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Hybrid CDMA/TDMA System

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ABSTRACT

This paper presents hybrid CDMA/TDMA system concept which is currently one candidate in ETSI for UMTS air interface. This concept is a TDMA based system with additional multiplexing of users by short spreading codes within each time slot. This paper is organized as follows. First, CDMA/TDMA system concept is introduced. Receiver algorithms of CDMA/TDMA are presented since joint detection of CDMA codes is an inherent part of the system both at the mobile station and at the base station. Implementation complexities of the mobile stations are also presented. Link level simulation results are shown. An analysis of differences between WB-TDMA, W-CDMA and CDMA/TDMA is presented. Finally, status of CDMA/TDMA in European standardization is discussed.

ABBREVIATIONS

CDMA	Code Division Multiple Access
CU	Central Unit
ETSI	European Telecommunications Standardization Institute
FDD	Frequency Division Duplex
GMSK	Gaussian Minimum Shift Keying
ISI	Intersymbol Interference
MAI	Multiple Access Interference
MMSE-BDFE	Minimum Mean Square Error Block Decision Feedback Equalizer
MUD	Multiuser Detection
ODMA	Opportunity Driven Multiple Access
OFDM	Orthogonal Frequency Division Multiple Access
QPSK	Quaternary Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RAU	Remote Antenna Unit
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications System
WB-TDMA	Wideband TDMA
W-CDMA	Wideband CDMA
ZF-BLE	Zero Forcing Block Linear Equalizer

1. INTRODUCTION

Hybrid CDMA/TDMA system a TDMA based system with additional multiplexing of users by short spreading codes within each time slot. The principle of this concept is shown in Figure 1.1.

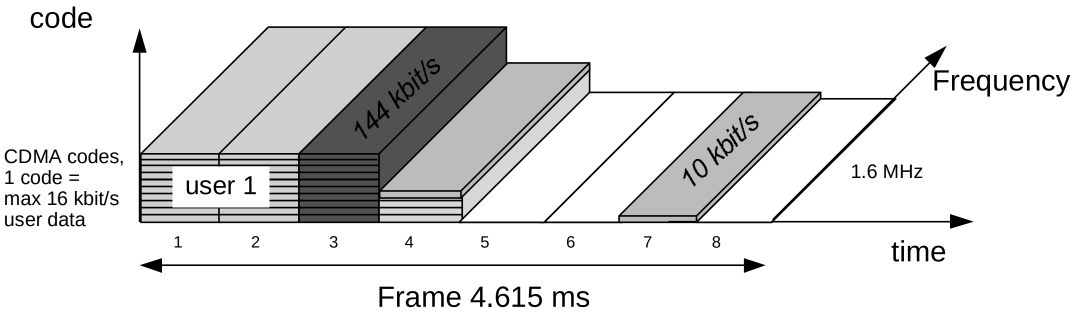

Figure 1.1. Hybrid CDMA/TDMA concept

The main parameters of CDMA/TDMA concept are shown in Table 1.1.

Table 1.1. Main parameters of CDMA/TDMA concept

Main multiple access parameters	
Multiple access	TDMA/CDMA
Channel spacing	1.6 MHz
Chip rate	2.167 Mchip/s
Duplexing method	FDD/TDD
Physical layer structure	
Frame length	4.615 ms
Time slot structure	8 slots / TDMA frame
Spreading	16 chip/symbol
Multirate	Multislot and multicode
Symbol modulation	QPSK / 16-QAM
Spreading modulation	GMSK
Frequency and interference diversity	Frequency and time hopping Frequency hopping rate: 200 Hz .. 1700 Hz
Power control dynamics	Uplink: 80 dB Downlink: 30 dB
Power control frequency	2 - 200 Hz
Handover	Mobile assisted handover
CDMA/TDMA receiver	
Detection	Coherent, based on training sequences
Receiver structures	Joint detection within one time slot

The basic carrier spacing is 1.6 MHz with the chip rate of 2.167 Mchip/s. The carrier spacing is 8 times wider than in GSM. Both frequency division duplexing (FDD) and time division duplexing (TDD) are supported with CDMA/TDMA. TDD could be applied to asymmetric and unpaired frequency allocations. TDD mode supports asymmetric capacity allocation between uplink and downlink. Frequency and time hopping are used for interference and frequency diversity. Both slow and fast (frame-by-frame) power control are considered. Coherent reception is based on training sequences and joint detection of all simultaneous CDMA codes is used.

