

7.3 Code Time Division Multiple Access

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7.3.1 Designs Rationale

The most popular multiple accessing techniques for cellular systems, Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA), have their own advantages, but also some disadvantages. In TDMA, there is no intracell interuser interference but the high peak-to-average power and the necessary frequency planning or dynamic channel allocation between adjacent cells detract from the utility of this scheme. On the other hand, CDMA excels in just these areas: a constant-envelope signal is transmitted and a cluster size of one can be used. However, a limiting factor in CDMA is intracell interuser interference. To combine the advantages of CDMA and TDMA, Massey (unpublished) proposed a wideband communications system for *indoor* cellular applications called *Code Time Division Multiple Access (CTDMA)* [31]. In particular, CTDMA can yield a peak-to-average power ratio of one and a cluster size of one. Moreover, interuser interference is resolved using the same techniques as the resolving of intersymbol interference in TDMA.

7.3.2 System Description

Code Time Division Multiple Access (CTDMA) incorporates both CDMA and TDMA aspects: whereas the signal sent over the air interface is spread in a CDMA fashion, the processing at the receiver is similar to that of a TDMA receiver. Hereafter, we describe its discrete-time baseband representation (cf. Figures 1 and 2) that will be used throughout this section.

The binary information sequence $b_k[\cdot]$ of user k , $0 \leq k < K$, is encoded and mapped to the complex sequence $x_k[\cdot]$ which has a symbol rate R_X . The sequence $x_k[\cdot]$ is oversampled (or “expanded”) and delayed by Θ_k chips to yield a symbol-level TDMA sequence $d_k[\cdot]$. The sequence $d_k[\cdot]$ is then sent through a linear filter $s[\cdot]$ of length L which is common to all users in one cell. Thus, in effect, $d_k[\cdot]$ has been “spread in time” by $s[\cdot]$, or alternatively $x_k[\cdot]$ has been spread in a DS-CDMA fashion by a spreading sequence $s[\cdot]$ and then delayed by Θ_k chips. The spread sequence $q_k[\cdot]$ passes through a user-specific multipath channel with impulse response $h_k[\cdot]$ and is distorted by additive white Gaussian noise with zero mean and variance $\sigma_z^2 = \mathcal{N}_0$, where \mathcal{N}_0 is the noise power density. The receiver then sees the sequence $r_k[\cdot]$.

In order to separate the users, the receiver of user k passes the incoming sequence $r_k[\cdot]$ through the *aperiodic inverse filter* $v[\cdot]$ [30] of the spreading se-

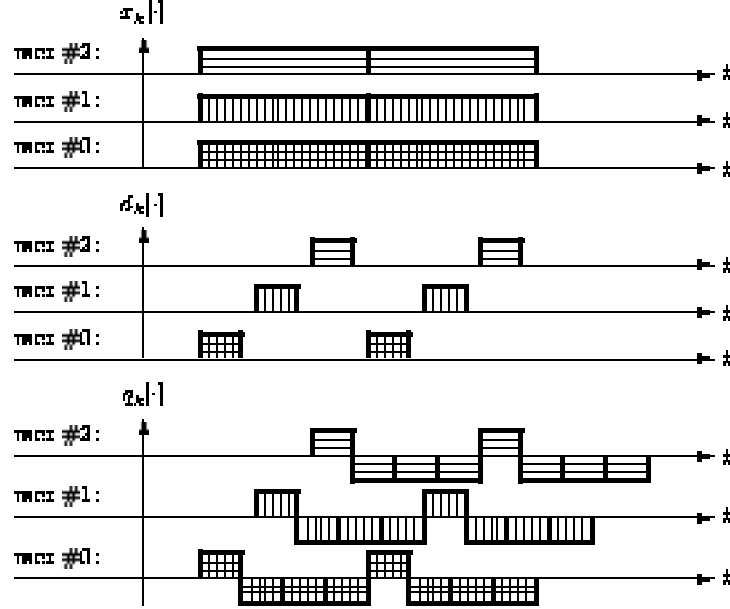


Figure 1: CTDMA example for $K=3$ users: The modulated/mapped information sequences $x_k[\cdot]$ (for clarity, we have only used “+1”-symbols), TDMA separation on a symbol level ($d_k[\cdot]$) and spreading in time by the common spreading sequence $\{+1, -1, -1, -1\}$ of length $L=4$ ($q_k[\cdot]$).

quence $s[\cdot]$. A perfect implementation of the inverse filter $v[\cdot]$ completely reverses the spreading and, if the durations of the impulse responses $h_k[\cdot]$ of the multipath channels do not exceed the TDMA guard time, perfectly separates the users such that there is no intracell interuser interference that usually appears in CDMA.

To assure a constant-envelope transmitted signal for each user, we shall hereafter assume that $|x_k[i]| = 1$ (all i) and $|s[n]| = 1$ (all $0 \leq n < L$), which yields a peak-to-average power ratio of one in the transmitted sequences $q_k[\cdot]$. The TDMA guard time is defined by the *relative user offsets* Δ_k , which are the transmission time differences (in chips) of the two adjacent users k and $k-1$, and which may be dynamically allocated. The *absolute user offsets* are then given by $\Theta_k = \sum_{i=0}^k \Delta_i$ (in chips).

The *aperiodic inverse filter* $v[\cdot]$ is defined by

$$(v * s)[n] = \sum_{l=-\infty}^{\infty} v[l]s[n-l] = \sum_{l=0}^{L-1} v[n-l]s[l] = \begin{cases} 1 & \text{if } n=0 \\ 0 & \text{otherwise,} \end{cases} \quad (1)$$

where we have used the fact that $s[n]=0$ for $n < 0$ and $n \geq L$. In theory, the

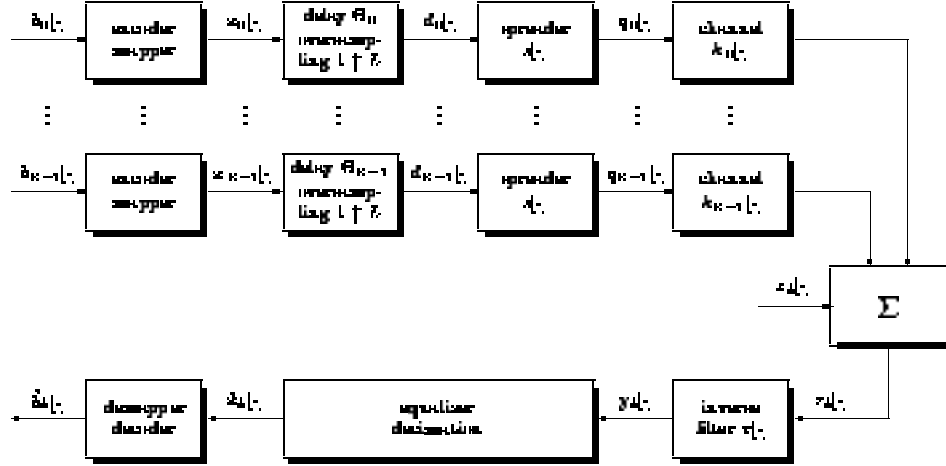


Figure 2: Block diagram of a CTDMA system.

inverse filter completely eliminates the sidelobes that appear in matched filter processing and that is the reason why the matched filter is not recommended in a CTDMA receiver. The drawback of the inverse filter is its poorer noise performance when compared to the matched filter, which is known to maximize the signal-to-noise ratio SNR at the filter output. However, there exist suitable binary (± 1) -sequences where the loss in SNR compared to the matched filter is less than 0.5 dB [30, 31, 33]. This loss is referred to as the inverse filter noise enhancement factor $\epsilon^{\{vs\}}$, which in turn defines the inverse filter processing gain $G^{\{vs\}} = L/\epsilon^{\{vs\}}$. Another drawback of the aperiodic inverse filter is that it has non-zero coefficients $v[n]$ in the entire range $-\infty < n < \infty$ [30]. Therefore, it must be implemented by a finite length approximation $v_N[\cdot]$ [30]. Usually, a length of $N = 3L$ in $v_N[\cdot]$ suppresses the sidelobes in $s[\cdot] * v_N[\cdot]$ well below 40 dB , which is sufficient for practical applications.

