Downlink and Uplink MC-DS-CDMA Sensitivity to Timing Jitter

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ABSTRACT

In this contribution, we consider the effect of timing jitter on the performance of the multicarrier direct-sequence CDMA (MC-DS-CDMA) system and compare the results for uplink and downlink transmission, assuming orthogonal spreading sequences. Theoretical expressions are derived for the performance degradation caused by the timing jitter, in the presence of a multipath channel. Assuming an AWGN channel, perfect power control and full load, it is shown that the performance degradation is independent of the number of carriers, the spreading factor and the spectral contents of the jitter, but only depend on the jitter variance. Further, we point out that, if the jitter spectrum is the same for all users, the degradation is the same for the downlink and the uplink.

1. INTRODUCTION

Multicarrier modulation has received considerable attention in the context of high data rate communications, as they combine a high bandwidth efficiency with an immunity to channel dispersion [1]-[3]. Recently, some new techniques, based on a combination of the multicarrier modulation technique and the code-division multiple access (CDMA) scheme were proposed in the literature (see [4] and the references therein). One of these combinations is the multicarrier direct-sequence CDMA (MC-DS-CDMA) technique which has been considered for mobile radio communications [5]-[8]. In the MC-DS-CDMA technique, the serial-to-parallel converted data stream is multiplied with the spreading sequence and then the chips belonging to the same symbol modulate the same carrier: the spreading is done in the time domain.

The use of a large number of carriers makes the multicarrier systems very sensitive to clock frequency offsets [9]-[10]. To avoid the degradation associated with a clock frequency offset, it was proposed in [9]-[10] to correct the timing offset of the transmitter clock (uplink) or of the receiver clock (downlink) by means of a timing synchronization algorithm. In this case, clock frequency offsets and constant timing offsets are eliminated, such that the multicarrier system is affected only by the timing jitter resulting from the synchronizer. The effect of timing jitter on different multicarrier systems has been studied in the literature [9]-[11]. For an AWGN channel, it has been shown that the performance degradation for orthogonal frequency division multiplexing (OFDM) [9] and multicarrier CDMA (MC-CDMA) [10], caused by timing jitter, is independent of the number of carriers, the spreading factor (in MC-CDMA) and the spectral contents of the jitter, but only depends on the jitter variance.

In this paper, we consider the effect of timing jitter on MC-DS-CDMA for both uplink and downlink transmission, and determine analytical expressions for the performance degradations in terms of the system parameters. With these results, we compare the sensitivities for uplink and downlink transmission.

2. SYSTEM DESCRIPTION

2.1. Uplink MC-DS-CDMA

The conceptual block diagram of the transmitter of an MC-DS-CDMA system for a single user is shown in figure 1. In MC-DS-CDMA, the complex data symbols to be transmitted at rate R_s, are first split into N_c symbol sequences at rate R_s/N_c. Each of these lower rate symbol sequences modulates a different carrier of the orthogonal multicarrier system. We denote by $a_{i,k,\ell}$ the data symbol transmitted by user ℓ on carrier k during the i^{th} symbol interval; k belongs to a set I_c of N_c carrier indices. The data symbol $a_{i,k,\ell}$ is then multiplied with a higher rate spreading sequence $\{c_{i,n,\ell}|n=0,...,N_s-1\}$ with spreading factor N_s, where $c_{i,n,\ell}$ denotes the n^{th} chip of the sequence that spreads the data symbols from user ℓ during the i^{th} symbol interval. Note that the spreading sequence does not depend on the carrier index k: all data symbols from user ℓ that are transmitted during the same symbol interval are spread with the same spreading sequence. It is assumed that $|c_{i,n,\ell}| = 1$. We denote by $\{b_{i,n,k,\ell}= c_{i,n,\ell}a_{i,k,\ell}/sqrt(N_s)|n=0,...,N_s-1;\ k$ Î $I_c\}$ the N_s components of the spread data symbol $a_{i,k,\ell}$. The components $b_{i,n,k,\ell}$ are serially transmitted on the k^{th} carrier of an orthogonal multicarrier system, i.e., the spreading is done in the time-domain. To modulate the spread data symbols on the orthogonal carriers, we use an N_F-point inverse fast Fourier transform (inverse FFT). To avoid that the multipath channel causes interference between the data symbols at the receiver, each FFT block at the inverse FFT output is cyclically extended with a prefix of N_p samples. This results in the sequence of samples $\{s_{i,n,m,\ell}|m=-N_p,...,N_F-1\}$

$$s_{i,n,m,\ell} = \frac{1}{\sqrt{N_F+N_p}} \sum_{k \in I_c} b_{i,n,k,\ell}\, e^{j2p\frac{km}{N_F}} \qquad (1)$$

