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A Performance Analysis of TDMA and CDMA Based Air Interface Solutions for UMTS High Bit Rate Services

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ABSTRACT

Universal Mobile Telecommunications System (UMTS) has a target maximum user bit rate of 2 Mbit/s. We present a performance comparison between four TDMA schemes and one CDMA scheme that all can provide the required user data rate. Evaluation considers link level performance, noise limited uplink range and cellular capacity. Three different environments, indoor large room, street micro cell and urban macro cell, have been used. Results show that when sophisticated methods are utilized schemes based on both TDMA and CDMA access methods can provide very similar performance for implementing UMTS high bit rate services when many different environments are considered.

1. INTRODUCTION

Currently European Telecommunications Standards Institute (ETSI) is developing standard for a third generation mobile telecommunication system. The systems under specification by ETSI is called Universal Mobile Telecommunication System (UMTS). Key requirements of UMTS include wide variety of services (video telephony, high quality audio, teleshopping, etc.), user bit rates up to 2 Mbit/s, high spectrum efficiency compared to existing systems and high flexibility to introduce new services [1].

Air interface solutions for high bit rate services have been earlier developed in many research projects e.g. in ATDMA [2], CODIT [3] and in [15]. Recently, both TDMA and CDMA based air interface solutions fulfilling the UMTS maximum user data rate requirement were published in [4, 8]. Based on those studies we present a performance comparison of the two basic multiple access schemes.

Paper is organized such that in chapter 2 the air interface solutions are very briefly described. Chapter 3 presents the performance comparisons and chapter 4 final conclusions.

2. TDMA AND CDMA BASED AIR INTERFACE SOLUTIONS

2.1 TDMA solutions

Table 1 shows the four different system options that have been studied [4]. All options use linear Offset Quadrature Amplitude Modulation (OQAM) methods. Options 1 and 3 utilize Binary Offset QAM (BIN-O-QAM) i.e. 4-Offset QAM and options 2 and 4 use Quaternary-Offset-QAM (QUAT-O-QAM) i.e. 16-Offset QAM. The latter is more bandwidth efficient but requires naturally higher Carrier-to-Interference ratio (C/I) for same link level performance. Carrier bit rates for all the options are GSM compatible in the sense that they are integer divisions from the GSM 13 MHz clock. Options 1 and 2 are based on single wide band carriers whereas the options 3 and 4 are multicarrier solutions.

Table 1. TDMA system options

	Option 1	**Option 2**	**Option 3**	**Option 4**
Carrier bit rate (Mbit/s)	6.5	6.5	4x1.625	2x3.25
Channel separation (MHz)	4	2	4	2
Modulation	Binary Offset QAM	Quaternary Offset QAM	Binary Offset QAM	Quaternary Offset QAM

Punctured rate 1/3 convolutional code is used for channel coding. Interleaving is diagonal over 16 TDMA frames resulting in 80 ms delay. In the case of multicarrier options the channel coded and interleaved bits are demultiplexed to different subcarriers in order to exploit the frequency diversity efficiently. Dominant Interference Cancellation (IC) technique is used to enhance system performance [5, 6, 7].

The GSM compatibility has been taken into account in the TDMA frame structure, too. The TDMA frame is 4.615 ms long and it consists of 8 time slots. User bit rate per slot is 256 kbit/s. By allocating all the slots to one user we get 2 Mbit/s. For more detailed description see [4].

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2.2 CDMA solution

CDMA air interface is based on system presented in [8]. Downlink solution is near-orthogonal multicode multirate synchronous transmission. Pilot code channel is exploited for channel estimation in RAKE-reception. Spreading codes are allocated from Walsh-Hadamard code set shortened by one chip. Gold codes of the same length are used as scrambling codes to separate different base stations. Dual channel QPSK spreading modulation is exploited. The same spreading code is used for both I and Q branches but the scrambling codes are different.