CTDMA Receiver Design

In a multipath environment, the transmitted signal propagates via a multipath channel with impulse response $h(t)$, an example of which is illustrated in Figure 3. In environments for which the excess delay is small, i.e., within a few chips, Δ_k may be made large enough to eliminate interuser-interference. More precisely, there is no interuser-interference in a multipath environment if

$$\Delta_k \geq \frac{\max\{\tau_E\}}{T_c},$$

where T_c is the chip duration. Since one may use the same frequency band in all cells, allowing a small increase in Δ_k causes no capacity degradation with respect to the classical schemes FDMA and TDMA that use different frequency bands in adjacent cells. E.g., $\Delta_k = 7$ provides the same capacity as a classical scheme with a cluster size of 7.

As soon as the excess delay exceeds the relative user-shift, however, such as in hilly terrain where τ_E is typically larger than $5\mu s$, interuser-interference occurs, e.g., for chip rates of 1.25MChips/s and $\Delta_k = 6\text{chips}$.

To combat this interference, one could simply shift the users further apart. At some point, however, the spectral efficiency would be too severely diminished so that we must allow some interuser interference in the received signal, i.e., an equalizer is needed. For example, one may want to use a Viterbi Algorithm to resolve the interference, but then one is throwing out “soft” information which is useful for the decoder [26]. A better choice for the equalizer is the Forward-Backward Algorithm [29], or some variant of this algorithm (see, e.g., [23] or the more recent [24]). A disadvantage of this maximum *a posteriori* equalizer is certainly that its complexity grows exponentially with the number of overlapping users, but because of the relative user shifts, the number of overlapping users in a CTDMA system is relatively small even for long multipath channels. For instance, in an outdoor environment, where a maximum excess delay of $\tau_E = 20\mu s$ is not unusual, and a relative user-shift of $\Delta = 4.8\mu s$ is used (which corresponds to 6 chips at 1.25MHz) there are only four overlapping users, which is still manageable. Moreover, this receiver concept is applicable to both the downlink and the uplink.

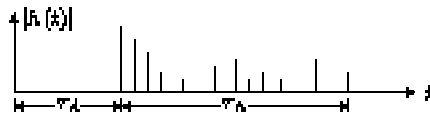


Figure 3: Example of a multipath channel impulse response $h(t)$ with absolute delay τ_A and excess delay τ_E .

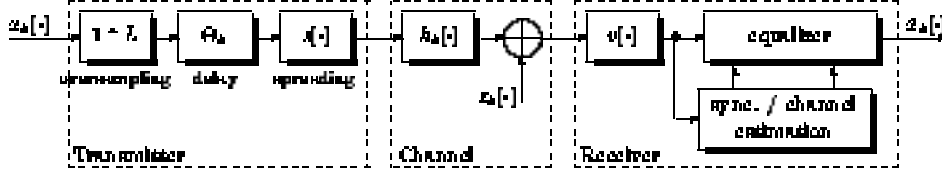


Figure 4: CTDMA transmitter, noisy multipath channel and CTDMA receiver.

Figure 4 shows the corresponding CTDMA transmitter, noisy multipath channel and receiver: the encoded and mapped data sequence $x_k[\cdot]$ of user k is oversampled with a factor of L , shifted by Θ_k chips and spread with $s[\cdot]$ in a CDMA fashion. The multipath channel $h_k[\cdot]$ and the additive white Gaussian noise sequence $z_k[\cdot]$ distort this transmitted signal. The receiver despreads the signal with the inverse filter $v[\cdot]$ of $s[\cdot]$, passes it through the equalizer and decimates this sequence by a factor of L in order to get the soft decision estimate $\hat{x}_k[\cdot]$ for $x_k[\cdot]$.

The necessary synchronization and channel estimation information can be obtained in an easy manner by using a pilot signal in both the downlink and the uplink. In the downlink one of the user slots is reserved for a symbol rate pilot, and in the uplink a pilot symbol is sent intermittently.

Cellular CTDMA

The considerations above are valid for a CTDMA system with *one* cell. An extension to several cells within the same frequency band is possible by using different spreading sequences and allowing intercell interuser interference.

For good system performance, we must require that all spreading sequences have a low inverse filter noise enhancement factor $\epsilon^{\{vs\}}$ (which limits the noise influence), that the spreading factor L is large enough for the signal bandwidth to be at least in the order of the coherence bandwidth (yielding a diversity gain) and that any particular cell's sequence causes as little interference as possible at the outputs of the inverse filters of all the other cells.

Given the basic binary spreading sequence $s[\cdot]$ of length L with inverse filter noise enhancement factor $\epsilon^{\{vs\}}$ and corresponding inverse filter processing gain $G^{\{vs\}}$, the “frequency-shifted” sequences

$$s^{\{m\}}[n] = s[n] e^{j \frac{2\pi mn}{L}}, \quad m = 0, 1, \dots, M-1; \text{ all } n, \quad (2)$$

where M is the *sequence cluster size*, are all constant envelop complex sequences with the same parameters L , $\epsilon^{\{vs\}}$, and $G^{\{vs\}}$. The “frequency” offset guarantees fairly good crosscorrelation properties between $s^{\{m\}}[\cdot]$ and $v^{\{n\}}[\cdot]$ for $m \neq n$, where $v^{\{n\}}[\cdot]$ is the inverse filter for the n -th sequence $s^{\{n\}}[\cdot]$. For

realization, $s^{\{m\}}[\cdot]$ can be implemented as $s[\cdot]$ with a carrier frequency offset mf_o , where

$$f_o = \frac{1}{L \cdot T_C} = \frac{1}{T_B}$$

(where T_C and T_B denote the chip and bit durations, respectively), i.e.,

$$s^{\{m\}}[n] = s[n] e^{j2\pi mn f_o T_C} ,$$

such that only one sequence generator and one inverse filter implementation are needed for all cells. Note that, in [22], this approach has been proposed for intracell user separation in Code Frequency Division Multiple Access (CFDMA).

7.3.3 System Performance

As the basic ± 1 spreading sequence, we shall use the length-32 sequence with a hex representation of **00F2D533** that provides the smallest noise enhancement of all sequences of the same length [32, 33]. Its inverse filter noise enhancement factor is only $\epsilon^{\{vs\}} = 0.74 \text{ dB}$, and it yields an inverse filter processing gain of $G^{\{vs\}} = 14.3 \text{ dB}$.

Instead of the true inverse filter $v[\cdot]$, which is of infinite length, a truncated version $v_N[\cdot]$ of length $N = 134$ chips is used, which has a *peak/off-peak ratio* (*POP-ratio*)

$$\rho_N^{\{vs\}} = \frac{|(v_N * s)[0]|}{\max_{m \neq 0} |(v_N * s)[m]|}$$

of $\rho_{134}^{\{vs\}} = 40 \text{ dB}$.

Simulation results for this CTDMA system in a fading environment are shown in Figure 5. These simulations were performed for a single cell in which there were 8 users ($\Delta_k = 4$) sending their data at 40 kSymb/s , which results in a chip rate of 1.28 MChips/s and in a gross symbol rate of 320 kSymb/s . Thus, the efficiency is only 25% ($= 1/\Delta_k = 1/4$) for this *single* cell. We note, however, that the efficiency will improve if one considers the *cellular* environment with frequency reuse, or if one makes Δ_k smaller.

The channel model used in the simulations was the COST-207 Rural Area model at a carrier frequency of 900 MHz and a velocity of 100 km/h . We put 4th-order Butterworth filters with baseband bandwidths of 625 kHz at the output and input of the transmitter and receiver, respectively. The channel response was estimated using a symbol rate pilot for the downlink and a pilot sent every four symbols for the uplink (note that this implies that the information rate for the uplink is reduced by 25%). As the channel response length was short, a matched filter with 3 fingers was used to provide the decoder with soft

inputs. The code used was the maximum d_{free} rate- $1/2$ binary convolutional code with constraint length 6 [25] decoded with the Viterbi Algorithm, and a $4 \times 2.5\text{ms}$ interleaver was used to mitigate the effects of fading. Perfect chip synchronization was assumed for all simulations. In Figure 5, the reference curve labelled “AWGN” is the error performance for an uncoded signal sent over the additive white Gaussian noise channel.

