MAI Analysis for Forward Link Mono-Dimensionally Spread OFDM Systems

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Abstract—This paper deals with the average value interface between link and system level simulations for mono-dimensionally spread OFDM systems in the forward link. In particular, we investigate the intra-cell interference statistics for different levels of multi-path channel correlation, and discuss how they impact the link-to-system level interface. We show that for low correlated channel coefficients, where the choice of the interfering spreading code has no impact on the MAI power, only one orthogonality factor can be used to determine the local mean SINR. Moreover, in this context, the MAI is shown to follow a Gaussian distribution for large spreading factor, and consequently, a unique relationship between the local mean SINR and average BER exists for all equalization strategies and system loads. For correlated channel coefficients however, one orthogonality factor per interfering spreading code is required to determine accurately the local mean SINR. In this context, the MAI Gaussian approximation is no longer valid, and high order statistical moments are required to characterize the MAI distribution. Therefore, in this context, one SINR-BER mapping per couple of equalization strategy and system load is required at the average value interface. This study is a first step in order to evaluate the capacity of forward link OFDM-CDMA systems.

I. INTRODUCTION

Multi-Carrier (MC) transmission techniques that combine Orthogonal Frequency Division Multiplexing (OFDM) with Code Division Multiple Access (CDMA) are considered as potential candidates for the forward link air interface of 4G wireless communication systems. In particular, MC-CDMA-based schemes seem to fulfill quite well the 4G forward link air interface requirements. In the literature, MC-CDMA refers to a well-known OFDM-CDMA combination that performs spreading along the frequency dimension, i.e. each CDMA chip is assigned to one sub-carrier [1]-[5]. MC-CDMA aims at making full use of the frequency diversity effect by placing the CDMA chips on independently faded sub-carriers. However, this breaks the orthogonality between the spreading codes and increases the level of multiple access interference (MAI). To combat the MAI limitation typical of MC-CDMA, another OFDM-CDMA combination called Orthogonal Frequency and Code Division Multiplexing (OFCDM) has been proposed recently in [6][7]. OFCDM aims at preserving orthogonality among the spreading codes by performing spreading along a time-frequency grid over which the multi-path channel remains flat. Thus, OFCDM relies on high time and/or frequency channel correlation in order to suppress the MAI at the expense of lower diversity gain. In the literature, performance evaluation of MC-CDMA and OFCDM schemes has mainly been carried out at the link level, i.e. the single radio link performance is evaluated [1]-[7]. However, in order to evaluate their efficiency compared to other existing systems, performance evaluation should also be conducted at the system level, where all radio links in the system are considered. System level simulations are typically used to determine capacity and coverage of the air interface. The system capacity is generally derived from the amount of traffic load at the maximum allowed outage level. An outage occurs when the local mean signal to interference plus noise ratio (SINR), where averages are taken over the fast fading, is less than the one required to achieve the target bit error rate (BER) and frame error rate (FER) [10]. Thus, at the input of system level simulations, one should provide a model of the local mean SINR as well as an accurate mapping between the local mean SINR and the average BER/FER. These inputs are generally provided by the link-to-system level interface [8][10]. This study is a first step in order to estimate the capacity of forward link MC-CDMA and mono-dimensionally (1D) spread OFCDM systems, i.e. spreading is done along either the time or the frequency dimension. It aims at investigating the average value interface ("average" as being related to local mean SINR) between link and system level simulations. More precisely, we first determine the local mean SINR by taking into account the impact of the interfering spreading codes on the MAI power in the general case of correlated channel coefficients. Then, we investigate the validity of the MAI Gaussian approximation for different levels of channel correlation, and discuss how this impacts the relationship between the local mean SINR and the average BER.

The rest of the paper is organized as follows. Section II describes the forward link MC-CDMA and mono-dimensionally spread OFCDM schemes. In Section III, we first develop an expression of the local mean SINR and then study the validity of the MAI Gaussian approximation and its impact on the SINR-BER relationship. The simulation parameters and environments followed by the simulation results are presented in Section IV. Finally, conclusions are drawn in Section V.

