Layered Space–Frequency Coded Downlink MC–CDMA in a Cellular System

Jouko Leinonen, Mikko Vehkaperä, Zexian Li and Markku Juntti

Centre for Wireless Communications
P.O. Box 4500, FIN-90014 University of Oulu, Finland
tel. +358 8 553 2968, fax. +358 8 553 2845
{jouko.leinonen, mikko.vehkapera, zexian.li, markku.juntti}@ee.oulu.fi

***Abstract*— We consider downlink multi–carrier code–division multiple–access (MC–CDMA) in a multi–cell environment. To achieve good error rate performance and high spectral efficiency, multiple transmit and receive antennas with strong space–frequency channel coding and layered space–time (LST) architecture are applied. We study the performance of the minimum mean squared error (MMSE) based receivers in an interference limited environment. The inter–cell interference suppression in MMSE detection and iterative detection method with soft co–antenna interference (CAI) cancellation are considered. The results indicate that the interference suppression methods in MMSE detection provide remarkable performance improvements, especially in the case of spatially correlated antennas. Furthermore, the considered MIMO MC–CDMA system seems to provide a very promising solution for achieving high date rates in downlink packet access for future cellular networks.**

I. Introduction

The combination of orthogonal frequency division multiplexing (OFDM) and code–division multiple–access (CDMA), known as multicarrier–CDMA (MC–CDMA), is a promising air interface for future communication systems [1]. OFDM is attractive due to its low equalization complexity and robust performance on highly dispersive communication channels. If cyclic guard interval is longer than the maximum delay spread of the channel, inter–symbol interference (ISI) can be mitigated completely. CDMA is combined with OFDM technique in order to provide efficient utilization of radio resources in the cellular communication systems.

In a rich scattering environment the use of multiple antennas at the transmitter and receiver provides potentially a dramatic capacity increase with respect to the single antenna systems [2]. The capacity of the multiple–input multiple–output (MIMO) channels can be exploited for example by pragmatic layered space–time (LST) architectures [3], where spatial multiplexing at the transmitter and spatial filtering at the receiver are commonly used. MC–CDMA system with groupwise LST architectures and space–time turbo coded modulation (STTuCM) [4], applied in space–frequency domain, has been previously studied in a single cell environment in [5], [6]. The 4×4 MIMO MC–CDMA with LST and space–frequency turbo coded modulation (SFTuCM) was found to be able to provide quadrupled throughput with several dB better frame error rate (FER) performance compared to the conventional turbo coded single–antenna MC–CDMA.

The benefit of the CDMA, compared to the other multiple access techniques such as time division multiple access (TDMA) and orthogonal frequency division multiple access (OFDMA), is to provide frequency reuse one in the cellular system with less complex radio resource management processing. However, the transmission at the same time and at same frequency in the adjacent base stations cause significant interference for the users in the neighboring cells [7]. The cellular MC–CDMA concepts has been considered previously, e.g., in [8], [9], [10]. The BLAST detection techniques with co-antenna interference (CAI) and inter–cell interference cancellation have been studied in [11], where convolutional coding and frequency flat fading channel is assumed. In this paper, we extend the work of broadband MIMO MC–CDMA in the multi–cell environment to consider layered transmission with space-frequency coding, frequency selective channel, iterative detection with CAI cancellation, inter–cell interference suppression by MMSE detection and impact of antenna correlation.

The paper is organized as follows. Section II describes the MC–CDMA system model. Section III explains the structure of the MMSE based multiuser detectors for the MIMO MC–CDMA system. Section IV presents the performance simulations of the considered systems. Section V concludes the paper.

II. System Model

A downlink MC–CDMA cellular system shown in Figure 1 with K users in each cell is considered. The desired user is located in the central cell. The same transmission parameters are used in all base stations and for all users. The MIMO MC–CDMA system has N_c subcarriers, N transmit antennas and M receive antennas. The input bits are encoded by conventional turbo coding (TC) or by SFTuCM [4]. We divide the N transmit antennas available in the system into $J = N/J_0$ independent layers, where J_0 denotes for the number of antennas associated with the specific encoder so that $J_0 = 1$ in single antenna turbo code and $J_0 = 2$ in SFTuCM. Vertical layering is applied, where the encoded