2. PHYSICAL CHANNEL STRUCTURE

2.1 TDMA frame structure

The unit FDD frame is presented in Figure 2.1. The length of the FDD frame is the same as in GSM, 4.615 ms which is 10000 chip periods in CDMA/TDMA.

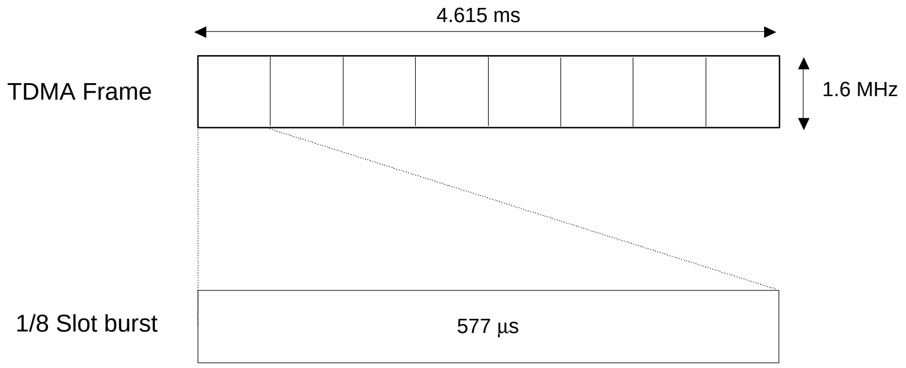

Figure 2.1. FDD frame

The TDD frame is of the same length as the FDD frame but it is divided into downlink and uplink parts. The switching point between uplink and downlink can be moved in the TDD frame to adopt asymmetric traffic. The minimum length of uplink and downlink parts is one slot. TDD frame is shown in Figure 2.2.

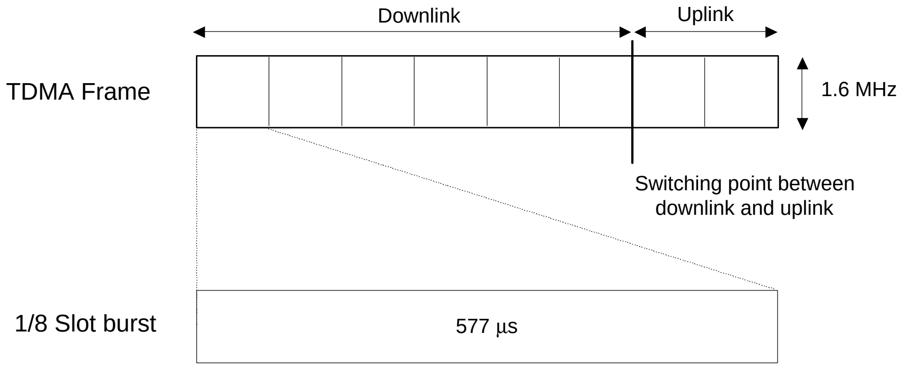

Figure 2.2. TDD frame

No additional guard periods are used in TDD operation. In the TDD frame structure, it is assumed that the same mobile station is not receiving in the last slot of the downlink part and transmitting in the first slot of the uplink part.

2.2 Burst structure

Two types of traffic bursts are defined: the Spread Speech/Data burst 1 (S1) and the Spread Speech/Data burst 2 (S2) shown in Figure 2.3 and Figure 2.4.

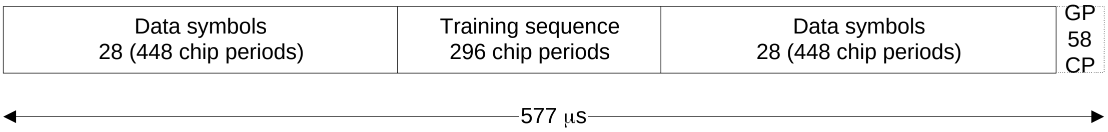

Figure 2.3. Burst structure of the Spread Speech/Data burst 1. GP stands for guard period and CP for chip periods.

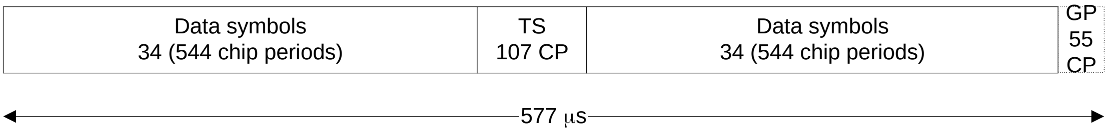

Figure 2.4. Burst structure of the Spread Speech/Data burst 2. TS stands for training sequence, GP for guard period and CP for chip periods.

