CELLULAR OFDM/CDMA DOWNLINK PERFORMANCE IN THE LINK AND SYSTEM LEVELS

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Abstract -- In this paper the link and system level performance of a cellular OFDM/CDMA downlink is evaluated. A system level simulator is built to utilise the link level simulation results and to derive the actual network capacity. Three service transmission rates, i.e., 12 kbits/s, 144 kbits/s and 2 Mbits/s have been studied in the evaluation of the suitability of OFDM/CDMA as an UMTS multiple access method. The work has been performed within the European Union ACTS program in the FRAMES project.

I. INTRODUCTION

The requirements for the Universal Mobile Telecommunications System (UMTS) capability set high demands on the air interface of the 3rd generation mobile networks. In Europe, within the Advanced Communications Technologies and Services (ACTS) programme, the FRAMES (Future Radio Wideband Multiple Access Systems) project has the objective to define and specify a UMTS air interface.

At the beginning of the FRAMES project several multiple access solutions were proposed. After the initial evaluations, two hybrids were configured, namely: Hybrid I, SMA (Slotted Multiple Access) based on TDMA type transmission with an optional CDMA component; and Hybrid II, CATS (Code And Time Division Multiple Access System) using continuos CDMA type transmission. The two FRAMES hybrids are described in more detail in [1]. In addition, other details on the FRAMES Multiple Access (FMA), can be found in this proceedings [2].

CATS applied asynchronous and synchronous modes in the uplink. For the downlink it used singlecode, multicode as well as OFDM/CDMA options.

OFDM has gained a lot of interest in the field of communications, where it has been used for example in broadcast applications like DAB and various DTV solutions [3-4]. OFDM has also been considered earlier for 3rd generation mobile communication systems [5]. The OFDM methods studied in this paper follow the latter applications using OFDM/CDMA modes to combat frequency selective multipath fading, and to offer more resistance towards co-channel interference typical to cellular environments. The model utilises MLSE type detector, although other detector types, as studied in [6], could be used. The interference cancellation type receiver has also been applied with OFDM/CDMA in [7].

The capacity of a multiple access option is one of the key criteria in the air interface evaluation process. As an input for capacity studies link level performance parameters, i.e. values such as E_b/N_o for given BER, are used. These type of link level measurements for different schemes have solid ground because commercial signal processing simulation programs can be used to obtain the link level results of various multiple access techniques.

However, the system level issues are more complicated, because each multiple access scheme has its own demands on the modelling to provide capacity calculations. Thus, dedicated tools or programs are often designed to adequately estimate capacity, and to obtain other useful information on the strengths and weaknesses of a particular multiple access scheme. For the OFDM/CDMA downlink model this is precisely the case, special adaptations were made to a system level program to access its performance. Therefore, in the following we will briefly present the link and system level methods utilised in the evaluation process.

II. THE LINK LEVEL MODEL

In the studies done within FRAMES hybrid II, CATS, the OFDM/CDMA symbol was formed with 1024 subcarriers, using 2.5 MHz bandwidth and resulting in 409.6 µs duration. Guard intervals were inserted between successive OFDM/CDMA symbols to avoid intersymbol interference from the channel multipath. The transmitted signal on N subcarriers of the qth OFDM symbol can be given as

$$\mathbf{y_q} = \mathbf{C}\mathbf{s_q} = [\mathbf{c}_1\mathbf{c}_2\ldots\mathbf{c}_u]\mathbf{s_q} \qquad (1)$$

where the N x u matrix $\mathbf{C}$ is the spreading code matrix, consisting of u length N spreading sequences as its' columns. $\mathbf{s_q}$ is an u vector consisting of the symbols transmitted with these u different spreading codes. The introduction of CDMA component brings frequency diversity to OFDM and allows better to combat the frequency selective fading on the subcarriers.

With long enough guard interval and the OFDM symbol being shorter than the time-coherence of the channel, the fading on each subcarrier will appear flat fading type and can be modelled with a complex attenuation term. Thus the received and de-multiplexed signal is then given as

$$\mathbf{z}_q = \mathbf{A}_q \mathbf{C}_q \mathbf{s}_q + \mathbf{w}_\mathbf{q} \qquad (2)$$

where $\mathbf{A}_q = \mathrm{diag}(a_{q,1}a_{q,2}\ldots a_{q,N})$ is the channel co-efficient matrix, where the coefficients are time varying complex numbers.