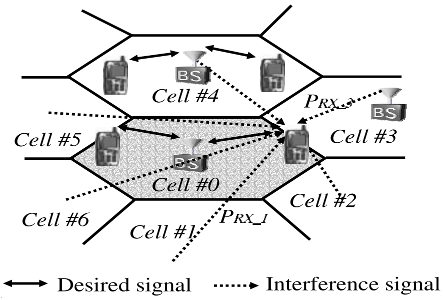

Fig. 1. Multi–cell model in the downlink case.

and modulation mapped symbols are multiplexed for transmit antenna groups [3]. A stream of $P = N_c/G$ QPSK mapped symbols $[x_1, \ldots, x_P]$ is assigned for each transmit antenna in one OFDM symbol. Each symbol x_p is multiplied with the spreading code $[d_1^k, \ldots, d_G^k]$ with length of G, where index k refers to the kth user. Note, that in the case of $K = G = 1$ the system uses conventional OFDM technique. The guard interval of length T_g is inserted as a prefix for the OFDM symbol to remove inter–symbol interference (ISI). One coded frame includes N_s OFDM symbols and N_sP coded symbols per transmit antenna. The kth user equivalent baseband transmitted MC–CDMA signal at the nth antenna is expressed as

$$s_n^k(t) = \sum_{i=-\infty}^{\infty} \sum_{p=1}^{P} \sum_{g=1}^{G} x_{p,n}^k(i) \mu_g^k p_s(t - iT_s) \exp\left(j2\pi(g + pP)\Delta f(t - iT_s)\right) \quad (1)$$

where T_s is the symbol duration, $\Delta f = 1/(T_s - T_g)$ is the minimum subcarrier separation, and $p_s(t)$ is the pulse waveform. A combination of the cell specific scrambling code and the spreading code sequence is denoted as μ_g^k.

The received signal consists of the desired signal, multiple access interference (MAI), i.e., intra–cell interference, inter–cell interference and Gaussian distributed thermal noise. After FFT and receiving the whole coded frame, the equivalent frequency domain received signal of the MIMO system at the ith OFDM symbol and the pth code symbol interval can be rearranged in the form

$$\boldsymbol{r}_p[i] = \boldsymbol{C}_{p,0}\boldsymbol{x}_{p,0}[i] + \sum_{q=1}^{6} \boldsymbol{r}_{p,q}[i] + \boldsymbol{\eta}_p[i], \quad (2)$$

where $\boldsymbol{C}_{p,q}$ is an equivalent channel–spreading matrix from the qth base station to the central cell. Perfect synchronization of the desired base station transmission is assumed. After omitting i, p and q to simplify notation, a received signal vector, a transmit symbol vector, and the noise are written as

$$\begin{aligned} \boldsymbol{r} &= [r_1^1, \ldots, r_1^G, \ldots, r_M^1, \ldots, r_M^G]^{\mathrm{T}} \in \mathbb{C}^{MG} \\ \boldsymbol{x} &= [x_1^1, \ldots, x_N^1, \ldots, x_1^K, \ldots, x_N^K,]^{\mathrm{T}} \in \mathcal{M}^{NK} \\ \boldsymbol{\eta} &= [\eta_1^1, \ldots, \eta_1^G, \ldots, \eta_M^1, \ldots, \eta_M^G]^{\mathrm{T}} \in \mathbb{C}^{MG}. \end{aligned} \quad (3)$$

The channel–spreading matrix can be presented as

$$\begin{aligned} \boldsymbol{C} &= [\boldsymbol{c}_{1,1} \cdots \boldsymbol{c}_{1,N} \cdots \boldsymbol{c}_{K,1} \cdots \boldsymbol{c}_{K,N}] \in \mathbb{C}^{MG \times NK} \\ \boldsymbol{c}_n^k &= [(\boldsymbol{c}_{1,n}^k)^{\mathrm{T}}, (\boldsymbol{c}_{2,n}^k)^{\mathrm{T}}, \ldots, (\boldsymbol{c}_{M,n}^k)^{\mathrm{T}}]^{\mathrm{T}} \in \mathbb{C}^{MG} \\ \boldsymbol{c}_{m,n}^k &= [H_{m,n}^{\nu+1} d_1^k, H_{m,n}^{\nu+2} d_2^k, \ldots, H_{m,n}^{\nu+G} d_G^k]^{\mathrm{T}} \in \mathbb{C}^G, \end{aligned} \quad (4)$$

where $\nu = (p-1)G$ and $H_{m,n}^{\nu+g}$ contains Rayleigh fading channel coefficient, path–loss and shadowing between the Tx antenna n and the Rx antenna m at the subcarrier $\nu + g$. Since the received signal is multiplied by the desired cell scrambling code, $\boldsymbol{C}$ includes spreading codes only.