The Speech/Data bursts 1 and 2 consist of two data symbol fields, training sequence field and guard period. The training sequence length of the Spread Speech/Data burst 1 is 296 chip periods long whereas the training sequence length of the Spread Speech/Data burst 2 is 107 chip periods long.

The use of the individual symbols in each burst is defined in Table 2.1 and Table 2.2. The overhead due to training sequence and guard periods in burst 1 is 40 % and in case of burst 2 the overhead is 15 %.

Table 2.1. The contents of the Spread Speech/Data burst 1 fields and the use of individual chips.

Chip number	**Length of field in chips**	**Length of field in symbols**	**Contents of field**
0-447	448	28	Data symbols
448-743	296	-	Training sequence
744-1191	448	28	Data symbols
1192-1249	58	-	Guard period

Table 2.2. The contents of the Spread Speech/Data burst 2 fields and the use of individual chips.

Chip number	**Length of field in chips**	**Length of field in symbols**	**Contents of field**
0-543	544	34	Data symbols
544-650	107	-	Training sequence
651-1194	544	34	Data symbols
1195-1249	55	-	Guard period

2.3 Modulation

In this chapter, distinction should be made between the data modulation and the spreading modulation. The spreading modulation is important in determining the linearity requirements for the power amplifier. It is also important for the adjacent channel interference. Data modulation again is important for the symbol detection. The basic modulation parameters are summarized in Table 2.3.

Table 2.3. Basic modulation parameters

Carrier chip rate	2.167 Mchip/s
Carrier spacing	1.6 MHz
Data modulation	QPSK 16QAM
Spreading modulation	Linearised GMSK
Spreading characteristics	16 chips/symbol
Symbol rate	135.41 ksymbol/s
Symbol duration	7.384 µs

The impulse response of the above mentioned chip impulse filter is the GMSK main impulse of duration five times the chip duration T_C and time bandwidth product 0.3. The impulse response $C_0(t)$ and the energy density spectrum $\phi_{C0}(f)$ of $C_0(t)$ are depicted in Figure 2.5.

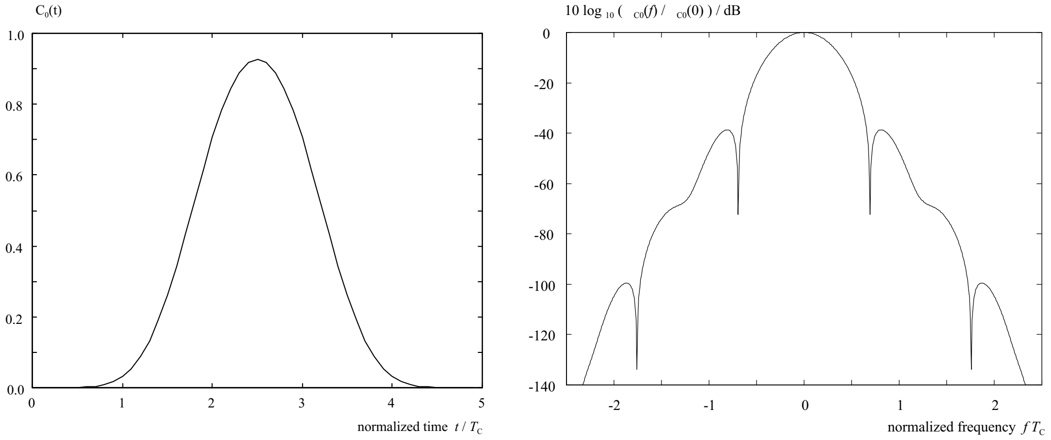

Figure 2.5. GMSK basic impulse $C_0(t)$ and the corresponding energy density spectrum $\phi_{C0}(f)$ of $C_0(t)$

2.4 Spreading codes

The spreading codes of CDMA/TDMA are generated based on Walsh-Hadamard codes followed by a multiplication with a Pseudo Random (PN) sequence. The length of the spreading codes is 16. Typically the number of simultaneous CDMA codes smaller than 16. Several sets of 16 CDMA codes can be generated by multiplying the 16 orthogonal binary Walsh-Hadamard CDMA codes with other PN sequences. In this way, different sets of binary CDMA codes can be used in different cells.

2.5 Channel estimation

The channel estimator provides an estimate of the mobile radio channels of K active users based on the received training sequence. The structure of the received signal is shown in Figure 2.6 and the parameters of the uplink channel estimation are shown in Table 2.4.