Fast Power Control (PC) based on signal-to-interference ratio with command rate of 1 kbit/s in the downlink is employed. Frame control header transmitted at Physical Control CHannel (PCCH) is used to inform the receiver about the transmission rate of the next frame. Pulse shaping is carried out with square root raised cosine filters.

Flexible channel coding strategy allowing the transmission rate to be adjusted at 100 bit/s steps is used. Inner code is rate 1/3 convolutional code with constraint 9. Additional Reed-Solomon outer code can be used for lower BER services. Convolutional interleaving introducing 100 ms one-way delay was employed.

Uplink is based on reference symbol aided coherent reception with variable processing gain multirate scheme. Dual channel OQPSK spreading modulation with VL-Kasami codes augmented with one bit is applied. The reference symbols (1 ksymbols/s) are multiplexed with the data. Fast power control based on signal-to-interference ratio with command rate of 2 kbit/s is employed. Pulse shaping is carried out with similar square root raised cosine filters as in the downlink.

An ordinary RAKE-receiver followed by MultiUser Detection (MUD) unit is utilized in the base station in order to reduce interference [9]. In this paper MUD is used only to reduce interpath interference in the link simulation. In the system simulations no gain from MUD in canceling multiple access interference is assumed. In addition, antenna diversity is used in the base station. Forward error correction is arranged in the same way as in the downlink except convolutional code of rate 1/2 is applied. For more detailed description see [8].

3. PERFORMANCE COMPARISON

3.1 Link level performance

The link performance simulations were made using the wideband channel models defined in CODIT (COde DIvision Testbed) project [10]. The performance was simulated in micro (dense urban linear street, line-of-sight), indoor (large room) and macro (urban) cells. Maximum excess delays of the channels vary from indoor cell 0.2 μs to macro cell 2 μs. Mobile station speed was 3 km/h in indoor cell. In micro and macro cells both 3 and 36 km/h was used. Target BER was 10^{-3}.

In TDMA simulations slow frequency hopping was utilized. Maximum Likelihood Sequence Estimation (MLSE) equalizer was used in other cases except for single carrier options in macro cell environment where Decision Feedback Sequence Estimation (DFSE) was employed [11, 12].

In CDMA simulations three different chip rates of 5, 10 and 20 Mchip/s where considered. In the downlink simulations enough RAKE-fingers were allocated to gather all the signal energy. In the uplink simulations the number of RAKE-fingers was restricted in the case of macro channel in order to limit the complexity of the base station receiver with multiuser detector. Delays were assumed to be known which makes to CDMA results a bit more ideal than TDMA results.

Tables 2 and 3 show corresponding E_b/N_0 results for 10 and 20 Mchip/s CDMA system and BIN-O-QAM TDMA having 12 and 20 MHz bandwidths. Note that TDMA reuse is 1.

When considering the results shown in Table 2 performance of both TDMA options is relatively close to each other except for macro channel where the single wide band option have to resort to suboptimal DFSE equalizing method. Performance loss seem to be around 2 dB.

Table 2. Comparison of E_b/N_0 performance of BIN-O-QAM TDMA options with FH-3 to 10 Mchip/s CDMA. TDMA reuse is 1. No antenna diversity was utilized. FH-3 = frequency hopping over three frequencies

	micro 3	**micro 36**	**indoor 3**	**macro 3**	**macro 36**
TDMA option 1 1x4 MHz carrier, FH-3	8.9	7.2	6.3	7.1	6.3
TDMA option 3 4x1 MHz carriers, FH-3	7.0	6.4	7.0	5.2	4.5
CDMA downlink, no PC	12.3	8.8	9.3	6.8	6.3
CDMA downlink with PC	6.4	4.5	4.2	6.0	6.3
CDMA uplink with PC	3.6	3.5	3.6	5.5	9.5

Table 3. Comparison of E_b/N_0 performance of BIN-O-QAM TDMA options with ideal FH to 20 Mchip/s CDMA. TDMA reuse is 1. No antenna diversity was utilized.

