Sensitivity of OFDM and MC-CDMA to Carrier Phase Errors

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Abstract
In this contribution, we investigate the effect of carrier phase errors on the performance of orthogonal frequency division multiplexing (OFDM) and multicarrier code-division multiple access (MC-CDMA). We show that OFDM and MC-CDMA have essentially the same sensitivities to carrier phase errors. A constant carrier phase offset yields no degradation of the system performance. We show that OFDM and MC-CDMA are quite sensitive to a carrier frequency offset : the degradation caused by this impairment is an increasing function of the number of carriers. Carrier phase jitter on the other hand gives rise to a degradation that is independent of the number of carriers, but only depends on the jitter variance.

I. Introduction

In the last decade, we witnessed an enormous growth in interest for multicarrier (MC) systems. The popularity of these MC systems can be mainly ascribed to its immunity to channel dispersion and its high bandwidth efficiency [1-2]. Furthermore, recent developments in DSP techniques have made MC systems suitable for implementation. These considerations demonstrate the applicability of MC systems for high data rate applications. One of the MC systems is the well-studied orthogonal frequency division multiplexing (OFDM) system. The conventional OFDM system has been proposed and/or accepted for a large number of applications, among which we can mention transmission over twisted pair cables (ADSL) [3-4], broadcasting of digital audio (DAB) and digital television (DTTB) [5-6], or mobile radio [7-8].
Recently, OFDM has been investigated in combination with code-division multiple access (CDMA) [9-11]. Among the investigated combinations we encounter the so called MC-CDMA system [12-13]. In MC-CDMA, the data symbols are first multiplied with a higher rate chip sequence and then modulated on the orthogonal carriers. The MC-CDMA system has been investigated in the context of high-rate communication over dispersive channels and has been proposed for downlink communication in mobile radio.
The use of a large number of carriers makes the MC system highly sensitive to some types of carrier phase errors. The influence of carrier phase errors between the carrier oscillators at the transmitter and the receiver on the performance of the OFDM system has been investigated in [14-17]. When using a free-running local oscillator, exhibiting a frequency offset and Wiener phase noise, it is shown in [15-16] that the performance of the OFDM system rapidly degrades with an increasing number of tones. In order to avoid this strong degradation, it was proposed in [17] to use a phase-locked local oscillator in order to get rid of the frequency offset and the phase noise components that fall within the bandwidth of the phase-locked loop (PLL). For the maximal load, it was shown in [17] that the degradation caused by the resulting jitter is independent of the number of tones and of the spectral contents of the jitter.
The sensitivity of MC-CDMA performance to carrier phase errors has been investigated in [18-19]. In [18], simulations show that when using a free-running local oscillator the degradation of the MC-CDMA system caused by a carrier frequency offset and Wiener phase noise is a rapidly increasing function of the number of carriers. As in conventional OFDM, the use of a phase-locked loop for down-converting the RF signal has been proposed in [19]. It was shown that the MC-CDMA performance degradation caused by the resulting phase jitter is independent of the number of carriers but only depends on the jitter variance.

In this contribution, we investigate the effect of carrier phase errors on the performance of OFDM and MC-CDMA. It will be shown that OFDM and MC-CDMA have essentially the same sensitivities to carrier phase errors.

II. The OFDM System

The conceptual block diagram of an OFDM system is shown in figure 1. In OFDM, the available bandwidth is split into a set of *N* orthogonal subchannels. A sequence of complex data symbols is split into frames of *N* symbols $\{a_{i,m}|m=0,...,N-1\}$, $a_{i,m}$ denoting the *m*th symbol transmitted during the *i*th symbol interval. The symbols $\{a_{i,m}\}$ modulate the orthogonal carriers, resulting in the time-domain samples $s_{i,k}$

$$s_{i,k} = \sum_m \sqrt{E_{sm}}\, a_{i,m} e^{j2\pi\frac{km}{N}} \tag{1}$$

where E_{sm} is the energy per symbol belonging to user *m*.