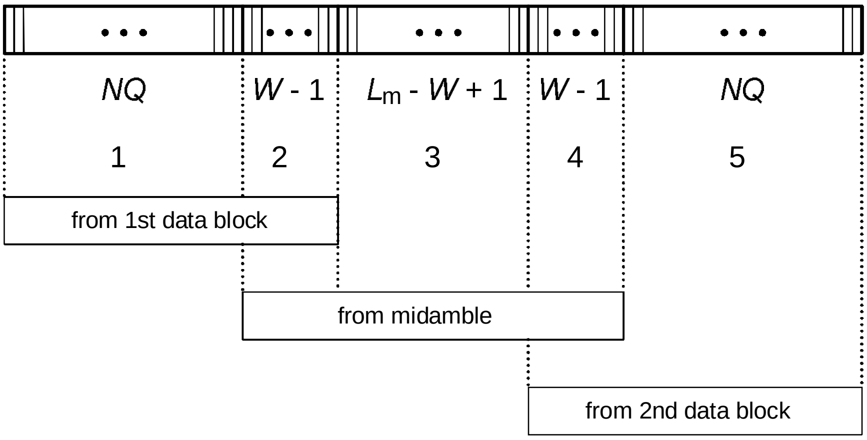

Figure 2.6. Structure of received signal from user k

Table 2.4. Parameters for channel estimation

Parameter	**Value**
Length of midamble	L_m = 107
Max. number of simultaneously active users	K = 8
Max. number of channel taps that can be estimated	W = 12
Max. excess delay than can be estimated	*W/2.167 Mchip/s = 5.5 µs*
Length of the spreading code	Q = 16
Number of data symbols per data block	N = 34

There are two different lengths of training sequences, 107 chips and 296 chips. The longer training sequence reduces the number of data symbol in a bursts from 2*34 to 2*28. The different lengths of midamble sequences allows estimation of different lengths of multipath channels. The midamble length of the Spread Speech/Data burst 1 is suited for estimating the different uplink channel impulse responses of 8 users within the same time slot with a time dispersion of up to about 15 µs. If the number of users is reduced, the tolerable time dispersion is increased. The midamble length of the Spread Speech/Data burst 1 is also suited for estimating the downlink channel impulse response with a time dispersion of 53.5 µs, independent of the number of active users; furthermore, for estimating the uplink channel impulse response with a time dispersion of up to about 53.5 µs in case all bursts within a slot are allocated to one and the same user.

According to a large number of channel measurements, the training sequence lengths are quite much overdesigned. The most important environment for transmission of high bit rates in UMTS is micro and indoor cells where the maximum excess delays are much less than 10 µs, typically only about 1 µs or less [7]. Therefore, the overhead due to training sequences could probably be reduced in CDMA/TDMA bursts. On the other hand, in CDMA/TDMA uplink the timing advance adjustments does not provide a perfect synchronization of the users within one time slot. An inaccuracy of a few chips need to be reserved for asynchronity reducing the maximum multipath delay that can be estimated.

2.6 Service mapping

The maximum bit rates with different burst types are shown in Table 2.5.

Table 2.5. Maximum bit rates in CDMA/TDMA

Note: In gross bit rates per slot, no overhead due to possible idle slots or associated control channels is included.

Burst type	**Modulation**	**Gross bit rate per single slot (kbit/s)**	**Total gross bit rate (using all slots) (Mbit/s)**
Spread Speech/Data 1	QPSK	24.3	1.55
Spread Speech/Data 1	16QAM	48.6	3.11
Spread Speech/Data 2	QPSK	29.5	1.89
Spread Speech/Data 2	16QAM	59.0	3.77

For low bit rate services, e.g. speech service, one code in one time slot of the frame is reserved for one connection. If higher bit rates are needed, either more codes within a time slot and more time slots are allocated for the connection. It is also possible to change the data modulation from QPSK to multilevel modulation 16-QAM and to change the code rate to change the user bit rate.

User bit rate can be changed by changing
- Number of time slots
- Number of codes / time slot (multicode modulation)
- Modulation (QPSK, 16-QAM)
- Channel code rate

In Table 2.6 the user bit rates of specific interest are listed. Further, examples of how these rates could be mapped onto code and time slots are also given.