The simulations indicate that one loses about 1 to 2 dB on the uplink due to poorer channel estimation. This loss could be reduced, of course, by sending a pilot symbol more often.

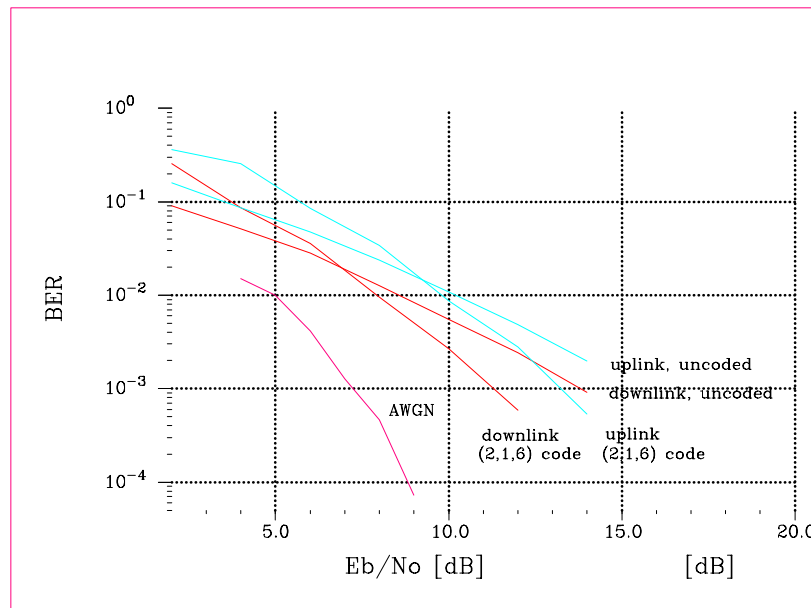


Figure 5: CTDMA error performance for the COST-207 RA100 channel model.

7.3.4 Service Provision

In this section we consider the implementation of several services: By means of orthogonal Walsh-Hadamard layers, orthogonal user families with symbol rather than chip level inter-family synchronization requirements are introduced. This approach is then applied to accommodate multiple and variable bit rates, and to separate connection-oriented and connectionless, as well as, in a different cell separation scenario, to provide a dynamic mixed-cell architecture. Note that, for sake of simplicity, no additional protocol information is considered in the described scenarios; these have to be added and the corresponding rates have to be changed accordingly for a real-world system.

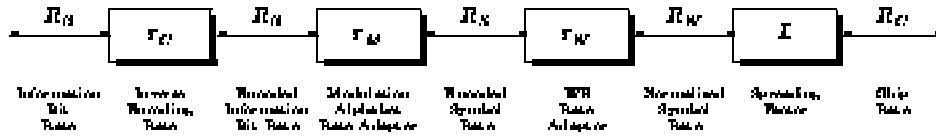


Figure 6: Rates overview of a generalized CTDMA system.

Rates Overview

Figure 6 shows the various rates in a generalized CTDMA system. The rate adaptors are used to generate a large variety of data rates. The CTDMA encoder converts the information bit rate R_B into the encoded information bit rate $R_E = r_C R_B$, where r_C is the inverse encoding rate of a rate- $\frac{1}{r_C}$ error correcting code. The adaption to the encoded symbol rate $R_S = r_M R_E$ is done via the modulation alphabet rate adaptor with factor r_M , where $r_M = 1/\log_2(A)$ and where A is the modulation alphabet size (in the case of BPSK, $A = 2$ and $r_M = 1$, and for QPSK, $A = 4$ and $r_M = 1/2$). We shall see below that these factors r_C and r_M have to be designed such that the requirements on R_S are met. These requirements are that only discrete values of R_S are allowed, namely $R_S = R_C f L$, $R_S = k R_C f L$, or $R_S = 2^{-k} R_C f L$ ($k = 1, 2, 3, \dots$).

This rate R_S is then adapted to the (fixed) normalized symbol rate R_W by means of a Walsh-Hadamard (WH) rate adaptor: If $R_S = R_W$ then there is no rate adaption necessary and $r_W = 1$. If $R_S \geq R_W$, multiple time slots are used for the transmission of this signal and $r_W = k$ ($k=1, 2, 3, \dots$). If $R_S < R_W$, a Walsh-Hadamard coding technique (cf. Section "Orthogonal Walsh-Hadamard Layers") increases the rate by factors of 2^k , and we get $r_W = 2^k$. In this latter case, 2^k such users can sometimes be assigned the same time slot.

This rate R_W is then multiplied by the spreading factor L in order to obtain the chip rate $R_C = L R_W$.

Orthogonal Walsh-Hadamard Layers

Given the basic CTDMA system with chip rate R_C , spreading factor L and encoded symbol rate $R_S = R_C/L$, several orthogonal Walsh-Hadamard (WH) layers can be implemented in CTDMA: Given a set of $Q = 2^k$ orthogonal WH sequences $w_q[\cdot]$ ($q = 0 \dots Q-1$) of length Q , the encoded symbols of the basic CTDMA system can be further encoded with these sequences $w_q[\cdot]$. We then get Q orthogonal user families, each providing basic symbol rates of R_S/Q .

Note that there is a need of an inter-family synchronization within Q symbol duration QT_S (which is the duration of Q WH symbols) corresponding to chip numbers 0 to $QL-1$: All chip numbers n in the range $0 \leq n < L-1$ can be used to allocate time slots, but not the ones in $L \leq n < QL-1$.

As examples, we hereafter depict the WH codes of lengths $Q = 2$ and $Q = 4$:

$$\begin{array}{ll} N = 2: & w_0[\cdot] = [+1, +1] \\ & w_1[\cdot] = [+1, -1] \\ N = 4: & w_0[\cdot] = [+1, +1, +1, +1] \\ & w_1[\cdot] = [+1, -1, +1, -1] \\ & w_2[\cdot] = [+1, +1, -1, -1] \\ & w_3[\cdot] = [+1, -1, -1, +1] \end{array}$$

We will see that this technique of layering signals is very convenient for both multiple and variable bit rates as well as, in some cases, for the design of dynamic mixed-cell architectures.

Multiple Bit Rates

Multiple information bit rates, i.e., different user bit rates, can be accommodated via appropriate design of the parameters r_C , r_M and r_W . Some examples are given in Table 7. If $r_W \gg 1$, more than one user can be allocated to the same time slot (as stated in “Rates Overview” and in “Orthogonal Walsh-Hadamard Layers”).

Variable Bit Rates

Variable information bit rates, i.e., information bit rates of one specific user that vary during transmission, can be accommodated the same way as above with multiple bit rates. Here, due to the statistical nature of the information bit rate change, no additional users can usually be allocated to the same time slot; the overall system however still benefits by a decreased intercell interference.

Connection-Oriented and Connectionless Service

We propose to use the WH codes of length $Q = 2$, i.e., $w_0[\cdot] = [+1, +1]$ and $w_1[\cdot] = [+1, -1]$ to separate connection-oriented and connectionless services.

The codes $w_0[\cdot]$ and $w_1[\cdot]$ can then be assigned to the connection-oriented and the connectionless services, respectively (or vice versa). As long as the inter-family synchronization requirements mentioned in the Section “Orthogonal Walsh-Hadamard Layers” are fulfilled and ideal inverse filtering is applied, both services do not interfere with each other. A practical inverse filter realization will however cause very little interference between the two service types.

Mixed-Cell Architecture

In “Cellular CTDMA” of Section 7.3.2, CFDMA was proposed to separate adjacent cells. Different cell types in a hierarchical mixed-cell architecture (where e.g. umbrella cells cover several underlying micro cells) can then be separated only by FDMA, i.e., by allocating non-overlapping frequency bands to different cell hierarchies. However, the cell separation within the same hierarchy can still be done by CFDMA. This is a rather rigid solution since the corresponding capacities cannot be shared between the layers.