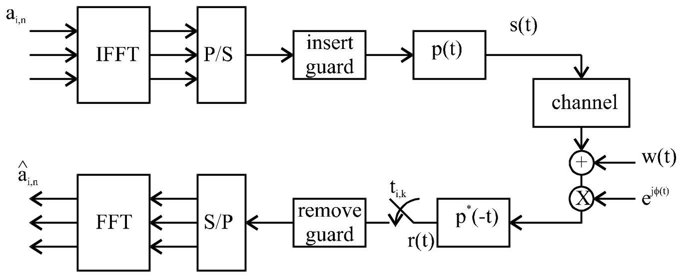

Figure 1 : Conceptual block diagram of an OFDM transceiver

Intersymbol interference, caused by the presence of a dispersive channel, can be avoided by cyclically extending the transmitted signal with a guard interval νT. The transmitted samples during the *i*th symbol interval yield $\{s_{i,k}|k=-\nu,...,N-1\}$, where the first ν samples are a duplication of the last ν samples : $\{s_{i,k}|k=-\nu,...,-1\}=\{s_{i,k}|k=N-\nu,...,N-1\}$. The resulting samples $s_{i,k}$ are fed to the transmit filter $p(t)$, a unit-energy square-root Nyquist filter with Fourier transform $P(f)$. The transmitted signal is applied to a dispersive channel with transfer function $H_{ch}(f)$ and is disturbed by additive white Gaussian noise, with uncorrelated real and imaginary parts, each having a power spectral density of $N_0/2$. At the receiver, the RF signal is down-converted to a baseband signal using a local oscillator. When the local oscillator and the oscillator used for up-converting the transmitted signal diverge, the signal is affected by the carrier phase error $\phi(t)$. The receiver consists of a filter $p^*(-t)$, matched to the transmit filter, whose output $r(t)$ is sampled at the instants $t_{i,k}=kT+i(N+\nu)T$. When the carrier phase error is slowly varying as compared to *T*, the samples $r_{i,k}$ can be written as

$$r_{i,k} = \sum_m h_{eq}\left(kT - mT;\phi_{i,k}\right)s_{i,m} + w_{i,k} \tag{2}$$

where $\phi_{i,k}$ is the carrier phase error at the instants $t_{i,k}$ and $h_{eq}(t;\phi)$ is an equivalent filter with Fourier transform $H_{eq}(f;\phi)$

$$H_{eq}(f;\phi) = e^{j\phi_{i,k}} H(f) \tag{3}$$

where $H(f)$ consists of the cascade of the transmit filter, the channel transfer filter and the receiver filter, i.e. $H(f)=H_{ch}(f)|P(f)|^2$.

Assuming the duration of $h_{eq}(t;\phi)$ does not exceed the duration of the guard interval, the transmitted signal is only disturbed by the signal transients during the guard interval, such that adjacent transmitted symbol intervals will not influence the considered symbol interval *outside* the guard interval. The receiver selects the *N* samples outside the guard interval for further processing and disregards the other ν samples. It can be verified that the samples $r_{i,k}$ outside the guard interval are given by

$$r_{i,k} = \sum_m \sqrt{E_{sm}} a_{i,m} H_m(\phi_{i,k}) e^{j2\pi \frac{km}{N}} + w_{i,k} \tag{4}$$

where $H_m(\phi_{i,k})=exp(j\phi_{i,k})H_m$ and

$$H_m = \frac{1}{T} \sum_{\ell=-\infty}^{+\infty} H\left(\frac{m}{NT} + \frac{\ell}{T}\right) \tag{5}$$

The selected samples are demodulated with a fast Fourier transform (FFT), yielding the samples at the input of the decision device

$$\begin{aligned} z_{i,m} &= \frac{1}{N} \sum_{k=0}^{N-1} r_{i,k} e^{-j2\pi \frac{km}{N}} \\ &= \sqrt{E_{sm}} a_{i,m} I_{i,m,m} + \sum_{\ell \neq m} \sqrt{E_{s\ell}} a_{i,\ell} I_{i,\ell,m} + W_{i,m} \end{aligned} \tag{6}$$

where $W_{i,m}$ is a zero-mean complex-valued Gaussian noise term with variance N_0 and

$$I_{i,\ell,m} = \frac{1}{N} \sum_{k=0}^{N-1} H_\ell(\phi_{i,k}) e^{j2\pi \frac{k(\ell-m)}{N}} \tag{7}$$

For $\ell \neq m$, the quantity $I_{i,\ell,m}$ denotes the intercarrier interference (ICI) at the mth output of the FFT, caused by the ℓth carrier during the ith symbol interval.