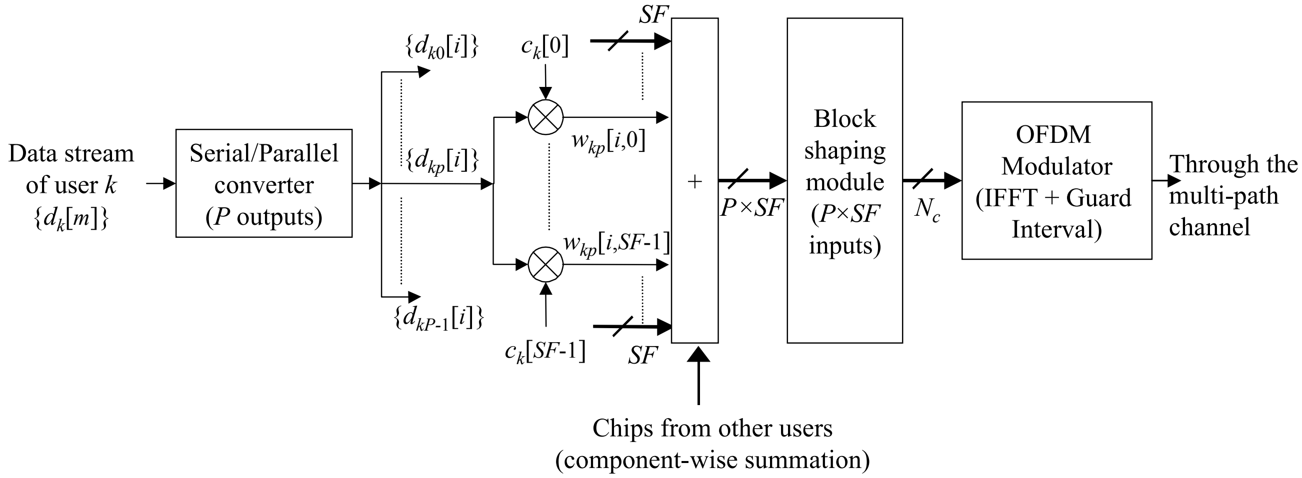

Figure 1: MC-CDMA and 1D-OFCDM baseband transmitter in the forward link.

II. SYSTEM DESCRIPTION

We consider the forward link transmission to K users. The transmission occurs simultaneously and synchronously using OFDM modulation with N_c available sub-carriers.

A. MC-CDMA and 1D-OFCDM transmitter model

A block diagram of the baseband model of the MC-CDMA and 1D-OFCDM transmitter in the forward link is depicted in Figure 1. After channel encoding and interleaving, the binary information of user k is mapped to QPSK modulation symbols. The resulting symbol stream $\{d_k[m]\}$ is then Serial/Parallel converted to P parallel streams, where m is the serial stream time index. Then, each parallel stream $\{d_{kp}[i]\}$ is spread by the spreading code $\{c_k[n]\}$ of length SF, resulting in the chip stream $\{w_{kp}[i,n]\}$, where i is the parallel stream time index and n is a chip index. The resulting chip streams of the K active users are then summed up prior to the block-shaping operation that maps the CDMA multi-user chips $\{w_p[i,n]\}$ to the N_c available sub-carriers according to the OFDM-CDMA combination. In MC-CDMA, spreading is performed along the frequency dimension with frequency interleaving, i.e. each CDMA chip $w_p[i,n]$ is mapped to the sub-carrier $p + nP$ and time slot $[iT_s,(i+1)T_s[$, where T_s stands for the total OFDM symbol duration. Since Frequency Spread (FS) OFCDM is nothing else than MC-CDMA without frequency interleaving, the chip $w_p[i,n]$ is then mapped to the sub-carrier $n + pSF$ and time slot $[iT_s,(i+1)T_s[$. In Time Spread (TS) OFCDM however, spreading is done along the time dimension, i.e. $w_p[i,n]$ is mapped to the sub-carrier p and time slot $[(i+n)T_s,(i+n+1)T_s[$. After the block-shaping operation, each time slot of N_c chips is then sent to the OFDM modulator, which performs the inverse fast Fourier transform (IFFT) operation and the guard interval insertion. The baseband signal is then RF modulated and transmitted through the multi-path channels of the K active users.

B. Multi-path channel model

As assumed in [4], we consider a normalized wide-sense stationary uncorrelated scattering (WSSUS) channel [9], with maximum delay smaller than the guard interval duration, resulting in zero inter-symbol interference. Furthermore, the channel is assumed to be time-invariant over the useful OFDM symbol duration T_u, and therefore the channel effect on sub-carrier n at time interval $[iT_s, (i+1)T_s[$ is reduced to the channel frequency response $h_k[i,n]$, which follows a zero mean complex-valued Gaussian distributed random process with variance equal to 1.