In the evaluation process, the subcarriers were grouped in 256 sets of 4 subcarriers, each of them conveying 8 bits with specific codes to provide frequency diversity. Figure 1 illustrates the frequency allocation of the sets, where each spread block is assigned to one specific set.

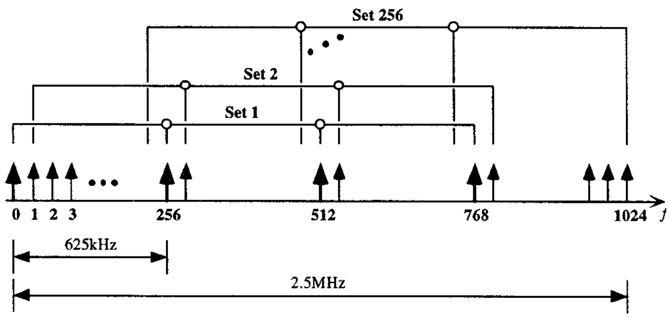

Fig. 1 Frequency allocation

The Maximum Likelihood Sequence Estimator (MLSE) method enabled detection with reasonable complexity. It evaluated the most likely transmitted sequence s_q by minimising the squared Euclidean distance δ^2 between the received and all possible transmitted sequences. Other sub-optimal and simpler approaches can also be found in [6].

The motivation to apply OFDM/CDMA technique in this paper only to the downlink was the feasibility of implementation, and the offered flexibility in terms of service mapping. Also low level of intra-cell interference was ensured. Furthermore, service mapping benefits from maximum diversity, by means of hopping, interleaving and distribution of the data on several subcarrier sets. In the uplink especially the synchronisation is more demanding.

III. LINK LEVEL RESULTS

The link level simulations were done with three different services. In the Macro-cell environment 12 kbit/s and 144 kbit/s were studied, and a pico-cellular channel model was used for 2 Mbits/s services.

Results were derived with both known channel parameters and with actual channel estimation having different amounts of overhead for pilot subcarriers. Fig. 2 illustrates non-optimised E_b/N_o values with the channel estimator used together with the results from the ideal estimation with known channel state. The results could be further improved to be nearer the ideal curve with more advanced channel estimator solutions.

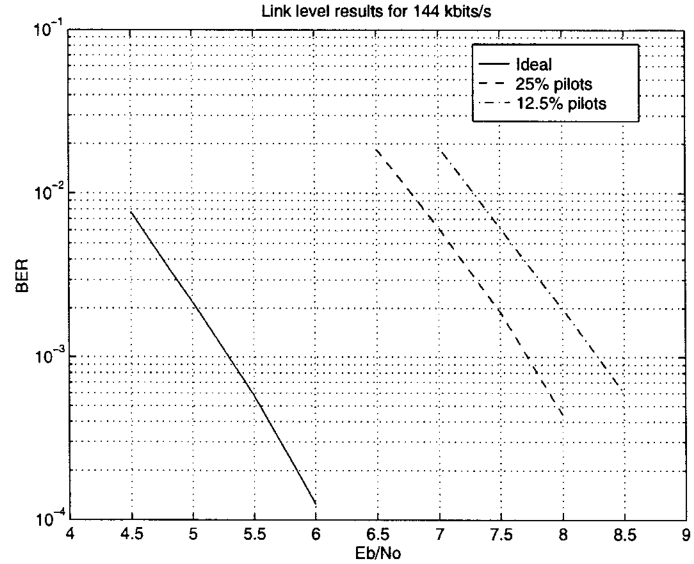

Fig. 2 E_b/N_o values with known channel parameters and with channel estimator using different amount of pilot subcarriers.

Table 1 Link level E_b/N_o values used in the system simulations

Service	E_b/N_o
12 kbit/s, macro	7.9 dB
144 kbit/s, macro	7,9 dB
2 Mbits/s, pico	6,5 dB

Table 1 illustrates E_b/N_o values used in the system simulations. Notice that for the 12 and 144 kbit/s services the non-optimised channel estimation values were used. For the 2 Mbit/s services the E_b/N_o level was estimated more realistically considering lower fading effects in the indoor environment. Table 2 illustrates other link level simulation parameters.