III. MMSE Detection in MIMO MC–CDMA

The MMSE based detectors for the multiple antenna MC–CDMA receivers used herein are based on the techniques presented in [5], [6], where a detailed description of the receivers can be found. We describe the receiver structures briefly and slight modifications to take inter–cell interference into account are presented.

A. Linear Symbol–Level MMSE Detector

In the joint space–frequency MMSE detector, the coded symbols $\boldsymbol{x}_0$ from (2) are jointly estimated over subcarriers and all transmit antennas. We assume that the channel of the desired cell is perfectly known at the receiver. The MMSE criterion based detector for the MIMO MC–CDMA system is [5],

$$\boldsymbol{W} = \left(\boldsymbol{C}_0 \boldsymbol{R}_{\boldsymbol{xx}} \boldsymbol{C_0}^{\mathrm{H}} + \boldsymbol{R}_{\mathrm{I}} + \boldsymbol{R}_{\boldsymbol{\eta\eta}}\right)^{-1} \boldsymbol{C}_0 \boldsymbol{R}_{\boldsymbol{xx}}, \quad (5)$$

where the matrix filter $\boldsymbol{W} = [\boldsymbol{W}_1 \boldsymbol{W}_2 \cdots \boldsymbol{W}_K] \in \mathbb{C}^{MG \times NK}$ is able to estimate the coded symbols for all users. The symbols are assumed to be uncorrelated between different antennas and subcarriers so that $\boldsymbol{R}_{\boldsymbol{xx}} = E_s \boldsymbol{I}_{NK}$, where E_s is the average energy of the transmitted symbols. Two different assumptions about the interference correlation matrix are used according to the knowledge of the interference channels. A) Fast fading of the interference channels is not known and the interference is assumed to be spectrally and spatially white so that $\boldsymbol{R}_{\mathrm{I}} = P_{\mathrm{I}} \boldsymbol{I}_{MG}$ [8], where P_{I} is the average power of the interference defined by the path loss and shadow fading. B) If the interference channels are known [11] and same spreading codes are assumed for each cell, the interference covariance is written as $\boldsymbol{R}_{\mathrm{I}} = \sum_{q=1}^{6} \boldsymbol{C}_q \boldsymbol{R}_{\boldsymbol{xx}} \boldsymbol{C}_q^{\mathrm{H}}$. The thermal noise term is $\boldsymbol{R}_{\boldsymbol{\eta\eta}} = N_0 \boldsymbol{I}_{MG}$.

The input for the symbol–level space–time maximum *a posteriori* (MAP) based turbo decoder is the soft output of the MMSE filter written as $\hat{\boldsymbol{x}} = \boldsymbol{W}_k^{\mathrm{H}} \boldsymbol{r}$. The space–time decoder for SFTuCM is presented in [4]. The residual interference of the output of the multiuser MMSE detector is approximated to be Gaussian distributed. The equivalent system model given for the decoder is $\hat{\boldsymbol{x}}_k = \boldsymbol{W}^{\mathrm{H}} \boldsymbol{r} = \boldsymbol{\Omega}_k \boldsymbol{x}_k + \boldsymbol{\varphi}_k \in \mathbb{C}^N$, where $\boldsymbol{\Omega}_k$ is equivalent channel estimate and residual inter–cell interference–MAI–plus noise term $\boldsymbol{\varphi}_k$ is considered to be Gaussian distributed with covariance $\boldsymbol{R}_{\boldsymbol{\varphi\varphi}}$ [5].

B. Linear Chip–Cevel MMSE Detector

The spreading codes of all users' in the desired cell must be available in the joint symbol–level MMSE multiuser detector. Spatial filtering and chip combining can be separated whereupon only the desired user signature is needed. Also the inversion of the $MG \times MG$ matrix in (5) is reduced to an inversion of a $M \times M$ matrix. The signal model in (2) can be rewritten as

$$\boldsymbol{r}^g = \boldsymbol{H}_0^g \boldsymbol{z}_0^g + \sum_{q=1}^{6} \boldsymbol{r}_q^g + \boldsymbol{\eta}^g, \qquad (6)$$