C. MC-CDMA and 1D-OFCDM receiver model

At the receiver, the signal received by user k during the i-th symbol interval is first OFDM-demodulated by removing the guard interval and applying the fast Fourier transform (FFT) operation. After chip demapping, each resulting parallel stream is detected using a single user detection technique, which consists in a chip-per-chip equalization followed by a despreading. Several equalization strategies have been considered in the literature: Orthogonality restoring combining (ORC), equal gain combining (EGC), maximum ratio combining (MRC), and minimum mean square error combining (MMSEC) [1][3][4]. MMSEC achieves the best performance among these equalization strategies. However, in addition to perfect estimation of the channel frequency responses $\{h_k[i,n]\}$, it requires knowledge of the system load K and the additive white Gaussian noise (AWGN) power spectral density (N_0). In the following, we assume knowledge of all these parameters at the receiver side, and consider in particular EGC and MMSEC for MC-CDMA, whereas MRC and MMSEC for 1D-OFCDM. After equalization and despreading, the parallel streams of decision variables are Parallel/Serial converted and channel decoded to recover the transmitted binary information.

III. THEORETICAL ANALYSIS

Without loss of generality, we consider the case $i = 0$ and $p = 0$, and suppress the indexes i and p. Therefore, the decision variable of the desired user k can be written as the summation of three terms, namely the useful signal, the MAI and the AWGN terms:

$$\hat{d}_k = \sqrt{G_k P_k} U_k d_k + \sqrt{G_k} \sum_{j \neq k}^{K} \sqrt{P_j} MAI_{kj} + N_k \qquad (1)$$

where G_k stands for the path loss of the link between the base station and user k, and P_j is the power allocated to user j. U_k is the useful signal factor given by:

$$U_k = \frac{1}{SF} \sum_{n=0}^{SF-1} \rho_k[n] \qquad (2)$$

where $\rho_k[n]$ is the real equalized channel coefficient for the n-th chip. MAI_{kj} represents the mutual interference between the desired user k and the interfering user j. It can be expressed similarly as in [1]-[3] as:

$$MAI_{kj} = d_j \sum_{n=0}^{SF-1} c_{kj}[n] \rho_k[n] \qquad (3)$$

where $c_{kj}[n]$ is the n-th chip of the sequence resulting from the component-wise product of the spreading codes $\{c_k[n]\}$ and $\{c_j[n]\}$, i.e. $c_{kj}[n] = c_k[n]c_j[n]$.

A. Local mean SINR model

In this section, we seek to determine an accurate expression of the local mean SINR, where averages are taken over a large time scale during which slow fading is constant but a large number of fast fades occurs. The general case of correlated channel coefficients is considered. Starting by the local mean useful signal power, one may easily find it equal to $G_k P_k \alpha_k$, where:

$$\alpha_k = E\{U_k^2\} = \frac{1}{SF} \Gamma_{\rho_k}[0] + \frac{2}{SF} \sum_{\ell=1}^{SF-1} \left(1 - \frac{\ell}{SF}\right) \Gamma_{\rho_k}[\ell] \qquad (4)$$

$\Gamma_{\rho_k}[\ell]$ is the statistical correlation function of $\rho_k[n]$, i.e. $\Gamma_{\rho_k}[\ell] = E\{\rho_k[n]\rho_k[n-\ell]\}$. Thanks to orthogonal spreading and wide-sense stationary channel, the variance of the mutual interference MAI_{kj} can be exactly expressed as:

$$\alpha_{kj} = \Gamma_{\rho_k}[0] ACF_{kj}[0] + 2 \sum_{\ell=1}^{SF-1} \Gamma_{\rho_k}[\ell] ACF_{kj}[\ell] \qquad (5)$$

where $ACF_{kj}[\ell]$ is the aperiodic correlation function of the sequence $\{c_{kj}[n]\}$ defined as:

$$ACF_{kj}[\ell] = \sum_{n=0}^{SF-\ell-1} c_{kj}[n] c_{kj}[n+\ell] \qquad (6)$$

The second term in (5) expresses the influence of the assigned spreading codes $\{c_k[n]\}$ and $\{c_j[n]\}$ on the interference power as a function of the equalized channel correlation. From (5), it is easy to find that α_{kj} is independent of the sequence $\{c_{kj}[n]\}$ in the two particular cases of quasi uncorrelated and quasi flat channels, i.e. $\Gamma_{\rho_k}[\ell]$ becomes quasi constant for $\ell \geq 1$. Otherwise, α_{kj} varies with respect to $\{c_{kj}[n]\}$. This variation increases as we move out from the two extreme cases of quasi uncorrelated and quasi flat channels. Consequently, in general, one orthogonality factor α_{kj} per sequence $\{c_{kj}[n]\}$ must be used to express the local mean MAI power. So, we have:

$$P_{MAI} = G_k \sum_{j \neq k}^{K} P_j \alpha_{kj} \qquad (7)$$

From (1), (4) and (7), the local mean SINR can be straightforwardly written as:

$$SINR_k = \frac{G_k P_k \alpha_k}{G_k \sum_{j \neq k}^{K} P_j \alpha_{kj} + 2N_0 \beta_k} \qquad (8)$$

where $\beta_k = E\{|z_k[n]|^2\}$, $z_k[n]$ stands for the channel equalization coefficient on the n-th chip. Thus, the parameters α_k, $\{\alpha_{kj}\}$, and β_k are the first required parameters of the link-to-system level average value interface. Their values are specific for each scenario that defines the multi-path channel correlation, the equalization strategy, and the family of spreading codes.

B. SINR-BER relationship

In this section, the relationship between the local mean SINR and the average BER is investigated. Over the considered time scale, the average BER is thus a measure of the bit error probability conditioned on the path loss G_k, the allocated powers $\{P_j\}$, and the system load K. Only the data symbols and the multi-path fades are considered as random variables. For QPSK symbol mapping and without channel coding, the bit error probability can be written as:

$$P_{eb} = \Pr\left(\mathrm{Re}(\hat{d}_k) > 0 / \mathrm{Re}(d_k) = \frac{-1}{\sqrt{2}} \right) \qquad (9)$$

When channel coding is considered, the soft decided values are used by the channel decoder to recover the transmitted information bits. The soft decided value of the information bit b_k corresponding to $\mathrm{Re}(d_k)$ is given by its log-likelihood ratio (LLR) as:

$$\lambda_k = \frac{2\sqrt{2} U_k \,\mathrm{Re}(\hat{d}_k)}{\frac{K-1}{SF-1}\left(\frac{1}{SF} \sum_{n=0}^{SF-1} \rho_k^2[n] - U_k^2 \right) + \frac{2N_0}{SF} \sum_{n=0}^{SF-1} |z_k[n]|^2} \qquad (10)$$

Similarly to [11], in (10), we assume Gaussian MAI distribution and set the parameters G_k, P_k, and $\{P_j\}$ to 1. Furthermore, we exploit the property of Walsh-Hadamard spreading codes that $c_{kj}[n]$ in half of the cases equals $-1/SF$ and in the other half equals $1/SF$. Thus, from (1), (9) and (10), the bit error probability appears to be function of the distributions of the three random variables U_k, Re(MAI_k), and Re(N_k), and their interdependency. Re(MAI_k) stands for the real part of the total MAI in (1). In the sequel, two cases are distinguished depending on whether the coefficients $\{\rho_k[n]\}$ are correlated or not.

1. Case of uncorrelated channel coefficients

In the case of uncorrelated channel coefficients, the law of large numbers (LLN) and the central limit theorem (CLT) apply to U_k for large SF (cf. (2)). The LLN approximates U_k with its mean value, whereas the CLT justifies the Gaussian approximation of U_k. Both approximations are very close to the real distribution of U_k, and they only require the knowledge of the mean and variance of U_k. In the same way, the CLT applies to the mutual interference MAI_{kj} for large SF (cf. (3)), and thus justifies its Gaussian approximation. The total interference MAI_k is therefore well approximated by a zero mean complex-valued Gaussian distribution with variance P_{MAI}, and this for any equalization strategy and system load. As well, the AWGN term N_k follows a zero mean complex-valued Gaussian distribution with variance $2N_0\beta_k$. By applying the CLT to U_k and assuming that U_k, Re(MAI_k), and Re(N_k) are independent random variables, the bit error probability is found to be:

$$P_{eb} = \frac{1}{2} erfc\left(\sqrt{\frac{0.5}{\left(1+\frac{1}{SINR_k}\right)\frac{\alpha_k}{E\{U_k\}^2}-1}} \right) \quad (11)$$