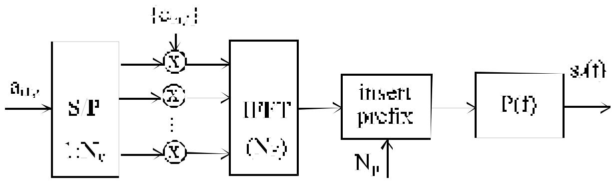

Figure 1: MC-DS-CDMA transmitter structure for a single user

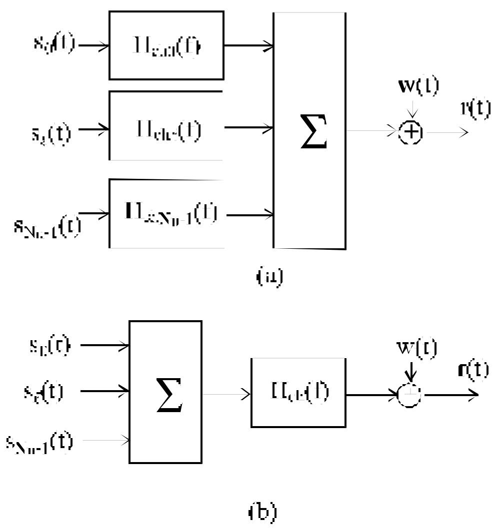

Figure 2: Channel structure for (a) uplink (b) downlink

The sequence $\{s_{i,n,m,\ell}|m=-N_p,...,N_F-1\}$ is fed to a square-root raised-cosine filter $P(f)$ with rolloff *a* and unit-energy impulse response $p(t)$. The resulting continuous-time transmitted complex baseband signal $s_\ell(t)$ is given by

$$s_\ell(t) = \sum_{i=-\infty}^{+\infty} \sum_{m=-N_p}^{N_F-1} \sum_{n=0}^{N_s-1} s_{i,n,m,\ell} \cdot p\left(t-\left(m+\left(n+iN_s\right)\left(N_F+N_p\right)\right)T-t_{i,n,m,\ell}\right) \quad (2)$$

where $1/T=(N_F+N_p)N_sR_s/N_c$ is the network reference clock frequency and $t_{i,n,m,\ell}$ is a time-varying delay representing the transmit clock phase of user ℓ. In the following, it is assumed that carriers inside the rolloff area of the transmit filter are not modulated, i.e., they have zero amplitude. Hence, of the N_F available carriers, only N_c carriers are actually used (N_c£$(1-a)N_F$), and assuming N_c to be odd, the set I_c of carriers actually used is given by $I_c = \{0, ..., N_c/2-1\}$ È $\{N_F - (N_c/2-1), ..., N_F-1\}$. The corresponding carrier spacing *Df* and system bandwidth *B* are given by

$$Df = \frac{1}{N_F T} = \frac{N_s}{N_c} R_s \frac{N_F+N_p}{N_F} \cong \frac{N_s}{N_c} R_s$$
$$B = N_c Df = \frac{N_c}{N_F T} = N_s R_s \frac{N_F+N_p}{N_F} \cong N_s R_s \quad (3)$$

The above approximations are valid for $N_p<<N_F$.

In a multiuser scenario, each user transmits to the basestation a similar signal $s_\ell(t)$. To separate the different user signals at the receiver, each user is assigned a unique spreading sequence $\{c_{i,n,\ell}\}$, with ℓ denoting the user index. In this contribution, we consider orthogonal sequences, consisting of user-dependent Walsh-Hadamard (WH) sequences of length N_s, multiplied with a complex-valued random scrambling sequence that is common to all N_u active users. Hence, the maximum number of users that can be accommodated equals N_s, i.e. the number of WH sequences of length N_s. Note that the number of carriers N_c can be chosen independently of the spreading factor N_s, which in turn equals the maximum number of users. Without loss of generality, we focus on the detection of the data symbols transmitted by the reference user ($\ell=0$).