Another promising, yet not deeply investigated cell separation technique, is to allocate the same spreading sequences and center frequencies to all cells and to adopt a *dynamic channel allocation (DCA)* technique (as is done for instance in DECT by applying a TDMA/TDD scheme) to maintain the required link quality. If the transmission of a user is distorted by strong interference, e.g., when the same time-slot in an adjacent cell is occupied by a very close user, one of this two users has to change the time-slot allocation. Since in this scenario, either none or only a few users are involved into mutual interference, an implementable *interferer separation (IS)* technique could be applied for capacity enhancements. This would be a more dynamic solution since capacities can softly be allocated to both hierarchies.

7.3.5 Chip Rates, Spreading Factors, Symbol Rates and Bit Rates

For given chip rates of 0.2, 1, 5 and $20MChips/s$, we have evaluated the corresponding symbol rates for the case of no WH code application ($Q = 1$), the case of length-2 WH code application ($Q = 2$) and the case of length-4 WH code application ($Q = 4$) and listed the results in Table 8. These results emphasize that a spreading factor of $L = 2^5 = 32$ rather than the previously considered case of $L = 169$ might be a good choice; Table 9 therefore summarizes the corresponding results for $L = 32$.

Table 7 then gives examples for possible rate scenarios for $L = 32$ and R_C in the order of 0.2, 1, 5 and $20MChips/s$. The following assumptions were made in this table:

Info Rate R_{in} [bits/s]	Intermod Rate R_{im}	Intermod Info Rate R_{in} [bits/s]	Modulation Alphabetic Rate R_{al}	Intermod Symbol Rate R_{sy} [symbols/s]	WHL Rate Adaptive R_{ad}	Intermod Symbol Rate R_{sy} [symbols/s]	Spreading Factor L	Chip Rate R_{ch} [Mchips/s]
18	R/2	40	1/2	20	1/4	R	3:2	0.18
18	R/4	20	1/2	10	1/2	R	3:2	0.18
12	R/3	20	1/2	10	1/2	R	3:2	0.18
8	R/2	20	1/2	10	1/2	R	3:2	0.18
8	R/4	10	1/2	5	1	R	3:2	0.18
128	R/2	320	1/2	160	1/4	40	3:2	1.28
128	R/4	160	1/2	80	1/2	40	3:2	1.28
84	R/2	160	1/2	80	1/2	40	3:2	1.28
84	R/4	80	1/2	40	1	40	3:2	1.28
32	R/2	80	1/2	40	1	40	3:2	1.28
32	R/4	40	1/2	20	2	40	3:2	1.28
18	R/2	40	1/2	20	2	40	3:2	1.28
18	R/4	20	1/2	10	4	40	3:2	1.28
12	R/3	20	1/2	10	4	40	3:2	1.28
8	R/2	20	1/2	10	4	40	3:2	1.28
8	R/4	10	1/2	5	8	40	3:2	1.28
612	R/2	1280	1/2	640	1/4	160	3:2	6.12
612	R/4	640	1/2	320	1/2	160	3:2	6.12
288	R/2	640	1/2	320	1/2	160	3:2	6.12
288	R/4	320	1/2	160	1	160	3:2	6.12
128	R/2	320	1/2	160	1	160	3:2	6.12
128	R/4	160	1/2	80	2	160	3:2	6.12
84	R/2	160	1/2	80	2	160	3:2	6.12
84	R/4	80	1/2	40	4	160	3:2	6.12
32	R/2	80	1/2	40	4	160	3:2	6.12
32	R/4	40	1/2	20	8	160	3:2	6.12
18	R/2	40	1/2	20	8	160	3:2	6.12
18	R/4	20	1/2	10	16	160	3:2	6.12
12	R/3	20	1/2	10	16	160	3:2	6.12
8	R/2	20	1/2	10	16	160	3:2	6.12
8	R/4	10	1/2	5	32	160	3:2	6.12
2048	R/2	6120	1/2	3060	1/4	840	3:2	20.48
2048	R/4	3060	1/2	1530	1/2	840	3:2	20.48
1024	R/2	3060	1/2	1530	1/2	840	3:2	20.48
1024	R/4	1530	1/2	765	1	840	3:2	20.48
612	R/2	1530	1/2	765	1	840	3:2	20.48
612	R/4	765	1/2	382	2	840	3:2	20.48
288	R/2	765	1/2	382	2	840	3:2	20.48
288	R/4	382	1/2	191	4	840	3:2	20.48
128	R/2	382	1/2	191	4	840	3:2	20.48
128	R/4	191	1/2	95	8	840	3:2	20.48
84	R/2	191	1/2	95	8	840	3:2	20.48
84	R/4	95	1/2	47	16	840	3:2	20.48
32	R/2	95	1/2	47	16	840	3:2	20.48
32	R/4	47	1/2	23	32	840	3:2	20.48
18	R/2	47	1/2	23	32	840	3:2	20.48
18	R/4	23	1/2	11	64	840	3:2	20.48
12	R/3	23	1/2	11	64	840	3:2	20.48
8	R/2	23	1/2	11	64	840	3:2	20.48
8	R/4	11	1/2	5	128	840	3:2	20.48

Figure 7: Rates examples of a generalized CTDMA system (protocol overhead neglected).

Chip Rate R_C [McKips/s]	Spreading Factor L	Encoded Symbol Rate R_S [kSymb/s] for Q orthogonal WH families		
		$Q = 1$	$Q = 2$	$Q = 4$
0.2	16	12.50	6.25	3.13
0.2	20	10.00	5.00	2.50
0.2	24	8.33	4.17	2.08
0.2	28	7.14	3.57	1.79
0.2	32	6.25	3.13	1.56
0.2	36	5.56	2.78	1.39
0.2	40	5.00	2.50	1.25
0.2	44	4.55	2.27	1.14
0.2	48	4.17	2.08	1.04
0.2	52	3.85	1.92	0.98
0.2	56	3.57	1.79	0.89
0.2	60	3.33	1.67	0.83
0.2	64	3.13	1.56	0.78
1.0	16	62.50	31.25	15.63
1.0	20	50.00	25.00	12.50
1.0	24	41.67	20.83	10.42
1.0	28	35.71	17.86	8.93
1.0	32	31.25	15.63	7.81
1.0	36	27.78	13.89	6.94
1.0	40	25.00	12.50	6.25
1.0	44	22.73	11.36	5.68
1.0	48	20.83	10.42	5.21
1.0	52	19.23	9.62	4.81
1.0	56	17.86	8.93	4.48
1.0	60	16.67	8.33	4.17
1.0	64	15.63	7.81	3.91
5.0	16	312.50	156.25	78.13
5.0	20	250.00	125.00	62.50
5.0	24	208.33	104.17	52.08
5.0	28	178.57	89.29	44.64
5.0	32	156.25	78.13	39.06
5.0	36	138.89	69.44	34.72
5.0	40	125.00	62.50	31.25
5.0	44	113.64	56.82	28.41
5.0	48	104.17	52.08	26.04
5.0	52	96.15	48.06	24.04
5.0	56	89.29	44.64	22.32
5.0	60	83.33	41.67	20.83
5.0	64	78.13	39.06	19.53
20.0	16	1250.00	625.00	312.50
20.0	20	1000.00	500.00	250.00
20.0	24	833.33	416.67	208.33
20.0	28	714.29	357.14	178.57
20.0	32	625.00	312.50	156.25
20.0	36	555.56	277.78	138.89
20.0	40	500.00	250.00	125.00
20.0	44	454.55	227.27	113.64
20.0	48	416.67	208.33	104.17
20.0	52	384.62	192.31	96.15
20.0	56	357.14	178.57	89.29
20.0	60	333.33	166.67	83.33
20.0	64	312.50	156.25	78.13

Figure 8: CTDMA chip rates R_C , spreading factors L and encoded symbol rates R_S for $Q = 1, 2$ and 4 orthogonal WH families (protocol overhead neglected).

Chip Rate R_C [$MChips/s$]	Spreading Factor L	Symbol Rate R_S [kSymb/s] for Q orthogonal WH families:		
		$Q = 1$	$Q = 2$	$Q = 4$
0.2	32	0.25	0.13	0.06
1.0	32	1.25	0.63	0.31
5.0	32	6.25	3.13	1.56
20.0	32	25.00	12.50	6.25

Figure 9: CTDMA chip rates R_C and encoded symbol rates R_S for a fixed spreading factor $L = 32$ and $Q = 1, 2$ and 4 orthogonal WH families (protocol overhead neglected).