The assumption of independent random variables is quite valid in this context of uncorrelated channel coefficients. When applying the LLN instead of the CLT to U_k, (11) reduces therefore to $0.5erfc\left(\sqrt{0.5SINR_k}\right)$. Consequently, in this context, a unique relationship exists between the local mean SINR and the average BER for all equalization strategies and system loads. When channel coding is assumed, the uniqueness of the SINR-BER relationship remains valid since the LLR λ_k in (10) becomes only function of $\mathrm{Re}\left(\hat{d}_k\right)$. This results directly from the application of the LLN approximation to all summations of fast fading coefficients in (10). Thus, in this context, only one look-up table (LUT) should be provided at the link-to-system level average value interface in order to map the local mean SINR to the average BER or FER.

2. Case of correlated channel coefficients

In the case of correlated channel coefficients, neither LLN nor CLT apply to U_k. In this context, the distributions of U_k and N_k are strongly affected by that of the equalized channel coefficient $\rho_k[n]$. As for U_k and N_k, the CLT does not apply to MAI_{kj} making not valid its Gaussian approximation. Thus, for low system loads, the Gaussian approximation of the total interference MAI_k is no more justified. However, for large system loads, if we assume that the (K-1) mutual interference MAI_{kj} in (1) are independent and identically distributed with zero mean and variances α_{kj}, and if there is no dominant value of $P_j\alpha_{kj}$, the CLT can therefore be applied to MAI_k in order to justify its Gaussian approximation. Otherwise, when one or few dominant values of $P_j\alpha_{kj}$ exist, the MAI distribution will be more likely that of the summation of their corresponding mutual interference, which in turn is not Gaussian distributed. In this case, higher order statistical moments than the variance are required to characterize the MAI distribution. For instance, by extending our knowledge to the fourth order statistical moment, i.e. Kurtosis, we find that the following PDF model approximates well the MAI distribution:

$$p_{\mathrm{Re}(MAI)}(x) = r\exp\left(-\lambda|x|^q\right) \quad (12)$$

where r, λ, and q are derived from the variance and Kurtosis of Re(MAI_k). Note that (12) includes both cases of Gaussian (q = 2) and non Gaussian (q < 2) MAI distributions. Consequently, the SINR-BER relationship will be generally function of the equalization strategy and the system load. Moreover, for MMSEC equalization, where $\rho_k[n]$ is also function of the noise PSD N_0, different SINR-BER relationships may also exist for different values of N_0. When channel coding is employed, the LLR λ_k in (10) becomes also function of the equalization strategy and the system load by other means than the distribution of $\mathrm{Re}\left(\hat{d}_k\right)$. Thus, in this context, one LUT per couple of equalization strategy and system load should be provided at the link-to-system level interface. This means that extensive link level evaluation must be performed in order to provide all the necessary LUT(s) at the link-to-system level interface.

IV. Numerical results

The MC-CDMA and FS-OFCDM schemes are considered in the forward link. No numerical results are provided for the TS-OFCDM scheme since the same conclusions can be drawn from its dual FS-OFCDM scheme. The propagation environment is modeled with the urban ETSI BRAN channel E, with a coherence bandwidth of approximately 4 MHz [12].

Table 1. Simulation parameters.

Occupied bandwidth	41.45 MHz
Number of sub-carriers	736
FFT size	1024
Sampling frequency	57.6 MHz
Spreading factor SF	32
Spreading code	Walsh-Hadamard
(E_b/N_0) ratio	10 dB
Channel coding	Turbo-code (rate ½)
Data modulation	QPSK
Detection technique	Single user detection
Equalization strategy	EGC, MRC, MMSEC
Local mean SINR	1 to 10 dB

The large scale channel fading including the path loss and the shadowing effect is not considered, i.e. G_k = 1. QPSK data symbols are assumed with normalized symbol energy 1, and the useful signal power P_k is set to 1. Moreover, we assume equal transmission powers $\{P_i = P_j\}$ to the (K-1) interfering users. This assumption allows us to simply consider the case of non valid MAI Gaussian approximation due to the existence of few dominant interfering codes. The interference transmission power P_j is chosen such that the local mean SINR equals a certain predefined value. The local mean SINR is taken in the range 1 to 10 dB without channel coding and 1 to 5 dB with channel coding. The most relevant simulation parameters are summarized in Table 1. Two scenarios with different levels of channel correlation are considered in the sequel. The first scenario considers the MC-CDMA scheme, which results in very low correlated channel coefficients, whereas FS-OFCDM scheme is considered in the second scenario resulting in significant channel coefficients correlation.