Table 2.6. Examples of service mappings

Required user bit rate (kbits/s)	**Code rate**	**Burst type**	**Modulation**	**Number of basic physical channels (code/time slots) per frame**
8	0.5	Spread Speech/Data 1/2	QPSK	0.5
64	0.5	Spread Speech/Data 1/2	QPSK	4
144	0.5	Spread Speech/Data 1/2	QPSK	9
384	0.5	Spread Speech/Data 1/2	QPSK	24
1024	0.5	Spread Speech/Data 1/2	QPSK	64
2048	0.5	Spread Speech/Data 1/2	16QAM	64

3. RADIO RESOURCE MANAGEMENT

For CDMA/TDMA two general concepts have been developed for radio resource management:

- Interference averaging
- Bunch concept

3.1 Interference averaging

The main idea of interference averaging concept is to provide a robust scheme supporting distributed radio resource management algorithms. The basic principle of this concept is to apply interference averaging strategies, e.g. frequency and time hopping, to reach a common interference level within the system. Thus, less complex radio resource management algorithms are required resulting in a less complex network infrastructure. No synchronization between base stations is needed in interference averaging concept.

3.2 Bunch

The bunch concept assumes that a limited number of Remote Antenna Units (RAUs) are connected to a central unit (CU). This is illustrated in Figure 3.1. All intelligence as well as a significant part of the signal processing is located in the CU. The CU controls a bunch of several synchronized RAUs and has knowledge about all allocated resources, transmitter powers, and path gains in the bunch. Micro and pico cell systems can not always be arranged in the normal hexagonal cell structure resulting in a high probability of overlap between cells. To improve the trunking efficiency the resources between the cells are shared. Therefore, a group of cells called a bunch can be formed. Bunches should be designed to handle areas with high traffic load (hot spot areas like micro or pico cells in urban environments). High capacity is important, even at the expense of increased algorithm complexity.

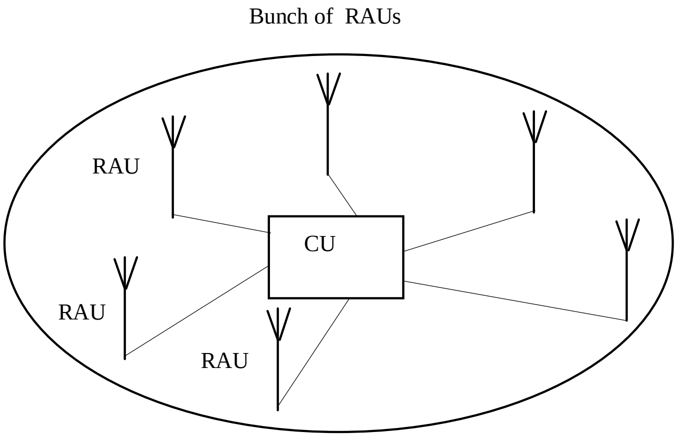

Figure 3.1. A bunch consists of a Central Unit (CU) and a number of Remote Antenna Units (RAUs)

Within the bunch, the main interference is caused by intra-bunch interference. To reach a minimization of this interference the knowledge of all allocated resources, transmitter powers and path gains together with synchronization between the cells is required.

It is of course inevitable that some bunches overlap each other and thus inter-bunch interference will arise, especially at the bunch borders. It is assumed that no inter-bunch synchronization is available. To overcome the inter-bunch interference an interference averaging strategy can be used.

4. CDMA/TDMA RECEIVER ALGORITHMS

In pure CDMA systems the separation of user signals is based on the processing gain and on the fast power control that keeps the received power levels equal. In hybrid CDMA/TDMA the processing gain is only 10*log10(16) = 12 dB and there is no fast power control. Therefore, multiuser detection (=interference cancellation, joint detection) of all simultaneous CDMA codes is needed in the receiver. The complexity of suboptimal multiuser detection in CDMA/TDMA is not terribly high since only a small number of simultaneous intra-cell interferers must be jointly detected. Two multiuser detection algorithms that have been considered for CDMA/TDMA are presented in this chapter: Zero Forcing Block Linear Equalizer (ZF-BLE) and Minimum Mean Square Error Block Decision Feedback Equalizer (MMSE-BLE). More multiuser detection algorithms for CDMA/TDMA have been described in [3], [4] and [5].

4.1 Zero forcing block linear equalizer (ZF-BLE)

A block diagram of zero forcing block linear equalizer is shown in Figure 4.1.