where $\boldsymbol{r}^g \in \mathbb{C}^{M\times 1}$ is the received signal at the gth subcarrier, $\boldsymbol{H}_q^g \in \mathbb{C}^{M\times N}$ is the channel matrix from the qth cell to central cell, and $\boldsymbol{\eta}^g \sim \mathcal{N}(\boldsymbol{0}, N_0\boldsymbol{I}_M)$ is the complex Gaussian random vector. The symbols $\boldsymbol{z}^g = [z_1^g, ..., z_N^g]$ to be detected are $z_n^g = \sum_k d_k^g x_{n,k}$, $n = 1, \ldots, N$. The filter matrix for the gth subcarrier of the pth symbol is

$$\boldsymbol{W}^g = \left(\boldsymbol{H}_0^g \boldsymbol{R}_{\boldsymbol{zz}} (\boldsymbol{H}_0^g)^{\mathrm{H}} + \boldsymbol{R}_{\mathrm{I}} + \boldsymbol{R}_{\boldsymbol{\eta\eta}}\right)^{-1} \boldsymbol{H}_0^g, \qquad (7)$$

where $\boldsymbol{R}_{\boldsymbol{zz}}$ is the covariance of $\boldsymbol{z}^g$ and $\boldsymbol{R}_{\mathrm{I}} = P_{\mathrm{I}}\boldsymbol{I}_M$ or $\boldsymbol{R}_{\mathrm{I}} = \sum_q \boldsymbol{H}_q^g \boldsymbol{R}_{\boldsymbol{zz}} (\boldsymbol{H}_q^g)^{\mathrm{H}}$. We assume that the spreading codes are random and the coded symbols are independent between antennas and users. Consequently, $\boldsymbol{R}_{\boldsymbol{zz}} \approx E_s(K/G)\boldsymbol{I}_N$. Symbol estimate for the user k in the antenna n is got by simple combining of G detected chips so that $\hat{x}_{k,n} = \sum_{g=1}^{G} s_k^g \hat{z}_n^g$, where $\hat{z}_n^g$ is nth element from output vector of the spatial filter $\hat{\boldsymbol{z}}^g = (\boldsymbol{W}^g)^{\mathrm{H}}\boldsymbol{r}^g$.

C. Iterative Detection and Decoding

In order to achieve better spatial receive diversity compared to the linear receiver, the principle of iterative detection and decoding (IDD) can be employed with the considered symbol–level SF–MMSE receiver [5]. The decoded decisions can be used for parallel interference cancellation (PIC) to mitigate the co-antenna interference (CAI) in an IDD based receiver. If hard decisions are used in interference cancellation, the error propagation may destroy the benefit of the IDD receiver. Thus, soft interference cancellation with IDD is seen to be advantageous and is considered herein.

Now we represent the received signal in (2) as

$$\begin{aligned} \boldsymbol{r} \;\; = \;\; & \boldsymbol{C}_{0,k,j}\boldsymbol{x}_{0,k,j} + \tilde{\boldsymbol{C}}_{0,k,j}\tilde{\boldsymbol{x}}_{0,k,j} \\ & + \tilde{\boldsymbol{C}}_0\tilde{\boldsymbol{x}}_0 + \sum_{q=1}^{6} \boldsymbol{r}_q + \boldsymbol{\eta}, \end{aligned} \qquad (8)$$

where first right hand side term is the kth user desired signal from layer j , the second term is the CAI of the desired user's received signal from layers $j' \neq j$, the third term denotes MAI and the fourth one is inter–cell interference term.

The initial soft decisions for the next detection iteration are made by using the linear symbol–level MMSE based detector described in Section III-A and the iterative decoder. The IDD receiver in which detection is based on the MMSE filtering [12] has been derived for MIMO MC–CDMA in [5]. The MMSE detector is updated based on the MMSE minimization written as

$$(\boldsymbol{W}_{k,j}, \Psi_{k,j}) = \arg\min_{\boldsymbol{W},\Psi} \mathrm{E}\left\{|\boldsymbol{x}_{k,j} - \boldsymbol{W}^{\mathrm{H}}\boldsymbol{r} - \boldsymbol{\Psi}|^2\right\} \qquad (9)$$

where $\boldsymbol{W}_{k,j} \in \mathbb{C}^{MG,J_0}$ is filter coefficient matrix and $\boldsymbol{\Psi}_{k,j} \in \mathbb{C}^{J_0}$ denotes the self–CAI cancellation term for the user k. Now the jth layer symbol estimate of SF–MMSE filter output is given by [5]