When the carrier phase error can be modelled as a random process, the quantities $I_{i,\ell,m}$ are random variables and can be decomposed as

$$I_{i,\ell,m} = E[I_{i,\ell,m}] + (I_{i,\ell,m} - E[I_{i,\ell,m}]) \tag{8}$$

where the first component is the average of $I_{i,\ell,m}$ with respect to the carrier phase error and the second contribution is the zero-mean fluctuation of the quantity $I_{i,\ell,m}$ about its average. Defining the signal-to-noise ratio (SNR) at the input of the decision device as the ratio of the average useful component to the sum of the powers of the other contributions, the SNR at the mth FFT output is given by

$$SNR_m = \frac{E_{sm} \left| E[I_{i,m,m}] \right|^2}{N_0 + \sum_{\ell \neq m} E_{s\ell} \left| E[I_{i,\ell,m}] \right|^2 + E_{sm} E\left[\left| I_{i,m,m} - E[I_{i,m,m}] \right|^2 \right] + \sum_{\ell \neq m} E_{s\ell} E\left[\left| I_{i,\ell,m} - E[I_{i,\ell,m}] \right|^2 \right]} \tag{9}$$

where the first noise contribution in the denominator of (9) is additive white Gaussian noise, the second term is the power of the average intercarrier interference component (ICI), the third contribution is the power of the fluctuation of the useful component, caused by the random character of the carrier phase jitter and the last term is the power of the fluctuation of the intercarrier interference component.

In the case of an ideal channel and in the absence of carrier phase errors, the quantities $H_m(\phi_{i,k})$ yield $H_m(\phi_{i,k})=1$, reducing the quantities (7) to $I_{i,\ell,m}=\delta_{\ell,m}$. The SNR (9) yields $SNR_m=E_{sm}/N_0$, hence the degradation caused by a non-ideal channel and/or the presence of carrier phase errors yields $D_m=10log((E_{sm}/N_0)/SNR_m)$ (dB).

III. The MC-CDMA System

The conceptual block diagram of the MC-CDMA system is shown in figure 2. The data symbols $\{a_{i,m}\}$ transmitted to user m during the ith symbol interval are multiplied with the corresponding chip sequences $\{c_{n,m}|n=0,...,N-1\}$, where $c_{n,m}$ is the nth chip of the sequence belonging to user m. Sequences belonging to different users are assumed to be orthogonal (e.g. Walsh-Hadamard codes). The resulting samples are modulated on the orthogonal carriers (OFDM), resulting in the time-domain samples

$$s_{i,k} = \sum_m \sum_{n=0}^{N-1} \sqrt{E_{sm}} a_{i,m} c_{n,m} e^{j2\pi \frac{kn}{N}} \tag{10}$$

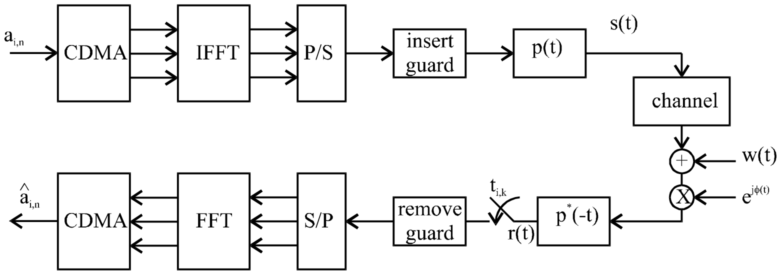

Figure 2 : Conceptual block diagram of a MC-CDMA transceiver

As described in section II, intersymbol interference can be avoided by introducing a guard interval. The resulting time-domain samples are fed to the transmit pulse p(t) and sent over the dispersive channel with Fourier transform $H_{ch}(f)$. The signal is disturbed by additive white Gaussian noise and a carrier phase error. At the receiver, the signal is applied to a filter matched to the transmit filter and sampled at the instants $t_{i,k}=kT+i(N+\nu)T$. As in conventional OFDM, the resulting samples $r_{i,k}$ can be written as (2), as the outputs of an equivalent filter $h_{eq}(t;\phi)$ with Fourier transform (3), where the transmitted samples were applied to. When the duration of the impulse response of $h_{eq}(t;\phi)$ does not exceed the duration of the guard interval, the samples $r_{i,k}$ outside the guard interval are given by

$$r_{i,k} = \sum_m \sum_{n=0}^{N-1} \sqrt{E_{sm}} a_{i,m} c_{n,m} H_n(\phi_{i,k}) e^{j2\pi \frac{kn}{N}} + w_{i,k} \tag{11}$$