The signal $s_\ell(t)$ transmitted by user ℓ reaches the basestation through a multipath channel with transfer function $H_{ch\ell}(f)$ that depends on the user index ℓ (see figure 2.a). The basestation receives the sum of the resulting user signals and an additive white Gaussian noise (AWGN) process $w(t)$. The real and imaginary parts of $w(t)$ are uncorrelated, and each have a power spectral density of $N_0/2$. The resulting signal is applied to the receiver filter, which is matched to the transmit filter, and sampled at the instants $t_{i,n,m}=(m+(n+iN_s)(N_F+N_p))T$ (see figure 3). Only the N_F samples with $m=0,...,N_F-1$ are kept for further processing. We assume that the length of the cyclic prefix is sufficiently longer than the maximum duration T_{ch} of the impulse responses of the composite channels with transfer functions $H_\ell(f) = |P(f)|^2 H_{ch\ell}(f)$ ($\ell=0,...,N_u-1$). The transmitter of each user adapts its transmit clock phase $t_{i,n,m,\ell}$ such that the samples used for further processing are not affected by interference from other FFT blocks. This adaptation introduces timing jitter $e_{i,n,m,\ell}T$. This timing jitter can be modeled as a zero-mean stationary random process with jitter spectral density $S_{e\ell}(f)$ and jitter variance $s_{e_\ell}^{2}$. The contribution of each user is affected by a different timing jitter process $e_{i,n,m,\ell}T$, as each user signal is generated with a different transmit clock.

The N_F selected samples are applied to an N_F-point FFT, followed by one-tap equalizers $g_{i,n,k}$ that scale and rotate the FFT outputs. We denote by $g_{i,n,k}$ the coefficient of the equalizer, operating on the k^{th} FFT output during the n^{th} FFT block of the i^{th} symbol interval. Each equalizer output is multiplied with the corresponding chip of the reference user's spreading sequence, and summed over N_s consecutive values to yield the samples $z_{i,k}$ at the input of the decision device.

The detection of the symbol $a_{i,k,0}$ is based upon the decision variable $z_{i,k}$. For small jitter variances ($s_{e_\ell}^{2}<<1$), the approximation $exp(j2px)$»$1+j2px$ can be used. This yields

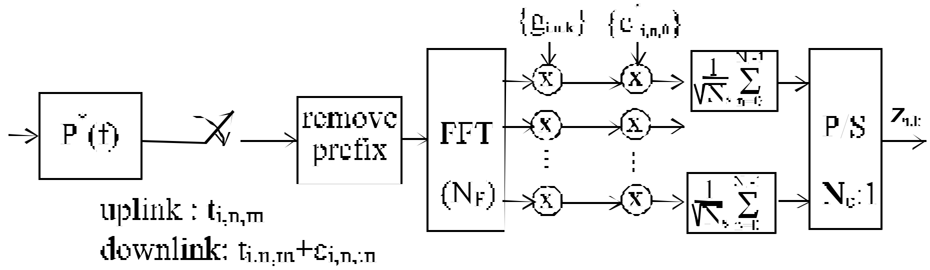

Figure 3: MC-DS-CDMA receiver structure

$$z_{i,k} = \sqrt{\frac{N_F}{N_F + N_p}} \sum_{\ell=0}^{N_u-1} \sum_{k' \in I_c} a_{i,k',\ell} I_{i,k,k',\ell} + W_{i,k} \qquad k \in I_c \quad (4)$$

where

$$I_{i,k,k',\ell} = \frac{1}{N_s} \sum_{n=0}^{N_s-1} c^*_{i,n,0} c_{i,n,\ell} g_{i,k,n} A_{i,n,k,k',\ell} \quad (5)$$

$$A_{i,n,k,k',\ell} = H_{k,\ell} \delta_{k-k'} + \tilde{H}_{k',\ell} \frac{1}{N_F} \sum_{m=0}^{N_F-1} j2\pi\varepsilon_{i,n,m,\ell} e^{-j2\pi \frac{m(k-k')}{N_F}} \quad (6)$$