$$\hat{\boldsymbol{x}}_{k,j} = \boldsymbol{W}_{k,j}^{\mathrm{H}}\left[\boldsymbol{r} - \tilde{\boldsymbol{C}}_{k,j}\mathrm{E}\{\tilde{\boldsymbol{x}}_{k,j}\}\right], \qquad (10)$$

where filter matrix is

$$\boldsymbol{W}_{k,j} = \left(\boldsymbol{A} + \boldsymbol{B} + \boldsymbol{D} + (N_0 + P_{\mathrm{I}})\boldsymbol{I}\right)^{-1} \boldsymbol{C}_{k,j}, \qquad (11)$$

where $\boldsymbol{A} = \boldsymbol{C}_{k,j}\boldsymbol{C}_{k,j}^{\mathrm{H}}$, $\boldsymbol{D} = \tilde{\boldsymbol{C}}\tilde{\boldsymbol{C}}^{\mathrm{H}}$, $\boldsymbol{B} = \tilde{\boldsymbol{C}}_{k,j}[\boldsymbol{I}_{N-J_0} - \mathrm{diag}(E\{\tilde{\boldsymbol{x}}_{k,j}\}E\{\tilde{\boldsymbol{x}}_{k,j}\}^{\mathrm{H}})]\tilde{\boldsymbol{C}}_{k,j}^{\mathrm{H}}$. Assumption A) of inter–cell interference given in Section III-A is used, i.e., interference is considered as an additional spectrally and spatially white noise as seen from (11). The matrix $\boldsymbol{B}$ represents covariance of the residual CAI. When the symbol estimates $\mathrm{E}\{\tilde{\boldsymbol{x}}_{k,j}\}$ given in [5] are correct with high probability $\boldsymbol{B} \rightarrow \boldsymbol{0}$.

IV. Simulation Results

The simulation results to illustrate the performance of the considered systems in single cell and cellular environment are presented in this section. The number of the subcarriers is $N_c = 1024$, frame length is $G \cdot P \cdot N = Nc \cdot N$ symbols and antenna configuration of $N = M = 4$ is considered. Parallel concatenated convolutional code with [7,5] generation polynomial in octal form or SFTuCM with eight state constituent codes is applied in encoding. Decoding is based on the conventional log-MAP decoding in turbo coded (TC) case and on iterative space–time decoder with SFTuCM [13]. Eight decoder iterations are performed. The bandwidth of the signal is 100 MHz. The power delay profile (PDP) is assumed to be exponentially decaying with 32 taps. The decay factor between two adjacent channel tap in the PDP is set to be -1.35 dB and path separation is 8 samples. Uncorrelated (UC) or correlated fading is applied for the different transmit-receive antenna pairs. The spatial correlation is attained by using the "Kronecker"-model, where MIMO spatial correlation matrix $\boldsymbol{R}_{\mathrm{MIMO}}$ is based on the Kronecker product so that $\boldsymbol{R}_{\mathrm{MIMO}} = \boldsymbol{R}_{\mathrm{Rx}} \otimes \boldsymbol{R}_{\mathrm{Tx}}$. The first row of the antenna correlation matrix $\boldsymbol{R}_{\mathrm{Tx}}$ at the transmitter is $[1\ 0.75444 + j0.0829\ 0.4109 + j0.0938\ 0.2313 + j0.0803]$ and at the receiver $\boldsymbol{R}_{\mathrm{Rx}}$ is $[1\ -0.3043\ 0.2203\ -0.1812]$ in a high correlated (HC) case. The cyclic prefix of length $T_g = 2560$ ns, i.e., 256 samples is used so that ISI is completely removed. The quasistatic fading is applied due to the assumption of low mobility. In addition, the perfect channel knowledge and synchronization of the desired base station transmission are assumed.