- The chip rates corresponding to the bandwidths 0.2, 1, 5 and 20 $MChips/s$ are assumed to be 0.16, 1.28, 5.12 and 20.48 $MChips/s$. This approach is very convenient since there are only factors of 2^k between these rates, i.e., $1.28 = 8 \times 0.16$, $5.12 = 4 \times 0.16$, $20.48 = 4 \times 0.16$.
- We assume a fixed modulation alphabet of $A = 4$ (QPSK modulation) resulting in a modulation alphabet rate adaptor of $r_M = 1/2$. Of course, $r_M = 1/\log_2\{A\}$ could also be varied, which could add even more flexibility to the system.
- We further assume that there is only one service type offered, i.e., there is no additional Walsh-Hadamard layer implemented to distinguish connection-oriented and connectionless services or to split into several cell-hierarchies as is the case in a mixed-cell architecture of the above mentioned DCA cell separation scenario. In these other cases the rates have to be changed accordingly.

The following observations can then be made from Table 7:

- The function of the inverse encoding rate r_C is, beside its main task to protect the data against errors, to translate the information rate R_B in some discrete realizations of R_E , since the CTDMA-chip rate is fixed. Since the corresponding values of R_S must be $R_S = R_C f L$, $R_S = k R_C f L$, or $R_S = 2^{-k} R_C f L$ ($k = 1, 2, 3, \dots$) and r_M is assumed to be $1/2$, R_E must then take on values $R_E = R_S f r_M$, i.e., $R_E = R_C f \{L r_M\}$, $R_E = k R_C f \{L r_M\}$, or $R_E = 2^{-k} R_C f \{L r_M\}$ ($k = 1, 2, 3, \dots$).
- The required service quality can, within the required values, still decide what order of inverse encoding rate r_C shall be implemented. In Table 7, it is usually either $5/2$ or $5/4$ (except, for $R_B = 12 kBits/s$, $r_C = 5/3$). It could, however, also take on any value described by $5/4 \times 2^k$ ($k = 0, 1, 2, \dots$).

Note again that these figures do not account for protocol overhead.

7.3.6 Compatibility with GSM

GSM is basically a TDMA system offering 8 users to transmit at approximately 24kBits/s each with an overlaid FDMA channel spacing of 200kHz . In order to reduce intercell interference to an acceptable level, a (frequency) cluster size of around 12 must be implemented.

A CTDMA system with 200kChips could be installed within these 200kHz -channels. If a relatively short sequence is used as a spreading sequence (e.g., $L = 32$), a symbol rate close to 12kSymbols/s corresponding to 24kBits/s (due to QPSK modulation in CTDMA) can be provided to each user. With appropriate time shifts, a pilot and at least one (but less than 8) users can be allocated to the same frequency in a specific cell. A frequency cluster size of about 1 then improves the overall Erlang capacity at least to the one of GSM.

After the cluster size is fixed, multiple adjacent channels can be combined in order to offer larger channel spacings and higher bit rates (wherever necessary).

7.4 Joint Detection CDMA

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7.4.1 Designs rationale

A key issue in the development of a new mobile radio system concept, evolving from second generation mobile radio, is the organization of the multiple access (MA). In a new mobile radio system concept, the MA can be based on the well-known basic MA principles [35, 36] code division multiple access (CDMA), frequency division multiple access (FDMA) and time division multiple access (TDMA). It is vital for the successful development of a new mobile radio system concept to thoroughly understand the key issues and hence the advantages and disadvantages of these three basic MA principles.

All of the second generation mobile radio systems are based on hybrid MA schemes. The most common hybrid MA scheme is F/TDMA already applied in GSM [37] and also proposed for the RACE II concept ATDMA [38]. Hence, it is reasonable to assume that third generation mobile radio systems such as UMTS (Universal Mobile Telecommunication System) and FPLMTS (Future Public Land Mobile Telecommunications System), which is also termed IMT-2000 (International Mobile Telecommunications 2000), are also going to use hybrid MA schemes. In this section, the designs rationale, i.e. the selection of the hybrid MA scheme, for a joint detection CDMA (JD-CDMA) mobile radio system concept developed within COST 231 shall be explained.

It is beyond question that UMTS and FPLMTS, providing global coverage, must use FDMA, consequently enabling frequency planning and reuse, flexible frequency allocation as well as intercell interference control [36]. Furthermore, the implementation of overlay concepts is eased by using FDMA. Now, it is the question whether FDMA shall be combined with only CDMA such as described in [39], only TDMA such as in [38] or a combination of both CDMA and TDMA, cf. e.g. [40]. The pros of TDMA are capacity advantage over CDMA, because intracell interference is avoided, and high degree of acceptance, because the most successful second generation mobile radio system GSM [37] uses TDMA. The main disadvantages of TDMA are increased intersymbol interference therefore requiring the application of adaptive equalizers, high momentary peak transmission powers leading to EMC problems, mutual synchronization of the users and lack of flexibility [36]. The pros of CDMA are frequency diversity, interferer diversity and a flexibility advantage over TDMA because user signals can be switched on and off independently and data rates can be chosen individually [36, 39]. The cons of CDMA are oc-

currence of intracell interference and its novelty to mobile radio and therefore lack of acceptance [36, 39].

Since none of the MA schemes CDMA and TDMA seems to incorporate the ultimate advantage, it is a tempting idea to inherit the capacity advantage of TDMA on the one hand and the flexibility advantage of CDMA on the other hand to a hybrid MA scheme, comprising a proper combination of FDMA, TDMA and CDMA and therefore termed F/T/CDMA. F/T/CDMA may enjoy broad acceptance by being based on known standards and is therefore a promising candidate for UMTS and FPLMTS.

The benefits of F/T/CDMA shall be discussed in this paragraph. Figure 10 shows two hybrid MA schemes. A total of 24 users is considered in the examples of Figure 10. In Figure 10a the conventional hybrid MA scheme F/TDMA, e.g. being used in GSM [37] where the time slots have duration Δt equal to $576.9 \mu\text{s}$ and the frequency slots have width Δf equal to 200 kHz, and in ATDMA [38] with Δt equal to e.g. $277.8 \mu\text{s}$ and Δf equal to 276.9 kHz, is depicted. Each of the rectangles in Figure 10a represents one user burst. An optional CDMA component is introduced into the F/TDMA MA scheme of Figure 10a, by pooling the narrow frequency slots, having width Δf , of spectrally adjacent users, e.g. of users five to eight in the first time slot to a wider frequency slot, and by occupying this wider frequency slot commonly by user signals five to eight in such a way that these user signals are spectrally spread by user specific CDMA codes to this wider frequency slot. This approach is schematically depicted in Figure 10b. The larger the number of pooled frequency slots, the more distinct the CDMA component. In the second time slot of Figure 10b, eight original narrow frequency slots of width Δf are pooled and in the third time slot of Figure 10b no pooling at all occurs and, consequently, no CDMA component is applied in this third time slot. As demonstrated in Figure 10b a CDMA component can be introduced very flexibly whenever it pays with respect to both capacity and flexibility. A dynamically reconfigurable hybrid MA and channel allocation scheme is thus obtained.