The receiver selects the N samples $r_{i,k}$ outside the guard interval for further processing and disregards the other ν samples. The selected samples are demodulated using a FFT. The nth output of the FFT is multiplied with the chip $c^*_{n,m}$ of the considered user m and then summed yielding the samples at the input of the decision device

$$\begin{aligned} z_{i,m} &= \frac{1}{N^2} \sum_{n=0}^{N-1} c^*_{n,m} \sum_{k=0}^{N-1} r_{i,k} e^{-j2\pi \frac{kn}{N}} \\ &= \sqrt{E_{sm}} a_{i,m} I_{i,m,m} + \sum_{\ell \neq m} \sqrt{E_{s\ell}} a_{i,\ell} I_{i,\ell,m} + W_{i,m} \end{aligned} \tag{12}$$

where $W_{i,m}$ is a zero-mean complex-valued Gaussian noise term with variance N_0 and

$$I_{i,\ell,m} = \frac{1}{N^2} \sum_{k=0}^{N-1} \sum_{n,n'=0}^{N-1} c_{n,\ell} c^*_{n',m} H_n(\phi_{i,k}) e^{j2\pi \frac{k(n-n')}{N}} \tag{13}$$

For $\ell \neq m$, the quantity $I_{i,\ell,m}$ denotes the multi-user interference (MUI) at the correlator output of the mth user originating from the ℓth user during the ith symbol interval.

When the carrier phase error can be modelled as a random process, the quantities $I_{i,\ell,m}$ can be decomposed as in (8). The signal-to-noise ratio at the input of the decision device belonging to user m is given by (9). In (9), the denominator is now composed of the sum of the powers of the additive white Gaussian noise, the average multi-user interference, the fluctuation of the useful component and the fluctuation of the MUI. In the computation of (9), we can use the approximations $E[c_{n,k}c^*_{n,k'}] \approx \delta_{k,k'}$ and $E[c_{\ell,k}c^*_{n,k}c^*_{\ell,m}c_{n,m'}] \approx N/(N-1)(\delta_{k,m}\delta_{k',m} - 1/N\delta_{k,k'}\delta_{m,m'})$, where $E[.]$ denotes the average over the sequences.

In the case of an ideal channel and in the absence of carrier phase errors, the quantities (13) yield $I_{i,\ell,m}=\delta_{\ell,m}$, resulting in the signal-to-noise ratio $SNR_m=E_{sm}/N_0$. Hence, as in section II, the degradation caused by a non-ideal channel and/or the presence of carrier phase errors is given by $D_m=10\log((E_{sm}/N_0)/SNR_m)$ (dB).

IV. Carrier Phase Errors

In this section, we investigate the sensitivity of the OFDM system and the MC-CDMA system to carrier phase errors. As we consider the case of downstream communication, all transmitted carriers exhibit the same carrier phase error, as they are up-converted by the same oscillator. In the following, we separately consider the case of a constant carrier phase offset, a carrier frequency offset and carrier phase jitter.

For a constant phase offset $\phi(t)=\phi$, the outputs of the FFT are rotated over an angle ϕ and are given by $H_m(\phi_{i,k})=exp(j\phi)H_m$. In the case of an ideal channel ($H_m=1$), it can be verified that a constant phase offset reduces the quantities (7) (OFDM) and (13) (MC-CDMA) to $I_{i,\ell,m}=e^{j\phi}\delta_{\ell,m}$. This indicates that a constant phase offset introduces no intercarrier interference, multi-user interference respectively, but only gives rise to a rotation of the useful component. As a phase rotation of the FFT outputs or the correlator outputs has no influence on the noise power, a constant phase offset can be compensated without loss of performance.