In the multi–cell environment, the average power of the received signal and the interfering signals depend on the shadow fading and on the path losses between the base stations and the desired mobile station in the central cell. The path loss obeys COST 259 non–line–of–sight microcell model and it is $L(d) = 10 \cdot 2.6 \cdot \log_{10}(d) + 20\log_{10}(4\pi/\lambda)$, where d is distance from the base station in meters and λ is the wavelength. Central frequency of 2 GHz is assumed. The shadow fading is assumed to be log-normally distributed with standard deviation of 8 dB. The equal transmission power is assumed for every base station and co-channel interferers are transmitting all the time. We assume that signal–to–noise–plus–interference ratio

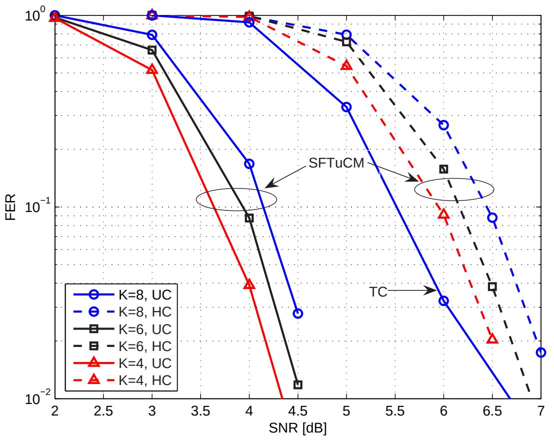

Fig. 2. Performance of the MIMO MC–CDMA with SFTuCM and linear SF–MMSE receiver in a single cell environment. Spreading factor is $G = 8$ and antenna configuration of $N = M = 4$.

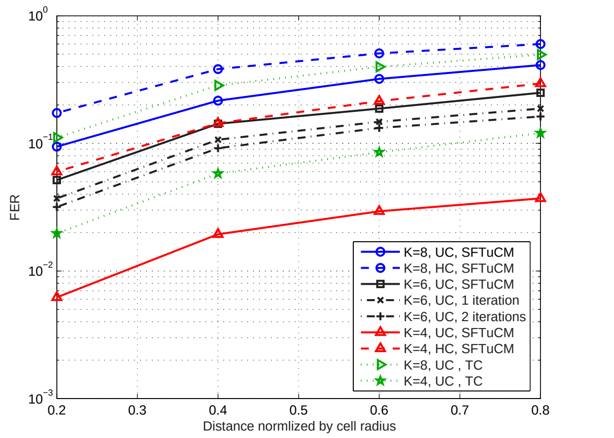

Fig. 3. FER vs. distance of a MC–CDMA system employing SFTuCM and symbol–level SF–MMSE receiver in multi–cell environment. Distance between base station and desired user is normalized by the cell radius. Spreading factor is $G = 8$ and antenna configuration of $N = M = 4$.

(SINR) can be kept positive with the help of soft handover. Thus, the channel realizations with SINR below zero are not considered due to the lack of soft handover in the simulation model.

Figure 2 shows the performance of the MIMO MC–CDMA system with TC and SFTuCM in single cell environment without path loss and shadowing. The curves represents the full loaded, $6/8 = 75\%$ loaded, and half loaded cases, respectively. We can note significant impact of the spatial correlation for the considered system.

The FER performance of the symbol–level and the chip–level receivers in a seven–cell environment with interference knowledge A) (see Section III-A) is shown in Figures 3 and 4 respectively. The distance of the user from the base station is normalized by the cell radius. We can see that the symbol–level receiver gives better performance than that of the chip–level one in the half loaded case. Figures 3 and 4 illustrate that good performance is not be achieved in fully loaded case because of the high interference due to the low soft handover threshold. In MC–CDMA the FER performance can be easily controlled by adjusting the number of the users at the cost of the reduced spectral efficiency of the system [9], [10]. The performance improves rapidly when there is no spatial correlation and the number of the users decreases. Figure 3 shows also the performance gain of the IDD receiver with the soft CAI cancellation compared to the linear receiver. The number of the users should be less than 75 % of the spreading factor in the uncorrelated case and less than 50 % of the spreading factor with spatial correlation that acceptable performance for the high rate downlink data packet transmission is achieved with suitable automatic repeat request (ARQ) protocol. Figures 2 and 3 also illustrate that multiplexed MIMO system with SFTuCM outperforms turbo coded system in FER performance.

Figure 5 shows the FER versus SINR performance of the MIMO MC–CDMA and OFDM systems when the knowledge of the interference channels is available at the receiver. The case A (csA) and case B (csB) of the knowledge of the interference channels are used (see Section III-A). Four interferers is assumed so that $P_{\mathrm{I},1} = P_{\mathrm{I},2} = 4P_{\mathrm{I},3} = 4P_{\mathrm{I},4}$, where $P_{\mathrm{I},q}$ is the received power from the qth cell. This represents usual interference distribution in the seven–cell model [11]. The OFDM system provides a slightly better performance than that of the MC–CDMA in fully loaded case. Especially, the significant improvement of the better interference suppression compared to the assumption of the spectrally and spatially white interference is attained with correlated antennas. The impact of the interference suppression in multi–cell environment is depicted in Figure 6. We see that OFDM system slightly outperforms MC–CDMA in fully loaded case as in Figure 5. Decreasing the number of the users to six in MC–CDMA, the acceptable performance is achieved also near the cell edge.