In the preceding link level results each service was specified by its user data rate and its maximum end-to-end delay. The latter took into account the coding time, interleaving of the corresponding symbols, and the complementary processes at the receiver. 12 kbit/s with 40 ms delay represented telephone or voice services, while 144 kbit/s with 100 ms delay represented data services. High data rate transmission at 2 Mbits/s did not have delay restrictions, the resulting delay from interleaving in the simulations was 40 ms. Interleaving had higher impact on E_b/N_o values of the lower rate services than those of the 2 Mbits/s transmissions.

Table 2 Link level simulation parameters

Channel estimation	12.5 % pilot overhead, 20 % total overhead including guard times.
Spreading	Walsh-Hadamard, length 8
Bandwidth	2.5 MHz, Carrier spacing 3 MHz.
Modulation	QPSK
Detector	256 state MLSE
Coding	1/2 Convolutional with constraint length 9
Pulse shaping	Raised cosine
OFDM symbol duration	0.4096 ms
Guard Interval	0.004 ms

Finally, it should be mentioned that the link level results presented in this paper are initial values with models simulated at full loads.

IV. SYSTEM LEVEL SIMULATOR

The system level performance, i.e. cellular capacity was evaluated in two different environments. The environments chosen for OFDM/CDMA for system level studies were macro and micro-cellular environments. The indoor environment at the system level is not covered in this paper. The simulation approach was static, i.e. independent snapshots were observed.

The basic equation for the C/I of a user and a carrier with OFDM/CDMA in the case of synchronously arriving signals is:

$$(C/I)_i = \frac{P_{Rx,i} G_p}{\sum_{\substack{j=0 \\ j \neq i}}^{N} \alpha_j \cdot P_{Rx,j} + \sum_{k=0}^{M} \beta_{IC} \cdot P_{Rx,k}^{tot} + N_0} \qquad (3)$$

In the above equation, $P_{Rx,i}$ is the receiver power of the carrier *i*. $P_{Rx,k}^{tot}$ is the total received power from BTS *k*. G_p is the processing gain, α_j is the orthogonality factor for intra-cell interference, β_{IC} models the orthogonality loss due to un-ideal channel estimation and due fading multipath channel, and N_0 models the thermal noise. Since the system level simulations model the interference limited case, N_0 can be neglected. The orthogonality factor α_j models how much the *j*th subcarrier that was received from the same BTS interferes the observed carrier. The parameter γ models the orthogonality between the signals from different BTS.

We can assume orthogonality inside the cell, since intra-cell interference was already included in the E_b/N_o values from the link level simulations. Thus, the term including its own cell interference will be

$$\sum_{\substack{j=0 \\ j \neq i}}^{N} \alpha_j \cdot P_{Rx,j} = 0 \qquad (4)$$

For inter-cell interference DS-CDMA type interference where the interference spreads over the whole bandwidth was assumed as signals come via different channels with different propagation delays and multipaths and thus do not remain orthogonal and as the subcarrier set allocation was random. Because the network is also asynchronous, both β_{IC} and γ will have value 1. Since the interference is not always spread over the whole bandwidth the value for γ would be then less than one and the bandwidth considered for the interference less than the total bandwidth. Also the use of Dynamic Channel Allocation (DCA) requires modifications to the used notation.

The equation for single carrier is now given as

$$(C/I)_i = \frac{P_{Rx,i} \cdot G_p}{\left[\sum_{k=0}^{M} \beta_{IC} \cdot P_{Rx,k}^{tot} \right] \cdot \gamma} \qquad (5)$$

The equation for a single user will be now

$$C/I = \frac{P_{Rx} G_p}{\left[\sum_{k=0}^{M} \beta_{IC} \cdot P_{Rx,k}^{tot} \right] \cdot \gamma} \qquad (6)$$

where

$$P_{Rx} = \sum_{i=0}^{N} \frac{P_{Rx,i}}{N} \qquad (7)$$

The power control concept is such that all the subcarriers (all the users) have the same transmission power within a BTS. The transmission power used depends on the measurements performed by all the mobiles. An approach where parts of the OFDM/CDMA symbols have slightly higher power, was also tested, but resulted in lower orthogonality inside the OFDM/CDMA symbol in the link level.