When the carrier oscillators at transmitter and receiver exhibit a frequency offset ΔF, the carrier phase error is given by $\phi(t)=2\pi\Delta Ft$. A constant carrier frequency offset gives rise to a deterministic phase error, hence no fluctuation of the useful component or intercarrier interference, multi-user interference respectively, is present. For a slowly varying phase error as compared to T, i.e. $\Delta FT<<1$, the quantities (7) and (13) reduce for an OFDM system to

$$I_{i,\ell,m} = e^{j2\pi i(N+\nu)\Delta FT} H_\ell G\left(\frac{\ell - m}{N} + \Delta FT\right) \tag{14}$$

and for a MC-CDMA system to

$$I_{i,\ell,m} = \frac{1}{N}\sum_{n,n'=0}^{N-1} c_{n,\ell} H_n G\left(\frac{n-n'}{N} + \Delta FT\right) e^{j2\pi i(N+\nu)\Delta FT} c^*_{n',m} \tag{15}$$

where

$$G(x) = \frac{1}{N}\sum_{k=0}^{N-1} e^{j2\pi kx} = e^{j\pi(N-1)x}\frac{\sin(\pi Nx)}{N\sin(\pi x)} \tag{16}$$

In the case of an ideal channel, the powers of the useful component and the intercarrier interference in the case of the OFDM system are given by

$$\begin{aligned} &E_{sm}\left|E\left[I_{i,m,m}\right]\right|^2 = E_{sm}\left|G(\Delta FT)\right|^2 \\ &\sum_{\ell\neq m} E_{s\ell}\left|E\left[I_{i,\ell,m}\right]\right|^2 = \sum_{\ell\neq m} E_{s\ell}\left|G\left(\frac{\ell-m}{N} + \Delta FT\right)\right|^2 \end{aligned} \tag{17}$$

and the powers of the useful component and the multi-user interference in the case of the MC-CDMA system are given by

$$\begin{aligned} &E_{sm}\left|E\left[I_{i,m,m}\right]\right|^2 = E_{sm}\left|G(\Delta FT)\right|^2 \\ &\sum_{\ell\neq m} E_{s\ell}\left|E\left[I_{i,\ell,m}\right]\right|^2 = \frac{1}{N-1}\sum_{\ell\neq m} E_{s\ell}\left(1-\left|G(\Delta FT)\right|^2\right) \end{aligned} \tag{18}$$

From (17) and (18) it follows that a carrier frequency offset introduces a carrier-independent attenuation, a user-independent attenuation respectively, of the useful component, as $|G(\Delta FT)|<1$ for $\Delta FT\neq 0$. As $|G((\ell-m)/N+\Delta FT)|\neq 0$ for $\ell\neq m$ and $\Delta FT\neq 0$, (17) indicates the presence of intercarrier interference. From (18) it follows that a carrier frequency offset gives rise to a non-zero multi-user interference.

In the case that all carriers, users respectively, have the same energy per symbol E_s and for the maximal load (all carriers are modulated in the case of OFDM and N users in the case of MC-CDMA) it can be verified that the degradation of the SNR for both OFDM and MC-CDMA becomes

$$D_m = -10\log\left|\frac{\sin \pi N \Delta F T}{\sin \pi \Delta F T}\right|^2 + 10\log\left(1+\frac{E_s}{N_0}\left(1-\left|\frac{\sin \pi N \Delta F T}{\sin \pi \Delta F T}\right|^2\right)\right) \tag{19}$$

In figure 3, the degradation (19) is shown as function of the product $N\Delta FT$. We observe a high sensitivity of the OFDM and MC-CDMA system performance to the carrier frequency offset. To obtain a small degradation, the carrier frequency offset must be limited to small frequency offsets : $\Delta F << 1/NT$. The degradation in figure 3 yields an upper bound for the degradation in the case of M<N modulated carriers for the OFDM case and M<N active users for the MC-CDMA case.