$H_{k,\ell}=H_\ell(mod(k;N_F)/(N_FT))/T$, $\tilde{H}_{k,\ell} = (mod(k;N_F)/N_F)H_{k,\ell}$, $mod(x;N_F)$ is the modulo-N_F reduction of x, yielding a result in the interval $[-N_F/2,N_F/2]$ and $W_{i,k}$ is the additive noise contribution, with

$$E\left[W_{i,k} W^*_{i,k}\right] = N_0 \delta_{i-i'} \delta_{k-k'} \frac{1}{N_s} \sum_{n=0}^{N_s-1} \left|g_{i,n,k}\right|^2 \quad (7)$$

The quantity $I_{i,k,k',\ell}$ denotes the contribution from the data symbol $a_{i,k',\ell}$ to the sample $z_{i,k}$ at the input of the decision device. The sample $z_{i,k}$ from (4) contains a useful component with coefficient $I_{i,k,k,0}$. This component can be decomposed into an average useful component $E[I_{i,k,k,0}]$ and a zero-mean fluctuation $I_{i,k,k,0}-E[I_{i,k,k,0}]$ about its average, i.e. the self-interference (SI). The quantities $I_{i,k,k',0}$ ($k' \neq k$) correspond to intercarrier interference (ICI), i.e., the contribution from data symbols transmitted by the reference user on other carriers. For $\ell \neq 0$, the quantities $I_{i,k,k',\ell}$ correspond to multi-user interference (MUI), i.e., the contribution from data symbols transmitted by other users. The equalizer coefficients are selected such that the coefficients $E[I_{i,k,k,0}]$ of the average useful component equal 1, for $k \in I_c$. This yields

$$g_{i,k,n} = \frac{1}{H_{k,0}} \quad (8)$$

It is instructive to consider the case where all timing offsets are zero, i.e., $\varepsilon_{i,n,m,\ell}=0$ for $\ell=0,\dots,N_u-1$. In this case, the quantities (6) reduce to

$$A_{i,n,k,k',\ell} = H_{k,\ell} \delta_{k-k'} \quad (9)$$

Hence, the contribution from user ℓ to the k^{th} FFT output $y_{i,n,k}$ is proportional to $b_{i,n,k,\ell}H_{k,\ell}$, which means that SI and ICI are absent. Further, as the factor $H_{k,\ell}$ does not depend on the chip index n, the orthogonality between the contributions from different users to the same FFT output is not affected, i.e. $I_{i,k,k',\ell}=0$ for $\ell \neq 0$, hence MUI is absent as well. This indicates that, in the absence of timing offsets, the only effect of the multipath channel on the uplink MC-DS-CDMA signal with cyclic prefix is to multiply the symbols from each user with a factor $H_{k,\ell}$ that depends on the user index ℓ and the carrier index k. The presence of this factor influences the signal-to-noise ratio at the input of the decision device, but does not give rise to interference.