Note that, the FER performance could be improved by increasing the soft handover threshold when site diversity is used in larger region. On the other hand, the higher threshold the more users become soft handover region [9]. So, it is desirable to keep the system to be able to operate with frequency reuse one in low SINR area also. Thus, the adaptivity of the system is needed to follow highly varying instantaneous channel state. The users in bad channel conditions should use robust transmit and receive methods, e.g., 2×4 MIMO instead of the layered technique. Correspondingly, the users in the good channel states could be served with higher throughput using layered 4×4 MIMO with higher order modulations.

V. Conclusion

In this paper, we considered a downlink MIMO MC–CDMA and OFDM system with space–frequency turbo coded modulation and LST architectures in multi–cell environment. The linear MMSE based receivers and iterative receiver structure with soft CAI cancellation were considered. The performance of the discussed system in the presence of inter–cell interference was studied via computer simulations. The inter–cell interference suppression in the MMSE detection improved

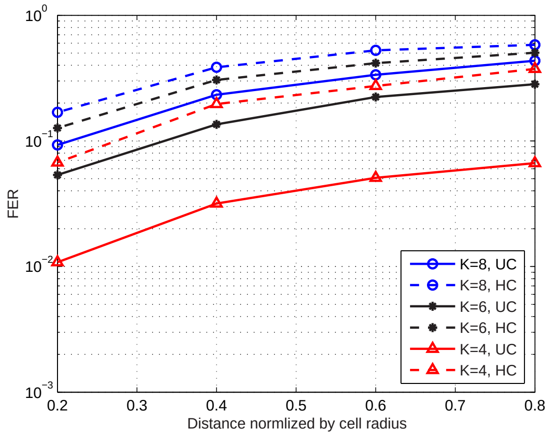

Fig. 4. FER vs. distance of a MC–CDMA system employing SFTuCM and chip–level SF–MMSE receiver in multi–cell environment. Distance between base station and desired user is normalized by the cell radius. Spreading factor is $G = 8$ and antenna configuration of $N = M = 4$.

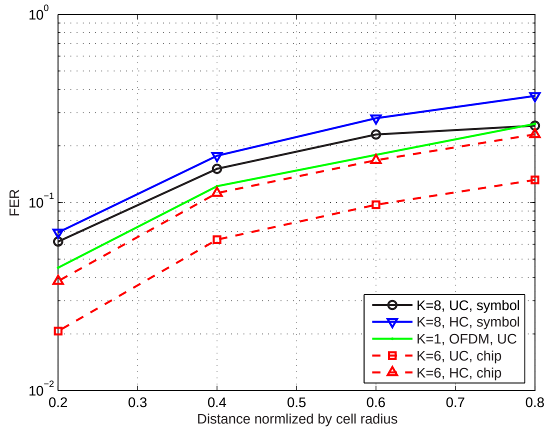

Fig. 6. FER vs. distance of a MC–CDMA system employing SFTuCM in multi–cell environment. Interference is known at the receiver. Spreading factor is $G = 8$ expect in the case of OFDM $K = G = 1$ and antenna configuration of $N = M = 4$.

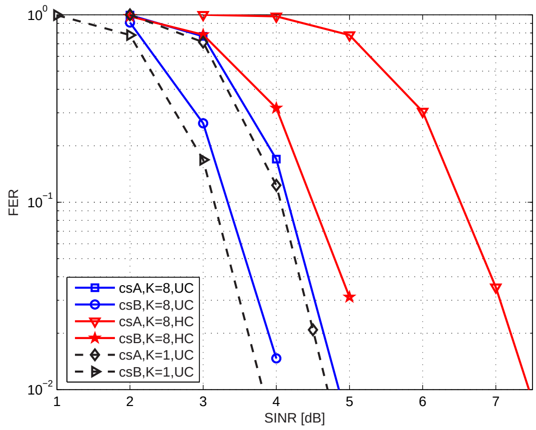

Fig. 5. Performance of the MIMO MC–CDMA with SFTuCM and the linear symbol–level MMSE receiver in interference limited environment. SNR = 20 dB and antenna configuration of $N = M = 4$.