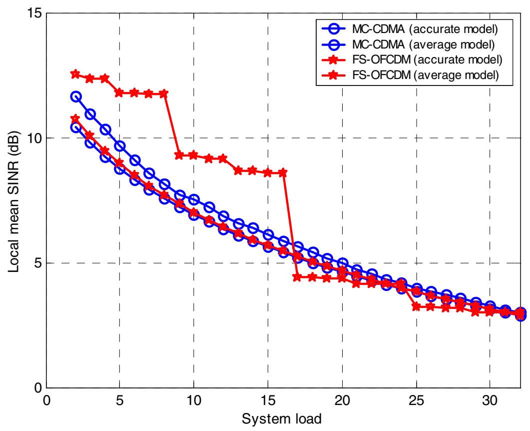

Figure 2: Accurate and average local mean SINR models.

Figure 2 illustrates the impact of the channel correlation on the local mean SINR. In both scenarios, EGC equalization is assumed, and P_j is chosen such that the local mean SINR is worth 3 dB for full system load, i.e. K = 32. In Figure 2, two SINR models are depicted. The first model applies the formula given in (8), and thus utilizes one orthogonality factor per interfering spreading code. This model is referred to as the accurate model and is illustrated with solid line curves. The second model utilizes the average orthogonality factor for all interfering spreading codes. This second model is referred to as the average SINR model and is illustrated with dotted line curves. As shown in Figure 2, the difference between the accurate and average SINR models is very small (near 0.25 dB in average) in the first scenario. However, in the second scenario, where the interfering spreading codes have a great impact on the interference power, a large difference of approximately 4 dB can be observed up to medium system loads. Thus, as discussed in Section III.A, one orthogonality factor can be used in the case of low correlated channel coefficients, whereas one orthogonality factor per interfering spreading code is required for accurate local mean SINR modeling in the case of correlated channel coefficients. It is important to recall that Walsh-Hadamard spreading codes are considered in Figure 2. The variation of the orthogonality factor with respect to the interfering spreading code can be more or less important when considering another family of spreading codes (e.g. Fourier, PN, Gold).

The impact of the channel correlation on the MAI distribution is illustrated in Figure 3. EGC equalization is assumed in the first scenario while MRC is assumed in the second one. Moreover, full system load (K = 32) and local mean SINR of 5 dB are assumed for both scenarios. In Figure 3, the real PDF of the real part of the MAI with its Gaussian and Kurtosis-based (cf. (12)) approximations are depicted for each scenario. In the first scenario, the three PDF curves are indistinguishable, which justifies the validity of the Gaussian approximation. In the second scenario however, the Gaussian approximation appears to be not valid while the Kurtosis-based PDF approximates well the real MAI PDF. Thus, in this context, the MAI distribution cannot be characterized from the only knowledge of its variance, however, it requires higher order statistical moments (e.g. Kurtosis). This may result in different MAI distributions, and consequently different SINR-BER relationships for different couples of equalization strategy and system load.

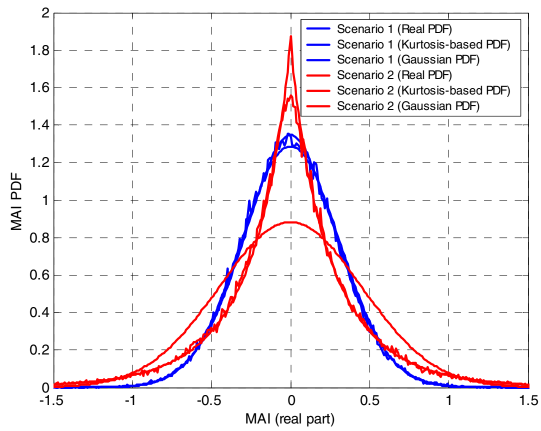

Figure 3: MAI PDF with its Gaussian and Kurtosis-based approximations.