2.2. Downlink MC-DS-CDMA

In downlink MC-DS-CDMA, the basestation synchronizes the N_u user signals ($t_{i,n,m,\ell}=t$ for $\ell=0,\dots,N_u-1$) and broadcasts the sum of the N_u user signals $s_\ell(t)$ from (2) to the different users. As shown in figure 2.b, this broadcast signal reaches the receiver of the reference user through a multipath channel with transfer function $H_{ch}(f)$. As in the uplink, we assume that the length of the cyclic prefix is sufficiently longer than the duration T_{ch} of the composite channel with transfer function $H(f) = |P(f)|^2 H_{ch}(f)$. The output of the channel is disturbed by AWGN $w(t)$ with uncorrelated real and imaginary parts, each having a power spectral density of $N_0/2$. Similarly as in uplink MC-DS-CDMA, the resulting signal is applied to the receiver filter of figure 3 in order to detect the data symbols transmitted to the reference user ($\ell=0$). The receiver adjusts its sampling clock phase so that the N_F samples to be processed are free from interference from other blocks. The sampling instants are denoted $t_{i,n,m}+\varepsilon_{i,n,m}T$, where $t_{i,n,m}= (m+(n+iN_s)(N_F+N_p))T$ and the timing jitter $\varepsilon_{i,n,m}T$ is a zero-mean stationary random process with jitter spectral density $S_\varepsilon(f)$ and jitter variance σ_ε^2; $1/T$ is the network reference clock frequency. Only the samples with indices $m=0,\dots,N_F-1$ are kept for further processing. As in uplink MC-DS-CDMA, the sample $z_{i,k}$ at the input of the decision device can be represented by (4). The quantities $I_{i,k,k',\ell}$ are given by (5), with $S_{e_\ell}(f)$ and $H_\ell(f)$ substituted by $S_e(f)$ and $H(f)$, respectively. As in the uplink, the samples $z_{i,k}$ are decomposed into a useful component, intercarrier interference (ICI), multiuser interference (MUI) and noise. The equalizer coefficients $g_{i,n,k}$, that are selected such that the coefficients $I_{i,k,k,0}$ of the useful component equal one, are given by (8), with $H_\ell(f)$ substituted by $H(f)$.

3. PERFORMANCE ANALYSIS

3.1. Uplink MC-DS-CDMA

The performance of the MC-DS-CDMA system is measured by the signal-to-noise ratio (SNR), which is defined as the ratio of the power of the average useful component (P_U) to the sum of the powers of the total interference (=SI+ICI+MUI) (P_I), and the noise (P_N) at the input of the decision device. Note that these quantities depend on the index k of the considered carrier. This yields

$$SNR_k(\varepsilon) = \frac{\frac{N_F}{N_F + N_P} P_{U_k}}{P_{N_k} + \frac{N_F}{N_F + N_P} P_{I_k}} \tag{10}$$

In (10), the powers of the useful component, the total interference and the noise are given by

$$\begin{aligned} P_{U_k} &= E_{s_{k,0}} \\ P_{I_k} &= \sum_{k' \in I_c} E_{s_{k',0}} \left| \frac{\tilde{H}_{k',0}}{H_{k,0}} \right|^2 (2\pi)^2 X_{k,k',0} \\ &+ \frac{1}{N_s - 1} \sum_{\ell=1}^{N_u - 1} \sum_{\substack{k' \in I_c \\ k' \neq k}} E_{s_{k',\ell}} \left| \frac{\tilde{H}_{k',\ell}}{H_{k,0}} \right|^2 (2\pi)^2 \left(Y_{k,k',\ell} - X_{k,k',\ell} \right) \\ P_{N_k} &= N_0 \frac{1}{\left| H_{k,0} \right|^2} \end{aligned} \tag{11}$$

where

$$X_{k,k',\ell} = \int_{-\infty}^{+\infty} S_{e_\ell}(f) \left| D_{N_F}\left(\frac{k'-k}{N_F} + fT \right) \right|^2 \cdot \left| D_{N_s}\left(fT\left(N_F + N_p \right) \right) \right|^2 df \tag{12}$$

$$Y_{k,k',\ell} = \int_{-\infty}^{+\infty} S_{e_\ell}(f) \left| D_{N_F}\left(\frac{k'-k}{N_F} + fT \right) \right|^2 df$$

and

$$D_M(x) = \frac{1}{M} \sum_{m=0}^{M-1} e^{j2\pi mx} = e^{j\pi(M-1)x} \frac{\sin(\pi Mx)}{M \sin(\pi x)} \tag{13}$$

In (11), $E_{s_{k,\ell}} = E[|a_{i,k,\ell}|^2]$ denotes the symbol energy transmitted on carrier k by user ℓ. In the absence of timing jitter ($\varepsilon_{i,n,m,\ell}=0$ for $\ell=0,\ldots,N_u-1$), the SNR (10) reduces to $SNR_k(0) = (N_F/(N_F+N_p))\, |H_{k,0}|^2 (E_{s_{k,0}}/N_0)$. The degradation (in dB), caused by the timing offsets is defined as $Deg_k = 10\log(SNR_k(0)/SNR_k(\varepsilon))$.