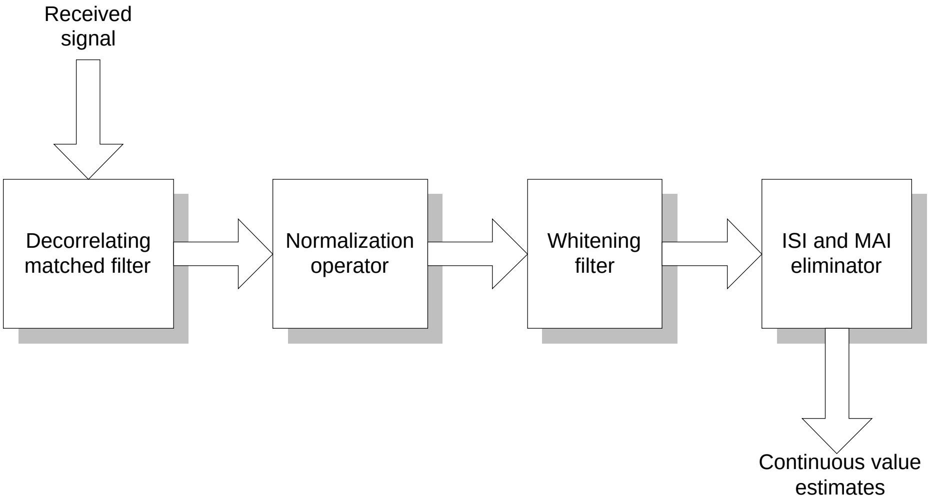

Figure 4.1. ZF-BLE receiver algorithm [3]
ISI = Intersymbol interference, MAI = Multiple access interference

Decorrelating matched filter is an extension of the conventional Rake receiver to the case of correlated noise. Decorrelating matched filter treats multiple access interference (MAI) as noise. Whitening filtering is used for noise whitening. Intersymbol interference (ISI) and MAI elimination is done by multiplying with a matrix inversion. Matrix inversion can be calculated with e.g. Cholesky decomposition [3].

4.2 Minimum mean square error block decision feedback equalizer (MMSE-BDFE)

The performance of MMSE equalizers is better than that of the corresponding ZF equalizers because the desired symbols, and the ISI and MAI and noise terms are decorrelated by a Wiener estimator. The drawback is that an estimate of the noise level is needed in MMSE equalizers. The performance of the equalizers with decision feedback is better than of the corresponding equalizers without decision feedback [4].

4.3 Complexity of ZF-BLE receiver

The computational complexity of both above mentioned receivers is essentially the same [4]. The complexity of the mobile receiver is important for making cheap terminals with low power consumption. Computational complexity of CDMA/TDMA receiver algorithms is shown in Table 4.1. It should be noticed that even if only one code within a time slot is used to transmit data to the mobile station, the mobile receiver must perform interference cancellation of maximum number of transmitted codes. So, the complexity of the mobile receiver is essentially the same for receiving 1 or 8 codes per slot. In Table 4.1 it is assumed that the maximum number of codes is 8 within a time slot. If a higher number of codes is used, the complexity increases non-linearly. Burst 2 is assumed in the complexity calculation. The complexity of CDMA/TDMA receiver is also compared to GSM equalizer with one slot reception. The number of real multiplications needed for GSM equalizer is assumed to be $4.0 \cdot 10^6$ per second.

Table 4.1. Complexity of CDMA/TDMA receiver baseband algorithms [1]

Bit rate	**Time slots**	**Codes / slot**	**Max number of codes**	**Real multiplications per second**	**Complexity compared to GSM**
8 kbit/s	1	1	8	$43.0 \cdot 10^6$	11 x GSM
144 kbit/s	4	3	8	$129.0 \cdot 10^6$	32 x GSM
2 Mbit/s	8	8	8	$344.0 \cdot 10^6$	86 x GSM

The complexity of CDMA/TDMA mobile receiver for 8 kbit/s speech service is more than ten times the complexity of GSM receiver. If cost efficient speech service should be supported with CDMA/TDMA, the terminal complexity may be too high compared to GSM receiver. Also, the complexity of 144 kbit/s reception is about 30 times more complex than GSM receiver which increases the baseband power consumption and makes the implementation more difficult.

5. LINK LEVEL PERFORMANCE

The link level performance of CDMA/TDMA is evaluated with intra-cell and inter-cell interference as shown in Figure 5.1. The simulation results are summarized in Table 5.1 and in Table 5.2.