	micro 3	**micro 36**	**indoor 3**	**macro 3**	**macro 36**
TDMA option 1 1x4 MHz carrier, ideal FH	4.6	4.8	4.5	6.2	6.2
TDMA option 3 4x1 MHz carriers, ideal FH	4.2	4.2	4.2	4.3	4.3
CDMA downlink, no PC	9.0	6.8	6.8	5.3	4.8
CDMA downlink with PC	4.0	4.0	3.6	5.3	4.8
CDMA uplink with PC	4.1	3.5	3.3	6.2	5.7

CDMA downlink without PC performs worse than TDMA in micro and indoor channels. In macro channel results are practically equal. With PC CDMA downlink outperforms TDMA by more than 2 dB in micro and indoor channels. Note the superior performance of CDMA uplink:

E_b/N_0 values are 1-5 dB better when compared to TDMA and CDMA downlink with PC in other channels than macro 3 km/h or macro 36 km/h. Relatively poor performance of CDMA uplink in macro channel is due to fact that not all energy was captured by Rake receiver. In addition, even poorer result for macro 36 km/h is due to use of BPSK data modulation instead of QPSK which was used in other cases. Results show, however, how critical the number of Rake fingers is to CDMA performance when the processing gain is very small. The same phenomena was experienced in CDMA downlink.

If we further widen the bandwidth (Table 3) results converge for all of the options very close to each other. Use of DFSE equalizer in single wide band carrier TDMA and limited number of Rake fingers in CDMA uplink somewhat deteriorate the results. Note that now TDMA gives practically same results in all environments even without PC as CDMA uplink with PC. CDMA downlink without PC is inferior to TDMA options in micro and indoor channels.

3.2 *Cell range*

The noise limited uplink cell range in indoor, micro and macro cell environments was calculated according to the empirical path loss models presented in [10]. For the macro cell environment, the Hata model was used (with a path loss factor of 3.6). For the micro cell environment, the Sakagami-Kuboi model with the base station height of 25 m was used. For the indoor environment, the Motley model, which assumes free space attenuation between walls, was used. In the indoor range calculation, an environment with three floors and 10 light walls was assumed.

As results are somewhat dependent on bandwidth and/or reuse factor (TDMA) the following comparison is for 10 Mchip/s CDMA vs. 12 MHz TDMA. For TDMA two scenarios are considered: reuse 1 and reuse 3. Moreover, as many hopping frequencies are utilized as possible. In all cases the single cell range is considered. Thus handover gains and handover margins play no role here. CDMA range results are based on link level simulations with constant maximum power, i.e. without power control. These link level results are shown in [9].

Due to limited space only micro 3 km/h results are shown in Tables 4 and 5. At reuse 1 TDMA options seem to give slightly better range. Note that difference between BIN-O-QAM and QUAT-O-QAM options is quite small: QUAT-O-QAM gives range that is about 80 % of the range of BIN-O-QAM. Increasing the reuse seems to affect more the QUAT-O-QAM than BIN-O-QAM. Even though CDMA with fast PC gave better link level performance in micro 3 km/h channel that advantage is lost here as no PC can be used. Thus TDMA options give somewhat better range at reuse 1 than CDMA but difference is not that big. Increasing the reuse factor shortens the TDMA ranges as link level performance deteriorates. At reuse 3 BIN-O-QAM TDMA ranges are very close to CDMA, though.

Table 4. Uplink range comparison of 10 Mchip/s CDMA and 12 MHz TDMA options for a single cell case in micro 3 km/h channel. TDMA reuse is 1. BTS antenna height is 25 m. Unit is km.