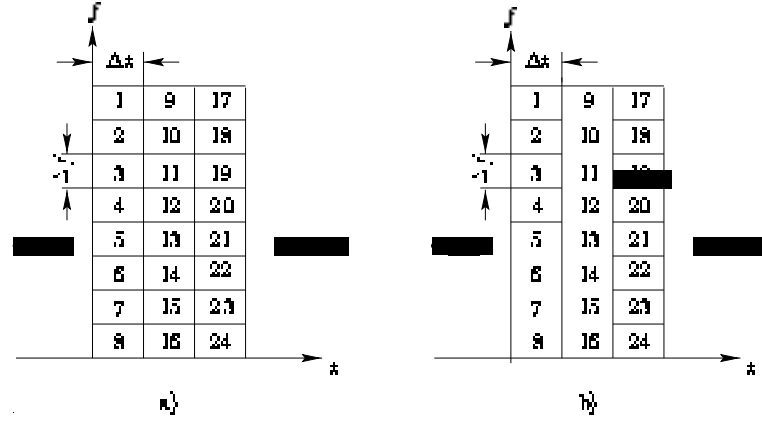


Figure 10: Hybrid multiple access schemes

- a) F/TDMA multiple access scheme used in GSM [37] and ATDMA [38]
- b) adaptive flexible multiple access scheme combining FDMA and TDMA with CDMA

7.4.2 System description

Uplink

In this section, the more elaborate uplink of the JD-CDMA mobile radio system concept shall be described in detail [40, 41]. Figure 11 shows the uplink frame structure which is, as mentioned above, similar to GSM [37] and ATDMA [38]. Table 1 contains an overview over the main system parameters [40, 41]. A maximum of K equal to 8 mobiles are simultaneously transmitting signals of bandwidth B equal to 1.6 MHz in the same frequency band of width B equal to 1.6 MHz. The above-mentioned user signals can be distinguished by their different user specific CDMA codes. The transmission occurs by using a single transmitter antenna per mobile. In the considered JD-CDMA mobile radio system, the user signals are received over K_a equal to one or two receiver antennas at the base stations. Thus, either no or dual receiver antenna diversity are considered [41, 42].

The structure of the bursts transmitted by each of the 8 mobiles is depicted in Figure 12. Each burst has duration T_{bu} equal to 500 μ s. The radio channel can be regarded as time invariant during that time period T_{bu} which is favourable with respect to the receiver complexity. According to Figure 12 each burst consists of two data blocks containing N equal to 24 quaternary data symbols, each block having a duration of 168 μ s, a user specific midamble of duration

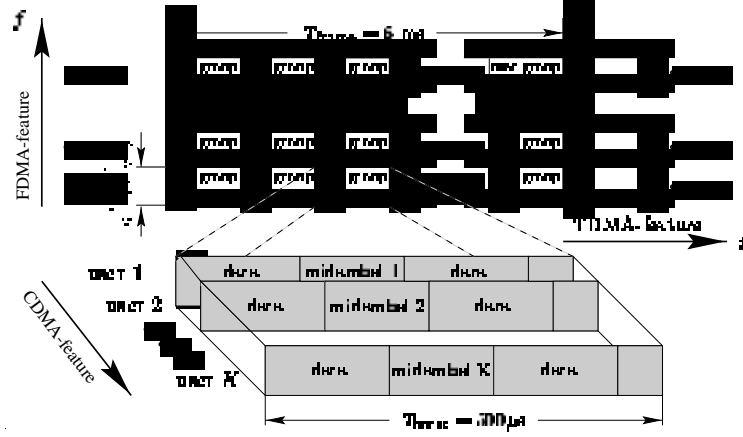


Figure 11: Uplink frame structure of the JD-CDMA mobile radio system concept

134 μs containing L_m equal to 268 binary midamble chips of duration T_c equal to 0.5 μs which is used for channel estimation [43], and a guard interval of duration T_g equal to 30 μs . Each quaternary data symbol has a period T_s equal to 7 μs and is spread by a user specific CDMA code of Q equal to 14 chips with a chip duration T_c equal to 0.5 μs . With respect to the TDMA component of the JD-CDMA mobile radio system, the eight different mobiles simultaneously transmit bursts in a time slot of duration T_{bu} equal to 500 μs . Twelve such time slots make up one TDMA frame of duration D_{bu} equal to 6 ms. Taking into account both CDMA and TDMA components, respectively, 96 different mobile users can be accommodated per frequency band of bandwidth B equal to 1.6 MHz [40]. By allocating more than one time slot as well as more than one user specific CDMA code to a particular mobile, services with different gross bit rates between 16 kbit/s and 1536 kbit/s can be provided. Due to the use of channel coding with code rate R_c equal to 1/2, the user bit rate can be varied between 8 kbit/s and 768 kbit/s depending on the required service.

The block structure of an uplink transmitter is shown in Figure 7.4.2. This uplink transmitter [40, 41] consists of

- a data source,
- a channel encoder, which is either a conventional convolutional encoder with code rate R_c equal to 1/2, constraint length 5 and octal generators 23, 35, or the Turbo-Code TC-BL of [44],
- a 4×96 block interleaver,

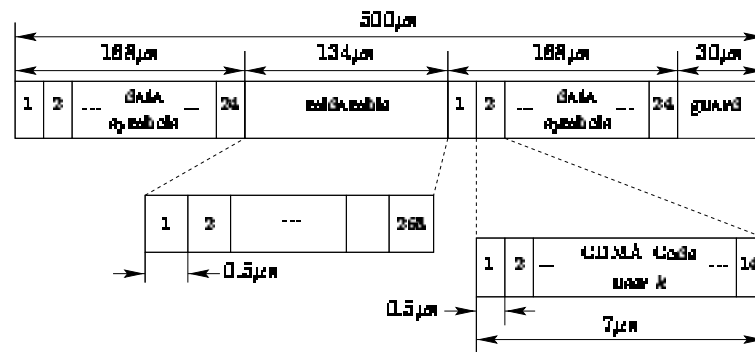


Figure 12: Uplink burst structure of the JD-CDMA mobile radio system concept

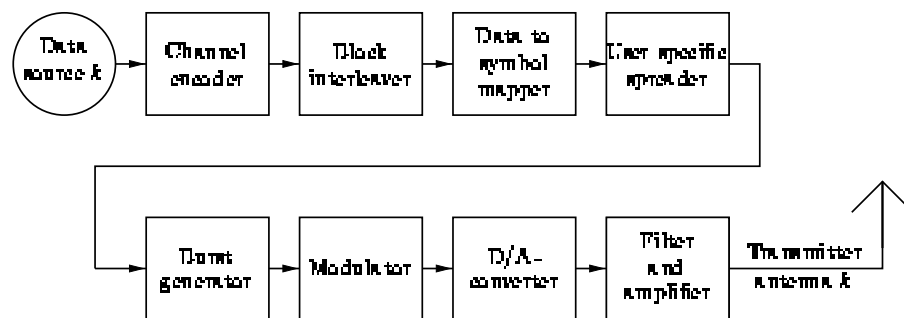


Figure 13: Block structure of an uplink transmitter of the JD-CDMA mobile radio system concept

general: number of receiver antennas user bandwidth duration of TDMA frame number of time slots per TDMA frame number of simultaneously active users per time slot data rate per user JD data detector	$K_a = 1, 2$ $B = 1.6 \text{ MHz}$ $D_{bu} = 6 \text{ ms}$ 12 $K = 8$ $8 \text{ kbit/s} \leq R \leq 768 \text{ kbit/s}$ ZF-BLE, MMSE-BLE, ZF-BDFE, MMSE-BDFE
filters: analogue transmitter filter analogue receiver filter digital receiver filter	Butterworth filter, order 4, cutoff frequency 1.6 MHz Butterworth filter, order 10, cutoff frequency 1.2 MHz ideal low pass filter, cutoff frequency 1MHz
burst structure: burst duration midamble chips guard interval data symbols per data block symbol duration data modulation scheme chips per symbol chip duration spreading modulation scheme	$T_{bu} = 0.5 \text{ ms}$ $L_m = 268$ $T_g = 30 \mu\text{s}$ $N = 24$ $T_s = 7 \mu\text{s}$ 4PSK $Q = 14$ $T_c = 0.5 \mu\text{s}$ linearized GMSK, time-bandwidth-product 0.3
channel encoder: NSC constraint length rate generators in octal RSC for Turbo-Code TC-BL constraint length rate generators in octal	$K_c = 5$ $R_c = 1/2$ 23, 35 $K_c = 5$ $R_c = 1/2$ 37, 21
block interleaver: interleaving matrix interleaving depth	4×96 $I_D = 4 \text{ bursts}$

Table 1: Important system parameters of the uplink

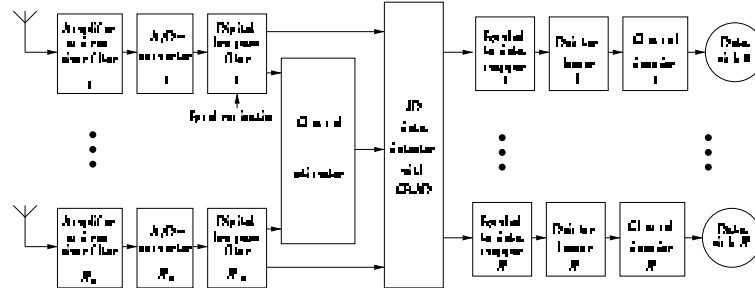


Figure 14: Base station receiver of the JD-CDMA mobile radio system concept

- ✦ a data to symbol mapper,
- ✦ a user specific spreader,
- ✦ a burst generator,
- ✦ a digital modulator,
- ✦ a D/A converter,
- ✦ a transmitter filter and an amplifier as well as
- ✦ a transmitter antenna.