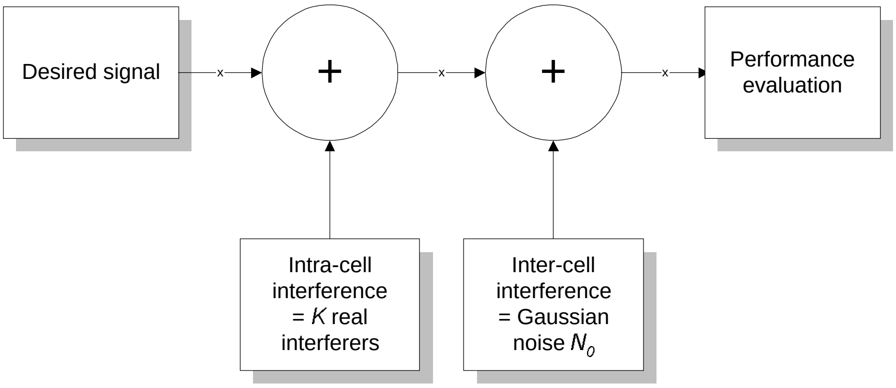

Figure 5.1. Interference modelling in link level simulations

Table 5.1. Link level E_b/N_0 performance of speech service with reception antenna diversity [1], [8]

	Number of intra-cell users *K*		
Environment	$K = 1$	$K = 4$	$K = 8$
Vehicular 120 km/h	$E_b/N_0 = 8.1$ dB	$E_b/N_0 = 8.4$ dB	$E_b/N_0 = 9.0$ dB
Outdoor to indoor 3 km/h	$E_b/N_0 = 8.4$ dB	$E_b/N_0 = 8.5$ dB	$E_b/N_0 = 8.7$ dB
Indoor 3 km/h	$E_b/N_0 = 8.4$ dB	$E_b/N_0 = 8.6$ dB	$E_b/N_0 = 8.9$ dB

According to Table 5.1 the degradation due to intra-cell interference is about 0.3..1.0 dB with 8 users. In outdoor to indoor and in indoor environment the degradation is smaller than in vehicular environment. The difference is due to more multipath propagation and higher mobile speed in vehicular environment which degrades the performance of joint detection. For comparison the E_b/N_0 requirement for GSM speech service is about 7-8 dB. E_b/N_0 values are important for noise limited range calculations.

Table 5.2. Link level E_b/N_0 performance of 144 kbit/s data service with reception antenna diversity [1] [8]

	Number of intra-cell users *K*		
Environment	$K = 1$	$K = 2$	$K = 3$
Outdoor to indoor 3 km/h	$E_b/N_0 = 3.6$ dB	$E_b/N_0 = 3.7$ dB	$E_b/N_0 = 4.0$ dB

Performance of 144 kbit/s with 300 ms delay is shown in Table 5.2. The required E_b/N_0 values are lower than for speech service because of longer time diversity with longer interleaving.

6. COMPARISON OF CDMA/TDMA, WB-TDMA AND W-CDMA

A short analysis of the basic differences between CDMA/TDMA and pure TDMA (Wideband TDMA = WB-TDMA) both with 1.6 MHz carrier spacing is shown in Table 6.1 [1] [2].

Table 6.1. Comparison of CDMA/TDMA and WB-TDMA

	CDMA/TDMA	WB-TDMA
Multiplexing of users within 577 μs time slot	Code division, up to 8 codes	Time division, up to 8 smaller slots
Intra-cell interference	Up to about 8 simultaneous users within one time slot	Orthogonal in time domain
Intra-cell interference cancellation	Joint detection receiver	Not needed
Inter-symbol interference	Small because of long symbol 7.4 μs, cancelled of ISI with joint detection	Equalizer needed, symbol length 0.38 μs
Inter-cell interference	Interference averaging or interference avoidance to combat inter-cell interference	
Inter-cell interference cancellation	Complex due to a large number of co-channel interferers	Possible because only a few dominant co-channel interferers
Burst length	577 μs Performance degradation for high mobile speeds (>100 km/h) if no channel tracking	72 μs / 278 μs No performance degradation with 72 μs burst length up to 1000 km/h
Peak to average power ratio for low bit rates	Moderate, supports higher average transmission powers	High, average power quite low for due to peak power limitation (multi-slot possible)
Envelope variations	Large variations with multicode transmission	Smaller variations
Power control dynamics	Uplink: 80 dB (joint detection does not tolerate large received power differences) Downlink: 30 dB	Uplink / downlink: 30 dB
Frequency reuse	1 or higher	

The difference between CDMA/TDMA and WB-TDMA in receiver complexity depends on the complexity of multiuser detection in CDMA/TDMA compared to equalization in WB-TDMA. In indoor and micro cellular environments the complexity of equalization is clearly lower than the complexity of multiuser detection. In long delay spread environments the complexity of WB-TDMA is high if optimal equalization is used but with decision feedback type equalizer the complexity of WB-TDMA receiver is reduced below joint detection CDMA/TDMA receiver.