	Tx power			
	1 mW	**100 mW**	**1 W**	**10 W**
CDMA uplink, no PC	0.19	0.61	1.10	1.99
1x4 MHz TDMA option 1 FH-3	0.20	0.65	1.18	2.12
1x2 MHz TDMA option 2 ideal FH	0.21	0.69	1.25	2.25
4x1 MHz TDMA option 3 FH-3	0.23	0.74	1.34	2.41
2x1 MHz TDMA option 4 ideal FH	0.21	0.69	1.25	2.26

Table 5. Uplink range comparison of 10 Mchip/s CDMA and 12 MHz TDMA options for a single cell case in micro 3 km/h channel. TDMA reuse is 3. BTS antenna height is 25 m. Unit is km.

	Tx power			
	1 mW	**100 mW**	**1 W**	**10 W**
CDMA uplink, no PC	0.19	0.61	1.10	1.99
1x4 MHz TDMA option 1 no FH	0.14	0.45	0.82	1.47
1x2 MHz TDMA option 2 FH-2	0.13	0.43	0.77	1.39
4x1 MHz TDMA option 3 no FH	0.18	0.58	1.05	1.89
2x1 MHz TDMA option 4 FH-2	0.15	0.47	0.85	1.53

As the comparison shows TDMA and CDMA ranges using same number of modulation levels are very much the same. This should not surprise anybody. If CDMA can be operated in practice using reuse 1 it will have better single cell range than TDMA with higher reuse factor because of better frequency diversity. If interference due to other users is taken into account that advantage of CDMA disappears.

3.3 *Cell capacity*

The capacity of the cellular network using either TDMA or CDMA based approaches was estimated with the aid of the simulations. Adjacent Channel Interference (ACI) was not taken into account which makes the results somewhat optimistic. The capacity was assessed only for the micro and the macro cells. The path loss in the macro cell was calculated with Okumura-Hata model [13]:

$$L = 131 + 36\log_{10}(d)\ [db] \qquad (1)$$

where d is the distance (in kilometers) from the transmitter to the receiver. The shadow fading is modeled by adding an uncorrelated Gaussian stochastic variable (mean 0 dB and standard deviation 6 dB) to the path loss L.

The capacity is assumed to be interference limited (or load limited) and the C/I threshold values were determined for the BER level 10^{-3} and outage requirement of 5 %. The interfering users in the other cells were assumed to be 2 Mbit/s users, too.

The micro cell environment was modeled using a Manhattan grid with block size of 100 m and junctions of 30 m x 30 m. The base stations were located in every second corners. The standard deviation for shadowing value was 4 dB. The path loss for line-of-sight connection was given by the following equations:

$$L_{LOS} = 82 + 20\log_{10}(\tfrac{d}{300}) \quad [db] \quad if\ d \le 300\,m \qquad (2)$$

$$L_{LOS} = 82 + 40\log_{10}(\tfrac{d}{300}) \quad [db] \quad if\ d > 300\,m \qquad (3)$$

where d is distance in meters. In the case of non-line-of-sight connection, the corner effect is taken into account by the following equation:

$$L = L_{LOS}(d_{CORNER}) + 17 + 0.05 d_{CORNER} + (25 + 0.2 d_{CORNER}) \log_{10}(\tfrac{d}{d_{CORNER}}) \qquad (4)$$

where d_{corner} is the distance between the transmitter and the corner and d is the distance between the transmitter and the receiver

In TDMA simulations the best network configurations were found by experimenting different reuse factors. The introduction of large reuse factors and wideband carriers (2-4 MHz) restricts the potential frequencies to be used for frequency hopping. This was taken into account both in the link and the network level simulations by modeling the actual hopping frequencies. The Rayleigh fading of the transmission channel is averaged in the link level simulations and the interference fluctuation due to a number of other users is averaged in the network simulations.

CDMA results for 10 Mchip/s chip rate are summarized into Table 6. When calculating the CDMA capacities it has been assumed that the channel spacing is the same 12 MHz as for TDMA. TDMA results for total operator bandwidth of 12 MHz are shown in the Tables 7 and 8.