The data source generates speech frames containing 192 bits. Each speech frame is encoded by the channel encoder. The 384 coded data bits are then interleaved by applying a block interleaver with an interleaver matrix of 4 rows and 96 columns. The 384 coded and interleaved data bits are then mapped onto 192 4PSK data symbols. Each 4PSK data symbol is spread by the user specific CDMA code allocated to mobile k . Then, I_D equal to 4 bursts as shown in Figure 12 are generated based on the 192 spread 4PSK data symbols and the user specific midambles [43, 41]. After linear modulation by using a linearized version of Gaussian minimum shift keying (GMSK) with time-bandwidth-product 0.3 and D/A conversion, the signal is passed through a Butterworth low pass filter of order 4 and cutoff frequency 1.6 MHz. Finally, this signal is amplified [41].

Figure 7.4.2 shows the block structure of the base station receiver. In the base station receiver, coherent receiver antenna diversity (CRAD) [42] is applied. This base station receiver [40, 41] consists of

- ✦ K_a receiver antennas,
- ✦ K_a amplifiers and receiver filters,
- ✦ K_a A/D converters,
- ✦ K_a digital low pass filters,
- ✦ K_a channel estimators,
- ✦ a JD data detector with CRAD, cf. Sect 6.6 and [41, 42],
- ✦ K symbol to data mappers,
- ✦ K 96×4 block deinterleavers,
- ✦ K channel decoders and
- ✦ K data sinks.

The amplified signal received at each receiver antenna k_a , $k_a = 1 \dots K_a$, is the sum of additive stationary noise and the 8 user signals, associated with the eight simultaneously active mobiles, which are distorted with the $8 \cdot K_a$ time varying and frequency selective mobile radio channels. After low pass filtering this amplified signal by using a Butterworth low pass filter of order 10 and cutoff frequency 1.2 MHz, A/D conversion takes place at a sampling rate of $2/T_c$ [41]. A synchronization unit at the receiver compensates for slightly different delay times of the K_a received signals. The set of samples is then digitally low pass filtered in order to allow decimation of the sampling rate to $1/T_c$. The particular parts of the received sequence stemming from the user specific midamble are processed by the K_a channel estimators. The JD data detector with CRAD which uses predetection maximal-ratio combining then determines continuous valued estimates for the $2 \cdot K \cdot N$ equal to 384 data symbols. The four suboptimum JD techniques ZF-BLE, MMSE-BLE, ZF-BDFE and MMSE-BDFE are available at the JD data detector with CRAD, cf. Sect. 6.6 and [41, 42]. The $2 \cdot N$ equal to 48 complex and continuous valued estimates of the data symbols transmitted by each mobile k , $k = 1 \dots K$, are then mapped onto a real valued data stream of 96 samples. After four bursts were processed, the 384 real valued samples are deinterleaved and convolutionally decoded by a soft input decoder. The K decoded data sequences are then transferred to the K data sinks.

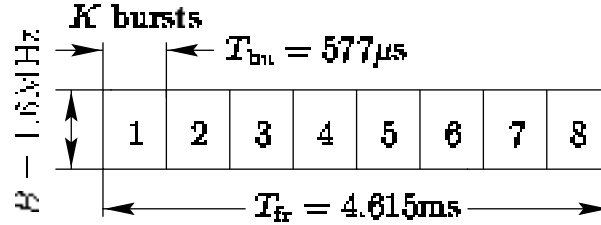


Figure 15: Downlink frame structure of the JD-CDMA mobile radio system concept

Downlink

In this section, the downlink of the JD-CDMA mobile radio system concept is briefly introduced [45]. We only refer to both the frame and burst structures, respectively. Due to their close relationship to the uplink transmitters and receivers, the downlink transmitters and receivers shall not be described here.

Figure 7.4.2 shows the downlink frame structure of the JD-CDMA mobile radio system concept. It is obvious from Figure 7.4.2 that the downlink is fully compatible with GSM [37]. Nevertheless, compatibility to ATDMA [38] can easily be achieved. Like in the uplink, K equal to 8 users are simultaneously active in the same frequency band of bandwidth B equal to 1.6 MHz and in the same time slot of duration T_{bu} equal to $577 \mu\text{s}$. Eight such time slots form one TDMA frame of duration T_{fr} equal to 4.615 ms. The transmission occurs by using a single transmitter antenna per base station. In the considered JD-CDMA mobile radio system concept, antenna diversity can be implemented in the downlink receivers in a similar fashion to the Japanese Personal Digital Cellular [46].

The minimum net data rate per user is set to be 13 kbit/s in the downlink. As it is the case in the uplink the data rate can be varied with respect to the desired service by assigning more than one time slot as well as more than one user specific CDMA code to a particular user. The maximum net bit rate is thus equal to 832 kbit/s. It is easy to see that in the downlink only a single radio channel must be estimated at the receiver in order to enable coherent reception. Therefore, the midamble used in the downlink is shorter, taking only T_m equal to $64.5 \mu\text{s}$, than the midamble required for the uplink channel estimation which is $134 \mu\text{s}$ long. The chip period in the downlink is the same as in the uplink, namely T_c equal to $0.5 \mu\text{s}$. However, the number of elements contained in a user specific CDMA code is 16 in the downlink. In contrast to the up-

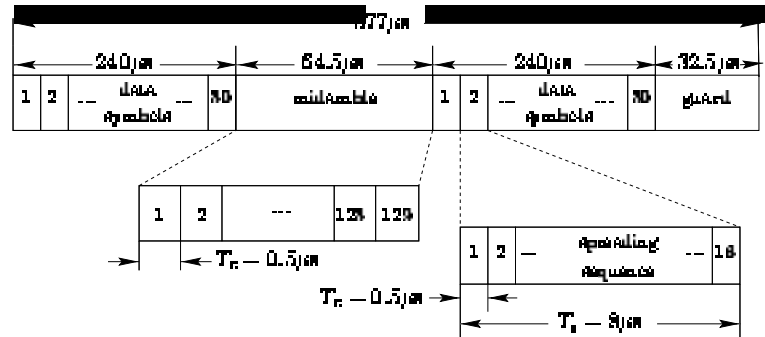


Figure 16: Downlink burst structure of the JD-CDMA mobile radio system concept

link, orthogonal binary user specific CDMA codes are applied in the downlink which enables a better performance than in the case of using nonorthogonal user specific CDMA codes, e.g. randomly chosen user specific CDMA codes.

Performance

The performance of the JD-CDMA mobile radio system concept was studied e.g. in Sect. 6.6 and [41, 42, 43].