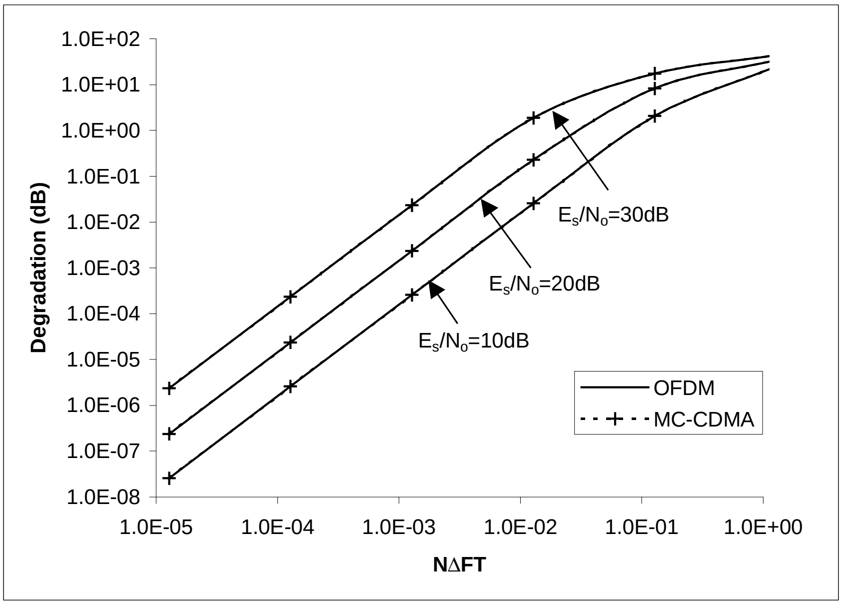

Figure 3 : Degradation as function of carrier frequency offset

In order to get rid of the frequency offset, a phase-locked local oscillator can be used for RF to baseband conversion. The residual phase jitter can be modelled as a zero-mean stationary process with jitter spectrum $S_\phi(f)$ and jitter variance σ_ϕ^2. For slowly varying phase jitter, the bandwidth f_B of the jitter spectrum $S_\phi(f)$ has to be small, i.e. $f_BT<<1$. The quantities (7) and (13) are random processes and assuming small jitter variances $\sigma_\phi^2<<1$, they can be approximated for the OFDM case by

$$I_{i,\ell,m} \cong H_\ell\left(\delta_{\ell,m} + \frac{1}{N}\sum_{k=0}^{N-1} j\phi_{i,k} e^{j2\pi\frac{k(\ell-m)}{N}}\right) \tag{20}$$

and for the MC-CDMA case by

$$I_{i,\ell,m} \cong \frac{1}{N}\sum_{n,n'=0}^{N-1} c_{n,\ell} H_n\left(\delta_{n,n'} + \frac{1}{N}\sum_{k=0}^{N-1} j\phi_{i,k} e^{j2\pi\frac{k(n-n')}{N}}\right) c_{n',m}^* \tag{21}$$

The useful component $I_{i,m,m}$ of (20) and (21) exhibits a random fluctuation and we observe that the phase jitter introduces intercarrier interference (20) and multi-user interference (21) ($I_{i,\ell,m}\neq 0$ for $\ell\neq m$). In the case of an ideal channel and when all carriers, respectively users, have the same energy per symbol E_s, it can be verified that for the maximal load the powers of the average useful component, the fluctuation of the useful component, the average intercarrier interference (multi-user interference) and the fluctuation of the ICI (MUI) for the OFDM (MC-CDMA) system are independent of the index m and are given by

$$
\begin{aligned}
&E_{sm}\left|E\left[I_{i,m,m}\right]\right|^2 = E_s \\
&E_{sm}E\left[\left|I_{i,m,m} + E\left[I_{i,m,m}\right]\right|^2\right] = E_s\int_{-\infty}^{+\infty} S_\phi(f)\left|G(fT)\right|^2 df \\
&\sum_{\ell\neq m} E_{s\ell}\left|E\left[I_{i,\ell,m}\right]\right|^2 = 0 \\
&\sum_{\ell\neq m} E_{s\ell}E\left[\left|I_{i,\ell,m} + E\left[I_{i,\ell,m}\right]\right|^2\right] = E_s\int_{-\infty}^{+\infty} S_\phi(f)\left(1-\left|G(fT)\right|^2\right)df
\end{aligned}
\tag{22}
$$