TDMA downlink capacities for reuse factor 1 in macro 3 km/h case range from 100 to 140 kbit/s/MHz/cell. This is somewhat higher than CDMA capacity of 80 kbit/s/MHz/cell. One reason for this is the IC which is used in TDMA also in the downlink direction. When the reuse factor is increased the TDMA capacities deteriorate so that at reuse factor 3 they are comparable to CDMA results. This shows how the usefulness of IC decreases as reuse factor increases. Absolute capacity in all of the cases is very low, though.

In micro 3 km/h case CDMA achieves the downlink capacity of 220 kbit/s/MHz/cell. Now TDMA results ranging from 160 to 300 kbit/s/MHz/cell for BIN-O-QAM schemes are comparable to the CDMA results. Note that QUAT-O-QAM gives better capacities (from 300 to 520 kbit/s/MHz/cell) in this environment than BIN-O-QAM. This is in line with results presented in [14].

Table 6. Capacity results of CDMA uplink and downlink for 10 Mchip/s chip rate and 12 MHz bandwidth. In uplink direction antenna diversity was employed.

	Capacity kbit/s/MHz/cell	
	macro 3	**micro 3**
CDMA downlink	80	220
CDMA uplink	220	460

Table 7. Capacity results of TDMA downlink for 12 MHz bandwidth.

	Capacity kbit/s/MHz/cell					
	macro 3			**micro 3**		
Option	**reuse 1**	**reuse 3**	**reuse 6**	**reuse 1**	**reuse 3**	**reuse 6**
1	100	60	N/A	280	160	N/A
2	100	60	40	520	340	N/A
3	140	100	N/A	300	160	N/A
4	100	60	40	460	300	N/A

Table 8. Capacity results of TDMA uplink for 12 MHz bandwidth. Antenna diversity was employed.

	Capacity kbit/s/MHz/cell					
	macro 3			**micro 3**		
Option	**reuse 1**	**reuse 3**	**reuse 6**	**reuse 1**	**reuse 3**	**reuse 6**
1	160	160	N/A	400	160	N/A
2	140	100	100	780	340	N/A
3	220	160	N/A	420	160	N/A
4	140	120	120	660	340	N/A

CDMA uplink capacities are very good. In macro and micro cells they are 220 and 460 kbit/s/MHz/cell, respectively. Here the MUD is used only to reduce interpath interference. TDMA uplink results in macro 3 km/h case are slightly worse even at reuse factor 1. In micro 3 km/h case CDMA results are slightly better than TDMA when same 4-level modulation is used. This is mainly due to fast PC that improves in this case the link level performance of CDMA quite considerably. Also here QUAT-O-QAM modulation gives clearly better results over the BIN-O-QAM modulation.

The main reason for higher micro cell capacities over macro cell capacities is the different propagation model in different environments. This causes higher cell isolation and thus higher capacity in micro cell.

The effect of fast power control in CDMA can be analyzed e.g. with micro 3 km/h uplink results. In link simulations without antenna diversity CDMA has 5.3 dB (3.6 dB vs. 8.9 dB) lower E_b/N_0 value than TDMA option 1. In capacity, however, the difference is only 15 % (460 vs. 400 kbit/s/MHz/cell). Fast power control in CDMA mobile improves the link performance in terms of received energy but increases the average transmission power and thus interference generated to other cell base stations. Another reason for high TDMA capacity is intercell interference cancellation at the base station.

4. CONCLUSIONS

As a conclusion on the performance comparison between all the TDMA options and the CDMA concept results are quite close to each other when transmission of 2 Mbit/s user data is considered. In some channel conditions the fast PC of CDMA gives some advantage in E_b/N_0 values when frequency diversity alone do not give the full benefit. However, link level results for 20 MHz bandwidth showed how no additional gain can be obtained from fast PC.

Advanced receiver structures including interference cancellation can be used to improve the capacity of both TDMA and CDMA networks. Therefore we can say that when sophisticated methods are utilized schemes based on both TDMA and CDMA access methods can provide very similar performance for implementing UMTS high bit rate services when many different environments are considered.

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