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7.5 References

- [1] M. Streeton, A. Urie and C. Mourot. "An Advanced TDMA Mobile Access System for UMTS," *IEEE Personal Communications*, February 1995.
- [2] *RACE Mobile Telecommunications Workshop*, Amsterdam, May 17-19, 1994.
- [3] *RACE Mobile Telecommunications Summit*, Cascais Portugal, 22nd-24th November 1995.
- [4] "ATDMA System Definition, Issue 4," *R2084/AMCF/PM2/DS/P/056/b1*, March 1995.
- [5] A. Urie and M. Streeton, "System model for adaptive cellular mobile systems," *Proceedings of 2nd International Conference on Universal Personal Communications*, 12-15 October 1993, Ottawa.
- [6] J. DeVile, "A reservation multiple access scheme for an adaptive TDMA air interface," *4th WINLAB workshop*, 19 Nov. 1993
- [7] D. J. Goodman, "Cellular Packet Communications," *IEEE Trans. Comms.*, Vol. 38, pp 1272-1280, August 1990.
- [8] E. Le Strat and A. Wautier, "Distance based dynamic adaptation of the air interface in TDMA," *Proceedings of the IEEE 2nd Symposium on communications and Vehicular Technologies in the Benelux*, Nov. 2-3 1994, Louvain-la-Neuve, Belgium.
- [9] C. Mourot, "A High bitrate transmission technique in mobile radio cellular environment," *Proceedings of the 42nd IEEE Veh. Tech. Conf., Denver, CO*, May 1992, pp 740-743.
- [10] "Ad hoc 8 kb/s speech coding Group," *ITU-TS SG15*,
- [11] "Digital PLMN channel structures and access capabilities at the radio interface (Um reference point)," *Q.1063, CCITT, Blue book 1988*,
- [12] "Report of System Performance," *R2084/DTM/SP4/DS/P/045/b1*, March 1995.
- [13] Alcatel France and Siemens, "Recommendations to SMG5 from RACE 2084 ATDMA Project," *Temporary doc. SMG5 TD (95) 386*, Presented at ETSI SMG5 #15, Dresden, 11-15/12/95

- [14] "LINK CDMA Consortium, "Workpackage 1000: Service Requirements"," *Project Deliverable*, Version 2.0, Feb. 1993.
- [15] "Framework and Services to be Supported by UMTS," *ETR/SMG-050201*, Annex C.
- [16] R.S. Swain, "UMTS & MBS System Requirements," *Race Communications Summit*, Cascais, Portugal, 22-24th November, 1995.
- [17] S.C. Swales, T. Busby, D.J. Purle and M.A. Beach, "A Comparison of CDMA Techniques for Third Generation Mobile Radio Systems," *43rd IEEE Vehicular Technology Conference*, New Jersey, USA, May 1993, pp.424-427.
- [18] "LINK CDMA Consortium, "Workpackage 2100: Summary of CDMA Traffic Capacity Analysis"," *Project Deliverable*, Version 1.2, Sept. 1993.
- [19] F. De Ferrari, C.I' Anson, M.Vocale and J.Waters, "Assessment Methods for a CDMA Trial System," *IEEE COMSOC'93*, Tokyo, Dec 1993.
- [20] N. Livneh, R. Meidan, M.Ritz and G. Silbershatz, "Frequency Hopping CDMA for future cellular Radio," *IEEE 42nd VTC*, pp404-404, May 1992.
- [21] S.C.Swales, J.P.Aldis, T.Busby, S.K.Barton and M.A.Beach, "A DS-CDMA Air Interface for UMTS," *ibid* [16],
- [22] Günther, C.G., Ruprecht, J., Habermann, J., Rüegg, R., Jung, P., "Code frequency division multiple access: A downlink multiplexing in support of effective multi-user equalization," *Proceedings of the 2nd International Conference on Universal Personal Communications ICUPC'93*, Ottawa, pp. 39-43, October 1993.
- [23] Hagenauer, J., Hoeher, P., "A Viterbi Algorithm with soft-decision outputs and its applications," *Proc. Globecom '89*, vol.3, pp. 47.1.1-47.1.7, Nov. 1989.
- [24] Li, Y., Vucetic, B., Sato, Y., "Optimum Soft-Output Detection for Channels with Intersymbol Interference," *IEEE Trans. Inform. Theory*, vol. IT-41, no. 3, pp. 704-713, May 1995.
- [25] Lin, S., Costello, D.J., *Error Control Coding: Fundamentals and Applications*, Prentice-Hall, Englewood Cliffs, N.J., 1983.

- [26] Massey, J.L., "Coding and Modulation in Digital Communications," *Proc. IEEE Int. Zurich Sem. Digital Comm.*, pp. E2(1)-(4), 1974.
- [27] Massey, J.L., *Code Time Division Multiple Access*, private correspondence (unpublished), 1989.
- [28] Proakis, J.G., *Digital Communications*, Singapore: McGraw-Hill, 1989.
- [29] Rabiner, R.L., "A Tutorial on Hidden Markov Models and Selected Applications in Speech Recognition," *Proc. IEEE*, vol. 77, no. 2, pp. 257-286, Feb. 1989.
- [30] Ruprecht, J., *Maximum-Likelihood Estimation of Multipath Channels*, ISBN 3-89191-270-6, Hartung Gorre Verlag, Konstanz, Germany, 1989.
- [31] Ruprecht, J., Neeser, F.D., Hufschmid, M., "Code time division multiple access: An indoor cellular system," in *Proceedings of the 42nd IEEE Vehicular Technology Conference*, Denver, 1992.
- [32] Ruprecht, J., Rupf, M., "On the search and construction of good invertible binary sequences", *Proceedings of the 1994 IEEE International Symposium on Information Theory ISIT'94*, Trondheim, Norway, 1994.
- [33] Ruprecht, J., Rupf, M., "On the design of aperiodic binary invertible sequences," to be published in *IEEE Trans. Info. Th.*, 1996/97.
- [34] Salmasi, A., Gilhausen, K.S., "On the system design of code division multiple access (CDMA) applied to digital and personal communication networks," *Proceedings of the 41st IEEE Vehicular Technology Conference*, St. Louis, 1991, pp. 57-62.
- [35] Simon, M. K.; Omura, J. K.; Scholtz, R. A.; Levitt, B. K.: *Spread spectrum communications*. Vol. III, Rockville: Computer Science Press, 1985.
- [36] Baier, P. W.: *CDMA or TDMA? CDMA for GSM?* Invited paper. *Proceedings of the 5th International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC '94)*, The Hague, pp. 1280-1284, 1994.
- [37] Mouly, M.; Pautet, M.-B.: *The GSM system for mobile communications*. Published by the authors, ISBN 2-9507190-0-7, 1992.

- [38] Cygan, D.; David, F.; Eul, H. J.; Hofmann, J.; Metzner, N.; Mohr, W.: RACE-II advanced TDMA mobile access project – an approach for UMTS. Proceedings of the 1994 International Zürich Seminar on Digital Communications, pp. 428-439, 1994.
- [39] Baier, A.; Fiebig, U.-C. G.; Granzow, W.; Koch, W.; Teder, P.; Thielecke, J.: Design study for a CDMA-based third-generation mobile radio system. IEEE Journal on Selected Areas in Communications, vol.12, pp. 733-743, 1994.
- [40] Blanz, J. J.; Klein, A.; Naßhan, M. M.; Steil, A.: Performance of a cellular hybrid C/TDMA mobile radio system applying joint detection and coherent receiver antenna diversity. IEEE Journal on Selected Areas in Communications, vol. 12, pp. 568-579, 1994.
- [41] Jung, P.; Blanz, J. J.; Naßhan, M. M.; Baier, P. W.: Simulation of the uplink of JD-CDMA mobile radio systems with coherent receiver antenna diversity. Wireless Personal Communications – An International Journal (Kluwer Academic Publishers), vol. 1, pp. 61-89, 1994.
- [42] Jung, P.; Blanz, J. J.: Joint detection with coherent receiver antenna diversity in CDMA mobile radio systems. IEEE Transactions on Vehicular Technology, vol. 42, 1995.
- [43] Steiner, B.; Jung, P.: Optimum and suboptimum channel estimation for the uplink of CDMA mobile radio systems with joint detection. European Transactions on Telecommunications and Related Technologies (ETT), special issue on “Multiple Access in Radio Communication Networks”, vol. 5, pp. 39-50, 1994.
- [44] Jung, P.; Naßhan, M. M.: Dependence of the error performance of Turbo-Codes on the interleaver structure in short frame transmission systems. Electronics Letters, vol. 30, pp. 287-288, 1994.
- [45] Naßhan, M. M.; Steil, A.; Klein, A.; Jung, P.: Downlink cellular radio capacity of a joint detection CDMA mobile radio system. To be presented at IEEE 45th Vehicular Technology Conference (VTC-1995), session on “Joint Detection for CDMA”, Chicago, 1995.
- [46] Lorenz, R. W.: Comparison of digital mobile radio systems in Europe (GSM) and in Japan (JDC) with special consideration of commercial aspects (in German). Der Fernmelde-Ingenieur, vol. 47, no. 1 & 2/93, 1993.

