provided by the Core Network related to the access segment
- Set-up, maintenance and release of an RRC connection
- Set-up, maintenance and release of radio bearers on the user plane
- Assignment, reconfiguration and release of radio resources for the connection
- Arbitration of radio resource allocation between cells
- RRC connection mobility functions
- Quality of Service control and radio resource allocation among the cells
- Admission and congestion control
- Control of the MS measurement reporting

40



The basic requirements for the Radio Resource control refer to:

- the need for broadcasting messages to the MSs in a given area (general control provided on the General Control SAP)
- the need for notifying paging messages and other mobile-specific information within a given area (notification control provided on the Notification SAP)
- the need for setting-up and releasing connections (point-to point or multiparty connections provided on the Dedicated Control SAP); for each control it must guarantee:
 - the correct transfer of messages along the connection
 - the correct management of priorities between signalling and non-signalling messages (e.g. short messages) sharing the same control channels.

The RRC connection is a signalling connection between the MS and the Radio Access Network.

The control of radio bearers includes the execution of the admission control algorithms and may include the setting-up of the radio parameters for Layers 1 and 2; this choice heavily conditions the splitting edge between radio dependent and independent functions that will be discussed in the following.

The control of radio resources for the connection is tied to the allocation/de-allocation of resources also along the same connection.

The RRC mobility functions refer also to handover and macrodiversity.

TD-CDMA characteristics

Multiple access scheme	TDMA/CDMA
Channel spacing	5 MHz
Carrier chip rate	3.84 Mchips/s
Spreading factor	1-16
Frame length	10 ms
Multirate concept	multislot /multicode
Modulation	QPSK
Burst Types	burst 1 long delay spread burst 2 short delay spread
Detection	Coherent, based on midamble

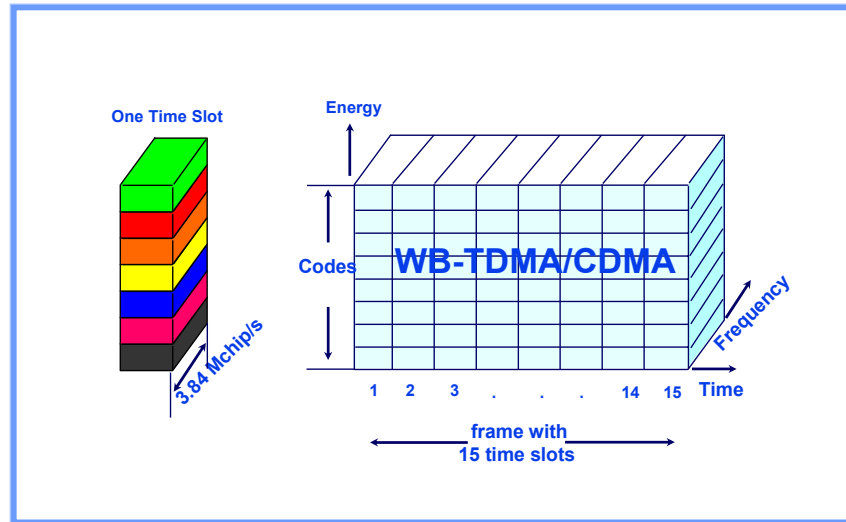
41



The TD-CDMA logical channel structure is similar to that adopted for the W-CDMA case. Traffic channel and control channels are envisaged:

- traffic channel, used to transfer user data or layer 3 signalling data
- control channels, further divided in common control and dedicated channels
 - Common Control Channels
 - BCCH Broadcast Channel (DL)
 - SCH Synchronisation Channel (DL)
 - FACH Forward Access Channel (DL)
 - PACH Paging Channel (DL)
 - RACH Random Access Channel (UL)
 - Dedicated Channel
 - DCCH Dedicated Control Channel-ACCH and SDCCH (DL&UL)
 - DTCH Dedicated Traffic Control (DL&UL)

TDD (TD-CDMA) technique



42

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The *Time Division Duplex* technique is based on an hybrid access TDMA-CDMA.

The time, frame and slot concepts have the same meaning explored for the GSM. A low bit rate connection implies a single slot per frame.

Each slot can transport more than one connection, each associated to a code (CDMA scheme).

The interference cancellation is used within each slot.

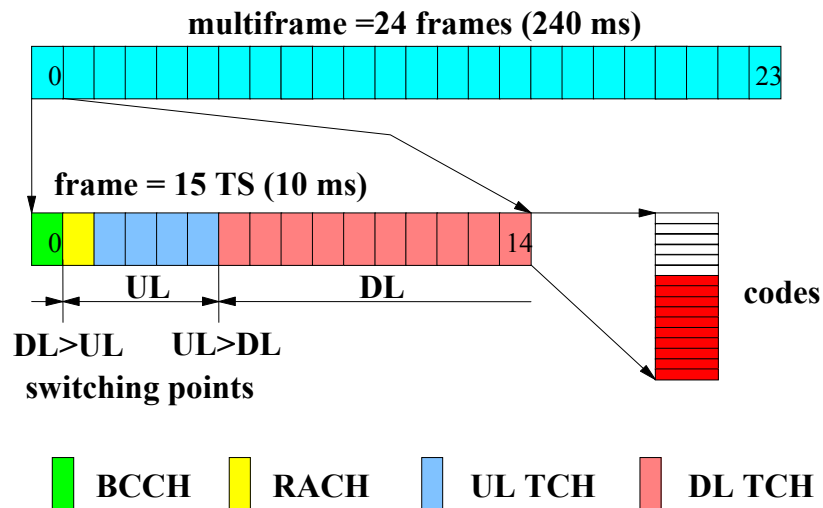
Slot and code resources are combined in such a way that different bit rates are made available, in function of the service requirements.