Figure 4 illustrates the average BER versus the local mean SINR in the first scenario with and without channel coding. Both MMSEC and EGC are considered for medium (K = 16) and full (K = 32) system loads. From Figure 4, we can observe that without channel coding, neither the equalization strategy nor the system load influences the SINR-BER relationship. This relationship is very close to the analytical expression given in (11), which assumes Gaussian MAI and deterministic useful signal factor (LLN approximation). The little difference (~ 0.3 dB at BER of 1%) between (11) and the real SINR-BER relationship is due to the LLN approximation of the useful signal factor U_k. When channel coding is considered, the system load still has no impact on the SINR-BER relationship. A little difference of approximately 0.5 dB at BER of 1 % is observed between MMSEC and EGC curves. This difference is mainly due to the dependency of the log-likelihood ratios (LLR) on the equalization strategy (cf. (10)).

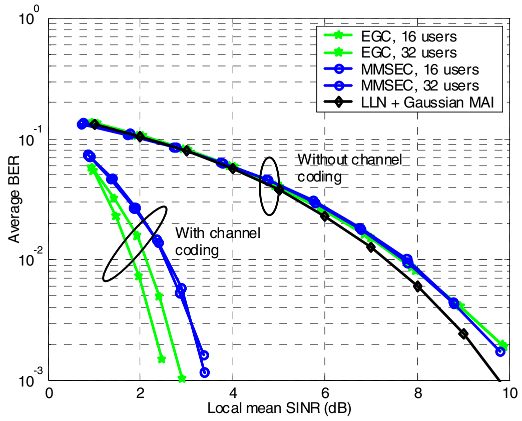

Figure 4: Average BER versus local mean SINR for MC-CDMA with and without channel coding.

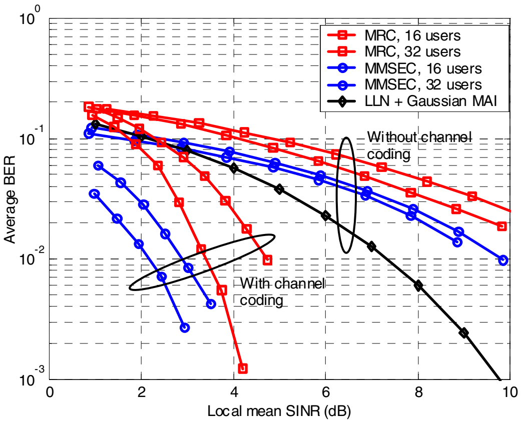

Figure 5: Average BER versus local mean SINR for FS-OFCDM with and without channel coding.

In Figure 5, the average BER versus the local mean SINR is illustrated in the second scenario. Both MRC and MMSEC equalizations with medium and full system loads are assumed. As it can be seen from Figure 5, different SINR-BER relationships exist for different couples of equalization strategy and system load. This is true whether channel coding is considered or not. The impact of the system load can be clearly observed in this scenario for both MRC and MMSEC equalizations. For instance, with channel coding at BER of 1%, we can observe a difference of 1.5 dB between MRC curves and 0.75 dB between MMSEC curves. As discussed in Section III.B.2, this is mainly due to the fact that the MAI is not Gaussian distributed, however, it requires knowledge of higher order statistical moments than its variance. The impact of the equalization strategy is also well observed in this scenario. For instance, with channel coding and for full system load and BER of 1%, the difference between MMSEC and MRC curves is around 1.25 dB. This is because in this scenario, the useful signal, the MAI and the noise terms distributions as well as the LLR become all dependent on the equalization strategy.

V. CONCLUSIONS

In this paper, the link-to-system level average value interface has been investigated for forward link mono-dimensionally spread OFDM systems. It has been shown that in the general case of correlated channel coefficients, the interfering spreading codes can have a great impact on the MAI power, and therefore, one orthogonality factor per interfering spreading code is required to determine accurately the local mean SINR. Furthermore, the MAI Gaussian approximation has been shown to be valid only in the case of low correlated channel coefficients. Otherwise, high order statistical moments are required to provide accurate modeling of the MAI distribution. Consequently, in the case of low correlated channel coefficients, a unique LUT mapping the SINR to the BER is sufficient at the link-to-system level interface for all equalization strategies and system loads. For correlated channel coefficients however, one LUT per couple of equalization strategy and system load is required. Further investigations will be devoted to study the inter-cell interference statistics in order to take them into account at the average value interface. The main perspective of this work is then the estimation of the system capacity.

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