From (22) it follows that the carrier phase jitter introduces no degradation of the average useful component nor an average ICI (MUI). Considering the low-pass nature of $|G(fT)|^2$ ($<1/NT$) and the high-pass nature of $1-|G(fT)|^2$ ($>1/NT$), we observe in (22) that the fluctuation of the useful component is mainly determined by the low frequency components ($<1/NT$) of the jitter, while the fluctuation of the ICI (MUI) is mainly determined by the high frequency components ($<1/NT$) of the jitter. The sum of the powers of the fluctuation of the useful component and the fluctuation of the ICI (MUI) is independent of the number of carriers N and the spectral contents of the jitter, but only depends on the jitter variance

$$
E_{sm}E\left[\left|I_{i,m,m} + E\left[I_{i,m,m}\right]\right|^2\right] + \sum_{\ell\neq m} E_{s\ell}E\left[\left|I_{i,\ell,m} + E\left[I_{i,\ell,m}\right]\right|^2\right] = E_s\sigma_\phi^2 \tag{23}
$$

where the jitter variance is given by

$$
\sigma_\phi^2 = \int_{-\infty}^{+\infty} S_\phi(f)\,df \tag{24}
$$

The degradation caused by the presence of the carrier phase jitter $D_m=10\log(1+E_s/N_0\sigma_\phi^2)$ is shown in figure 4. The degradation in figure 4 yields an upper bound for the degradation in the case of M<N modulated carriers for the OFDM case and M<N active users for the MC-CDMA case.

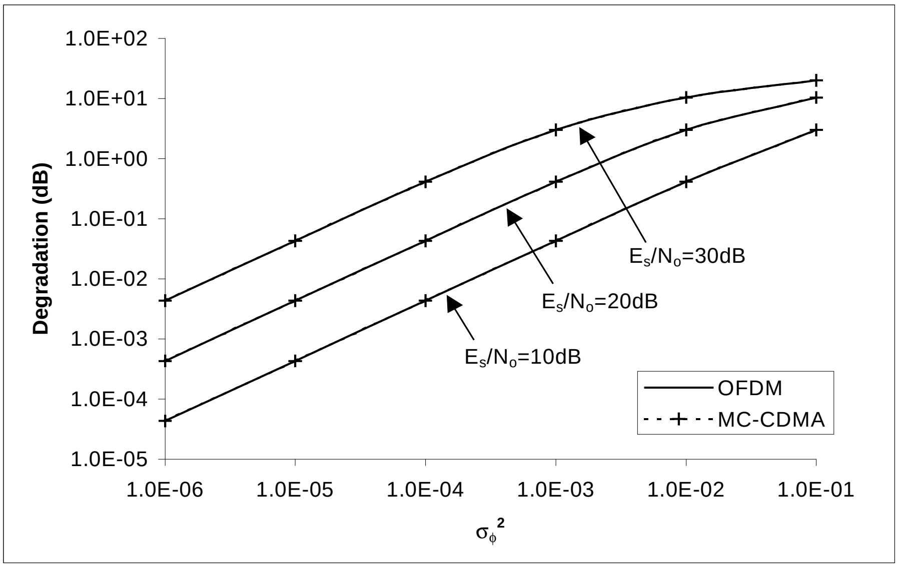

Figure 4 : Degradation as function of carrier phase jitter

V. Conclusions

We have investigated the sensitivity of OFDM and MC-CDMA to carrier phase errors. We found that OFDM and MC-CDMA have essentially the same sensitivities to carrier phase errors. For a constant phase offset, the OFDM system and the MC-CDMA system exhibit no degradation of the SNR in the presence of a non-zero constant phase offset. In the presence of a carrier frequency offset, the OFDM and MC-CDMA system performances both rapidly degrade for an in increasing number of carriers. To eliminate this high sensitivity, we proposed the use of a phase-locked local oscillator for the down-conversion of the RF signal. The resulting carrier phase jitter gives rise to a degradation of the OFDM and MC-CDMA performance that is independent of the number of carriers N and the spectral contents of the jitter, but only depends on the jitter variance. An overview of the sensitivities of the OFDM system and the MC-CDMA system is shown in table 1.

	OFDM	MC-CDMA
constant phase error	no degradation	no degradation
carrier frequency offset	degradation increases with N high sensitivity	degradation increases with N high sensitivity
carrier phase jitter	independent of *N*, independent of spectral contents phase jitter	independent of *N*, independent of spectral contents phase jitter

Table 1 : Sensitivity of OFDM and MC-CDMA to carrier phase errors

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