In order to clearly isolate the effect of the timing jitter, we assume that the channels are ideal, the jitter spectrum equal for all users, the maximum load ($N_s=N_u$) and all users have the same energy per symbol on each carrier (i.e., $|H_{k,\ell}|=1$, $S_{e_\ell}(f)=S_e(f)$ and $E_{s_{k,\ell}}=E_s$ for $k \in I_c$, $\ell=0, \ldots, N_s-1$). In this case, the quantities $X_{k,k',\ell}$ and $Y_{k,k',\ell}$ are independent of the user index ℓ. In the following, we drop the user index. The total interference power in this case is given by

$$P_{I_k} = E_s (2\pi)^2 \sum_{k' \in I_c} \left(\frac{mod(k';N_F)}{N_F} \right)^2 Y_{k,k'} \tag{14}$$

and the degradation is given by

$$Deg_k = 10\log\left(1 + SNR(0)(2\pi)^2 \sum_{k' \in I_c} \left(\frac{mod(k';N_F)}{N_F} \right)^2 Y_{k,k'} \right) \tag{15}$$

In figure 4, the degradation (15) is shown as function of the carrier index, for $N_F=64$, $N_c=57$, $SNR(0)=10$ dB and $\sigma_\varepsilon^2=10^{-1}$. As we observe, the maximum degradation occurs for carriers close to the edge of the rolloff area, i.e. for $k \approx (N_c-1)/2$ and $k \approx N_F - (N_c-1)/2$. For given k, the degradation (15) depends on the number N_c of modulated carriers, as in (15), the summation over k' ranges over the set I_c of N_c modulated carriers. An upper bound on this degradation is obtained by extending in (15) this summation interval over all N_F available carriers, i.e., $k'=0,\ldots,N_F-1$. This yields

$$Deg_k \leq 10\log\left(1 + SNR(0)(2\pi)^2 \sum_{k'=0}^{N_F-1} \left(\frac{mod(k';N_F)}{N_F} \right)^2 Y_{k,k'} \right) \tag{16}$$

This bound is also shown in figure 4, for $k = 0, \ldots, N_F-1$. For given k, the upper bound (16) on the degradation is independent of the number N_c of modulated carriers, and becomes maximum for the carrier $k=N_F/2$. The upper bound is reached when all carriers are modulated ($N_c=N_F$; $\alpha=0$). When $\alpha>0$, the upper bound (16) yields an accurate approximation for the actual degradation on carriers near the center of the signal band.

Let us consider the average SNR, which is obtained by replacing in (10) the powers of the average useful component, the total interference and the noise by their arithmetical average over all carriers; this corresponds to considering the average interference power over all carriers. The degradation Deg_{Av} of this average SNR turns out to be independent of the jitter spectrum, the spreading factor, and for $N_F>>1$, independent of the number of carriers:

$$Deg_{Av} \leq 10\,log\left(1+SNR(0)\frac{p^2}{3}s_e^2\right) \qquad (17)$$

where $SNR(0)=(N_F/(N_F+N_p))E_s/N_0$ is the signal-to-noise ratio in the absence of timing jitter, and the jitter variance is given by

$$s_e^2 = \int_{-\infty}^{+\infty} S_e(f)df \qquad (18)$$

The average degradation is shown in figure 5 as function of the jitter variance, along with the actual degradation from (15) for $k\,\hat{I}\,I_c$, the maximum (over k) of the actual degradation (15) and the upper bound (16) for $k=(N_c-1)/2$, for $N_F=64$, $N_c=57$, $SNR(0)=10$ dB. As we observe, the bound (16) nearly coincides with the actual maximum degradation (15), and for a substantial number of modulated carriers the actual degradation is close to the maximum degradation; this illustrates the importance of the bound (16). Further, the average degradation is close to the maximum degradation and to the actual degradation for a substantial number of modulated carriers: this illustrates the importance of the average degradation (17). For small jitter variance, the degradation is proportional to s_e^2.