significantly the performance compared to the assumption of spatially and spectrally white interference especially in the case of correlated antennas. The soft CAI cancellation iterations was shown to further improve the performance also in the multi–cell environment. Our results indicated that the considered MC–CDMA system is a feasible candidate for future high date rate downlink packet transmission when equipped with a suitable ARQ protocol. Further research is required to investigate the adaptive transmission methods, such as adaptive modulation with SFTuCM and adaptive antenna configuration selection, in interference limited environment.

VI. Acknowledgements

Part of this work has been performed in the framework of the IST project IST-2003-507581 WINNER, which is partly funded by the European Union. The authors would like to acknowledge the contributions of their colleagues in WINNER. Part of this work was supported by the National Technology Agency of Finland, Nokia, the Finnish Defence Forces, Elektrobit, Instrumentointi and Infotech Oulu Graduate School.

References

[1] S. Hara and R. Prasad, "Overview of multicarrier CDMA," *IEEE Commun. Mag.*, vol. 35, no. 12, pp. 126–133, Dec. 1997.

[2] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Pers. Commun., Kluwer*, vol. 6, pp. 311–335, 1998.

[3] X. Li, H. Huang, G. J. Foschini, and R. A. Valenzuela, "Effects of iterative detection and decoding on the performance of BLAST," in *Proc. IEEE Global Telecommun. Conf.*, 2000, vol. 2, pp. 1061–1066.

[4] D. Tujkovic, *Space-Time Turbo Coded Modulation for Wireless Communication Systems*, Ph.D. thesis, volume C184 of Acta Universitatis Ouluensis. University of Oulu Press, Oulu, Finland, 2003.

[5] M. Vehkaperä, D. Tujkovic, Z. Li, and M. Juntti, "Layered space-frequency coding and receiver design for MIMO MC-CDMA," in *Proc. IEEE Int. Conf. Commun.*, Paris, France, June 20–24 2004, vol. 5, pp. 3005–3009.

[6] M. Vehkaperä, D. Tujkovic, Z. Li, and M. Juntti, "Receiver design for spatially layered downlink MC-CDMA system," *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, May 2005.

[7] S. Catreux, P.F. Driessen, and L.C. Greenstein, "Simulation results for an interference-limited multiple-input multiple-output cellular system," *IEEE Commun. Lett.*, vol. 4, no. 11, pp. 334–336, 2000.

[8] S. Tsumura, M. Vehkaperä, Z. Li, D. Tujkovic, M. Juntti, and S. Hara, "Performance evaluation of turbo and space-time turbo coded MC-CDMA downlink in multi–cell environment," in *Proc. IEEE Int. Symp. Pers., Indoor, Mobile Radio Commun.*, Barcelona, Spain, Sept. 5–8 2004.

[9] S. Abeta, H. Atarashi, and M. Sawahashi, "Forward link capacity of coherent DS-CDMA and MC-CDMA broadband packet wireless access in a multi-cell environment," in *Proc. IEEE Veh. Technol. Conf.*, Boston, MA, USA, Sept. 24–28 2000, vol. 5, pp. 2213–2218.

[10] H. Atarashi, S. Abeta, and M. Sawahashi, "Broadband packet wireless access appropriate for high-speed and high-capacity throughput," in *Proc. IEEE Veh. Technol. Conf.*, Rhodes, Greese, May 6–9 2001, vol. 1, pp. 566–570.

[11] D. Huaiyu, A.F. Molisch, and V. Poor, "Downlink capacity of interference-limited mimo system with joint detection," *IEEE Trans. Wirel. Commun.*, vol. 3, no. 2, pp. 442–453, Mar. 2004.

[12] M. Sellathurai and S. Haykin, "TURBO-BLAST for wireless communications: Theory and experiments," *IEEE Trans. Signal Processing*, vol. 50, no. 10, pp. 2538–2546, Oct. 2002.

[13] D. Tujkovic, M. Juntti, and M. Latva-aho, "Space-time turbo coded modulation: Design and applications," *EURASIP Journal on Applied Signal Processing, Special Issue on Space-Time Coding and its Applications, Part-I*, vol. 2002, no. 3, pp. 236–248, Mar. 2002.