Thus, in the power control algorithm the C/I was measured for each mobile and the power balancing was made without command errors. The power control error due to the errors in measurements, channel state changes and errors in signalling, was modelled by adding a lognormal variable with 3 dB variance to the transmission power level.

In the macro-cellular environment, the following pathloss notation was used, with the assumption for the carrier frequency to be around 2.0 GHz.

$$L = 29 + 36\log_{10}(R) + 31\log_{10}(f) \qquad (8)$$

The shadow fading in the macro-cellular environment was modelled as a lognormally distributed variable with standard deviation 10 dB. The macro-cellular base stations were placed on a hexagonal grid

In the system level micro-cell simulator the base stations were located in every second street corner as illustrated in Fig. 3. The shadowing in the micro-cell environment was a lognormally distributed variable with 4 dB standard deviation. The buildings along the streets formed a heavy separation between micro-cells on different streets. The attenuation as a function of distance was modeled with a three slope model. Slopes are non-line-of-sight slope, and line-of-sight slopes for short distances and for long distances. If the connection between transmitter and receiver was a line-of-sight link, the attenuation is calculated as

$$L_{LoS} = \begin{cases} 82 + 20\log(\frac{x}{300}), if \quad x \le 300 meters \\ 82 + 40\log(\frac{x}{300}), if \quad x > 300 meters \end{cases} \quad (9)$$

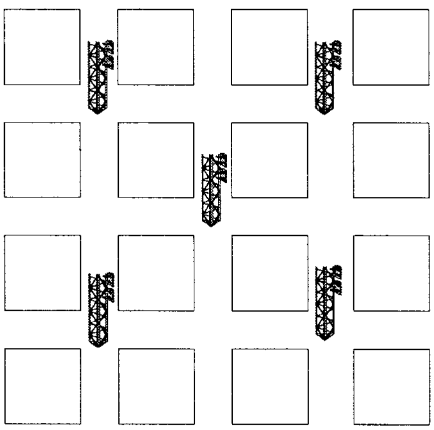

Fig. 3 The base station deployment in micro-cellular system level simulator.

At a distance of 300 meters a breakpoint marks the separation between two line-of-sight segments. Turning round a corner causes an additional loss, L_{corner},. Attenuation between a transmitter and a receiver that have non-line-of-sight connection constitutes a line-of-sight segment, a non-line-of-sight segment, and an additional corner attenuation, as seen in (10).

$$L_{nLoS} = L_{LoS}(x_{corner}) + 17 + 0.05x_{corner} + (25 + 0.2x_{corner})\log(\frac{x}{x_{corner}}) \quad (10)$$

Line-of-sight attenuation is calculated between a corner and receiver, and non-line-of-sight connection between a corner and transmitter.

V. CAPACITY RESULTS

Table 3 illustrates the values from the cellular capacity simulations for 12 kbits/s, 144 kbits/s and 2 Mbits/s without Dynamic Channel Allocation (DCA) techniques.

Table 3 OFDM/CDMA spectral efficiency values for 5 % outage with reuse order of 3.

Service	Spectral efficiency [kbit/s/cell/MHz]
12 kbits/s	58 (macro-cell)
144 kbits/s	60 (macro-cell)
2 Mbits/s	240 (micro-cell)

Other results including DCA, showed potential for improvement up to 45-50 % with the lower rate services.

In the spectral efficiency values scaling corresponding 3 MHz carrier spacing was assumed. The signal -3 dB bandwidth is 2.75 MHz, but the actual carrier spacing to be used depends on the requirements set to the spectral mask and also from the spectral spreading due to the power amplifier. In the base station transmitter the use of highly linear amplifier is not considered to be that critical when compared to the mobile terminal. Thus moderate spectral spreading can be expected and the required carrier spacing is supposed to be 3 MHz or less.

Based on the studies it could be noted that reuse 1 with OFDM/CDMA does not provide optimum results, higher reuse order is clearly needed for efficient operation.