3.2. Downlink MC-DS-CDMA

As in uplink MC-DS-CDMA, the performance is measured by the SNR, defined in (10). The powers of the average useful component, the total interference and the noise are given by (11), with $S_{e\ell}(f)$ and $H_\ell(f)$ substituted by $S_e(f)$ and $H(f)$, respectively for $\ell=0,...,N_u-1$. In this case, it follows from (12) that the quantities $X_{k,k',\ell}$ and $Y_{k,k',\ell}$ are independent of the user index ℓ.

To clearly isolate the effect of the carrier frequency offset, we consider the case where the channel is ideal ($|H_k|=1$, $k\,\hat{I}\,I_c$), the maximum load ($N_s=N_u$), and the energy per symbol is the same for all carriers and all users ($E_{sk,\ell}=E_s$ for $k\,\hat{I}\,I_c$, $\ell=0,...,N_s-1$). In this case, the degradation is given by (15). As in uplink transmission, an upper bound on the degradation is obtained by extending the summation over k' in (15) over all N_F available carriers, yielding (16). Further, similarly as in the uplink, we can define the average SNR by replacing in (10) the powers of the average useful component, the total interference and the noise by their arithmetical average over all carriers. The degradation of this average SNR, for $N_F>>1$, is given by (17).

Hence, the degradation in the downlink is the same as in the uplink, assuming that the jitter spectra in the uplink are the same for all users. This degradation is independent of the number of carriers, the spreading factor and the spectral contents of the jitter, but only depends on the jitter variance.

4. Conclusions and Remarks

In this contribution, we have determined the effect of timing jitter on the performance of MC-DS-CDMA, for both uplink and downlink transmission, assuming orthogonal spreading sequences. We have determined analytical expressions for the SNR at the input of the decision device, and the degradation of the SNR caused by timing jitter. We have compared the resulting degradation for both uplink and downlink transmission, under the assumption of the full load ($N_u=N_c$). When the jitter spectra of the different users are the same, the degradation turns out to be the same for the uplink and the downlink. Furthermore, we have shown that the degradation of the MC-DS-CDMA system is independent of the number of carriers, the spreading factor and the spectral contents of the jitter, but only depends on the jitter variance.

It can be verified from [10]-[11] that the degradation (17) for MC-DS-CDMA is exactly the same as the corresponding degradations for OFDM and MC-CDMA, assuming that the three multicarrier systems have the same carrier spacing.

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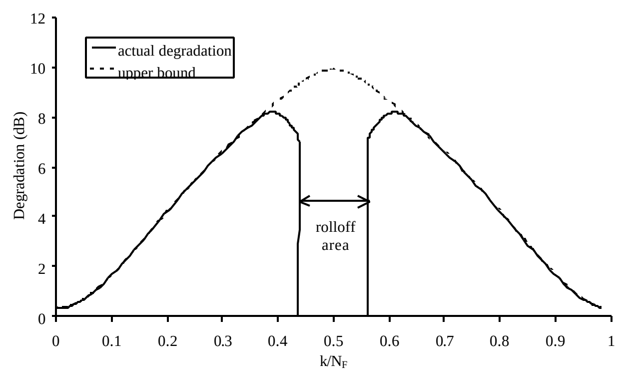

Figure 4: Performance degradation caused by jitter variance ($N_F=64$, $N_c=57$, $SNR(0)=10$ dB, $s_e^2=10^{-1}$)

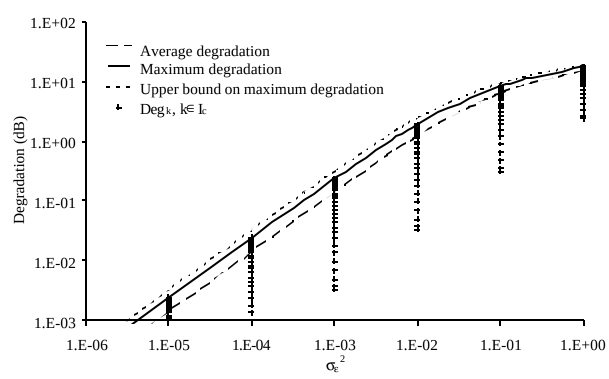

Figure 5: Maximum and average degradation caused by jitter variance ($N_F=64$, $N_c=57$, $SNR(0)=10$ dB)

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