A link performance comparison between CDMA/TDMA and WB-TDMA is shown in Table 6.2. The same interleaving over 4 TDMA frames has been assumed for both multiple access schemes.

Table 6.2. Performance comparison of CDMA/TDMA and WB-TDMA for speech service

	CDMA/TDMA	**WB-TDMA**
Vehicular 120 km/h, 8 users on 1.6 MHz carrier	E_b/N_0 = 8.1 dB	E_b/N_0 = 6.2 dB
Vehicular 120 km/h, 32 users on 1.6 MHz carrier	E_b/N_0 = 8.4 dB	E_b/N_0 = 6.2 dB
Vehicular 120 km/h, 64 users on 1.6 MHz carrier	E_b/N_0 = 9.0 dB	E_b/N_0 = 6.6 dB
Indoor 3 km/h, 8 users on 1.6 MHz carrier	E_b/N_0 = 8.4 dB	E_b/N_0 = 5.5 dB
Indoor 3 km/h, 32 users on 1.6 MHz carrier	E_b/N_0 = 8.6 dB	E_b/N_0 = 5.5 dB
Indoor 3 km/h, 64 users on 1.6 MHz carrier	E_b/N_0 = 8.9 dB	E_b/N_0 = 6.9 dB

According to Table 6.2 CDMA/TDMA needs about 2.0..3.0 dB higher E_b/N_0 than WB-TDMA. Both schemes have the same amount of frequency and time diversity. The difference is due to different receiver algorithms. In WB-TDMA a 5-tap soft output Viterbi algorithm has been used for equalization while in CDMA/TDMA a ZF-BLE algorithm has been used. WB-TDMA offers a better performance with lower receiver complexity.

An analysis of the basic differences between CDMA/TDMA and pure CDMA (Wideband CDMA = W-CDMA) is shown in Table 6.3.

Table 6.3. Comparison of CDMA/TDMA and W-CDMA

	CDMA/TDMA	**W-CDMA**
Intra-cell interference	Joint detection receiver, no fast power control	Fast power control + long spreading codes, optional MUD
Receiver complexity	High complexity due to mandatory joint detection	Low complexity Rake receiver
E_b/N_0 performance	Higher E_b/N_0 requirements because no fast power control	Lower E_b/N_0 requirements because of fast power control
Inter-cell interference	Interference averaging with frequency and time hopping (or interference avoidance)	Interference averaging with processing gain
Frequency reuse	1 or higher	1
Spectrum requirements for one cell layer	1.6 MHz carrier With reuse > 1 and frequency hopping more spectrum needed	5.0 MHz
Macro diversity	No	Yes, not mandatory for

(soft handover)		non-real time services
Support for TDD	Flexible TDD	No flexible TDD
Single cell capacity	> 1 Mbit/s/MHz/cell	< 1 Mbit/s/MHz/cell

7. STATUS OF CDMA/TDMA PROPOSAL IN STANDARDIZATION

In European standardization in ETSI there are five concept groups

- W-CDMA
- OFDM
- WB-TDMA
- CDMA/TDMA
- ODMA

One concept will be chosen in ETSI within a few months to be standardization for UMTS. Hybrid CDMA/TDMA is one of the five concept groups in ETSI. The main concern about CDMA/TDMA is the lack of experiences on the link and system level performance of real implementations. Also the details of the CDMA/TDMA concept are quite much open.

Hybrid CDMA/TDMA has not been considered for standardization outside Europe. Therefore, it has no changes to become a global air interface.

8. CONCLUSIONS

Hybrid CDMA/TDMA system concept aims at combining the advantages of CDMA and TDMA. It is based on TDMA where there is an additional code division within each time slot. The CDMA/TDMA receiver is based on joint detection of all CDMA codes with one time slot. When comparing the CDMA/TDMA concept to pure TDMA, it does not offer any gain in performance. Also the complexity of CDMA/TDMA mobile receiver is higher than the complexity of TDMA or CDMA receiver. In European standardization CDMA/TDMA is one candidate for UMTS radio access system.

9. REFERENCES

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