The power control algorithm used had problems since the users share the same OFDM/CDMA symbol. Thus, setting different power level for different users was difficult. This resulted in that for part of the users the received signal level was too high, and thus generating unnecessary interference to the surrounding cells. This was the main reason for the lower capacity with 12 kbits/s and 144 kbits/s when compared to the 2 Mbits/s service.

With 2 Mbits/s the problem with OFDM/CDMA power control was not relevant as a single 2.5 MHz carrier can support only a single user and thus power level can be adjusted optimally accordingly. The cell isolation was also much better in the micro-cellular environment than in the macro-cellular environment.

VI. CONCLUSIONS

The link and system level performance of cellular OFDM/CDMA downlink was evaluated in this paper. As a multiple access method the OFDM/CDMA can fulfil UMTS requirements in providing the required range of services up to 2 Mbits/s.

From the system level results can be concluded that for cellular applications OFDM/CDMA works better with higher reuse values than 1, when the power control mechanism is not optimised. Also the case of having several users sharing the same OFDM/CDMA symbol in the environments with low cell isolation causes degradations in capacity as the power control implementation for several low rate users is difficult.

The power control commands needed when coupled with DS-CDMA in the uplink caused some limitations since the OFDM/CDMA symbols used in the present model were too long for the fast power control mechanisms used. Thus command rates in the order of 1 or 2 kHz could not be implemented in the downlink transmission for the mobile direction. However, it should be noted that the symbol length could be reduced with other configurations.

Therefore, when using adaptable power control and shorter symbols, OFDM/CDMA downlink coupled with DS-CDMA detection techniques in the uplink, would be an interesting alternative to balance restrictions seen in typical DS-CDMA systems. For example, OFDM/CDMA based systems tend to be less susceptible to traffic loads. Changes in the length of the symbol would affect the diversity properties of the OFDM/CDMA.

On the other hand, the use of present OFDM/CDMA model could also perform well when put together with FRAMES Multiple Access (FMA) Mode 1. There the transmission is naturally slotted, and applicability is not be restricted to the use of fast power control and reuse factor of 1, expedient in DS-CDMA based systems to obtain high capacity gains. In the further work of the FRAMES project the OFDM/CDMA will be studied as a modulation option within the FMA Mode 1 work.

In an environment having higher cell isolation, OFDM/CDMA achieves comparable capacity with 2 Mbit/s with a minimum power control when compared to DS-CDMA downlink utilising RAKE receivers in the mobile terminals. This kind of examples of the utilisation of OFDM can also be found for example in the ACTS project WAND [8] where OFDM is used for indoor wireless LAN type high bit rate applications.

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REFERENCES

[1] T. Ojanperä et al.,"FRAMES - Hybrid Multiple Access Technology", ISSSTA'96 Mainz, Germany. In Proceedings, pp. 320-324, September 1996.

[2] T. Ojanperä et al., "Comparison of Multiple Access Schemes for UMTS", VTC'97, Phoenix, Arizona, USA, In Proceedings, May 1997.

[3] M. Alard and R. Lassalle, "Principles of Modulation and Channel Coding for Digital Broadcasting for Mobile Receivers," EBU Review, Tech. No. 224, Aug. 1987, pp. 47-69.

[4] K. Fazel, S. Kaiser, P. Robertson and M.J.Ruf, "A Concept of Digital Terrestrial Television Broadcasting," Wireless Personal Communications, vol. 2, No. 1 pp. 9-27, 1995.

[5] K. Fazel, S. Kaiser and M. Schnell, "A Flexible and High Performance Cellular Mobile Communications System Based on Orthogonal Multi-Carrier SSMA, " Wireless Personal Communications, vol. 2, No. 1, pp. 121-144, 1995.

[6] S. Kaiser, "On the Performance of Different Detection Techniques for OFDM-CDMA in Fading Channels," Globecom'95, Singapore, In Proceedings, pp. 2059-2063.

[7] K. Kalliojärvi, "Interference Cancellation in OFDM-CDMA Systems", IEEE Nordic Signal Processing Symposium, Espoo, Finland. In Proceedings, September 24-27.1996, Espoo, Finland

[8] J. Mikkonen, J. Kruys, "The Magic WAND: a Wireless ATM Access System", ACTS Mobile Telecommunications Summit, Granada, Spain, In Proceedings, pp. 535-542, November 1996.