The codes allocated over a single time slot (0.666 ms) can be associated to the single connection. The number of codes per slot is not fixed but depends on the requested bit rate (*spreading factor*).

The maximum *spreading factor* is 16.

A *scrambling* sequence is used to identify any single cell.

TDD - frame structure



43

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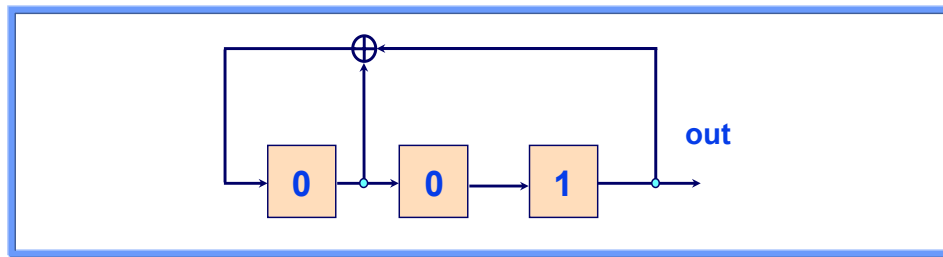
The ETSI proposal for the TD-CDMA access scheme is based on:

- 15 slots per frame; 10 ms frame duration (the same as for the FDD case)
- 24 frames per multi frame; 240 ms multi frames
- switching points between up and down sessions to adapt to the varying UL/DL asymmetric traffic
- 16 orthogonal codes (Walsh) are available for each time slot.

The code management within a given time slot can assign one or more orthogonal codes to a given transport channel.

Multi code/multi slot arrangements are then used to cope with high bit rate services.

Pseudo-Noise sequences



- They are obtained by means of linear shift registers (with feedback defined by a characteristic polynomial)
- A N-cell LSR can provide a PN sequence with period $2^N - 1$
- PN sequences are suitable for multiple access because their autocorrelation function decrease sharply after time shifts of few chips (i.e., equal to zero everywhere but the origin)

44

The *Pseudo Noise* sequences are obtained through linear *shift registers* with *feedback* (characteristic polynomial).

They may supply PN sequences with $2^N - 1$ period if N is the number of stages of the *Shift Register*.

Different sequences show a low correlation, function of their distance along the generation sequence.

They can hence be used to identify different sources.

The sequences should have a zero correlation (zero *cross-correlation*). PN sequences do not have such characteristics but, conversely, they do not introduce any limit in the number of available codes.

TD-CDMA spreading codes and resource allocation

- In the TD-CDMA component a physical channel is identified by a combination of carrier, time slot and code.
- Resources are allocated to cells by means of slow DCA:
 - slot clustering
 - each slot can be used in both uplink and downlink transmission, according to the needs
- resources are allocated to bearers by means of fast DCA:
 - high bit rate services can be provided allocating to a same user several codes in a same or different time slots.

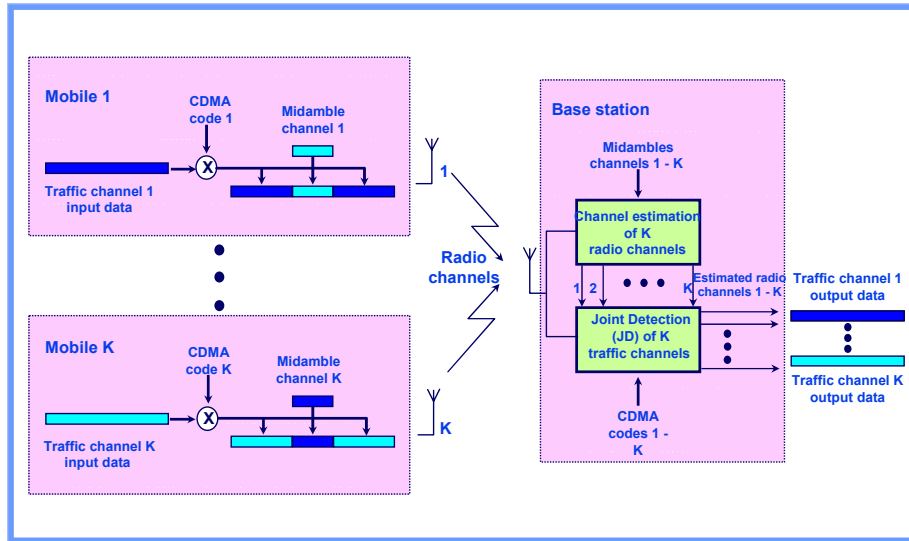
45

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Each connection (original bit sequence) within a given time slot is spread through a code belonging to the *Orthogonal Variable Spreading Factor* family.

The TDD technique is suited for asynchronous traffic: the time segregation between the up and the down link can be moved in favour of e.g. the down link.

Joint detection basic principle



46

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The *joint detection* technique reduces the mutual interference (in the limit this interference can be fully eliminated).

The receiver knows all the spreading sequences used by the users over a single slot. It jointly demodulates all the signals. The output is a vector of information flows, one per signal.

In a traditional CDMA system, the information flows are detected singularly.

If the joint detection is used on the receiving side, a channel estimate is performed per each flow hence, exploiting the codes knowledge, the signals are separated and independently detected. The output offers the k original flows.