# Comparison of Downlink and Uplink MC-DS-CDMA Sensitivity to Carrier Frequency Offsets

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## Abstract

*In this paper, we study the sensitivity of uplink and downlink MC-DS-CDMA to carrier frequency offsets, assuming orthogonal spreading sequences. For both uplink and downlink MC-DS-CDMA, we show that the performance rapidly degrades for an increasing ratio of maximum frequency offset to carrier spacing. We point out that the degradation in the uplink is larger than in the downlink, because only the former is affected by multi-user interference. For a given (small) ratio of maximum frequency offset to carrier spacing, enlarging the spreading factor in a fully loaded system does not affect the downlink degradation, but strongly increases the uplink degradation.*

## 1. Introduction

Due to the enormous growth of wireless services (cellular telephones, wireless LAN's, ...) during the last decade, the need for a modulation technique that can reliably transmit high data rates at a high bandwidth efficiency arises. Particularly multicarrier (MC) systems have received considerable attention, as they combine a high bandwidth efficiency with an immunity to channel dispersion [1]-[8]. These MC systems include different combinations of multicarrier modulation and code-division multiple access (CDMA), that have been investigated in the context of high-rate multi-user communication over dispersive channels [5]-[8].

A major disadvantage of multicarrier systems is their high sensitivity to frequency offsets between the carrier oscillators at the transmitter and the receiver, especially when the number of carriers is large. The effect of carrier frequency offsets on multicarrier systems has been reported in [9] for orthogonal frequency-division multiplexing (OFDM), and in [10]-[11] for MC-CDMA (which combines multicarrier modulation with frequency-domain spreading).

In this contribution, we investigate the effect of carrier frequency offsets on multicarrier direct-sequence CDMA (MC-DS-CDMA), which combines multicarrier modulation with time-domain spreading [5], [7].

## 2. System Description

### 2.1. Uplink MC-DS-CDMA

The conceptual block diagram of the transmitter of an MC-DS-CDMA system is shown in figure 1 for a single user. In MC-DS-CDMA, the complex data symbols to be transmitted at a rate $R_s$ are split into $N_c$ symbol sequences, each having a rate $R_s/N_c$ and each modulating a different carrier of the multicarrier system. The data symbol $a_{i,k,\ell}$ denotes the $i^{\text{th}}$ data symbol transmitted by user $\ell$ on the carrier with index $k$, with $k$ belonging to a set $I_c$ of $N_c$ carrier indices. The symbol $a_{i,k,\ell}$ is multiplied with a spreading sequence $\{c_{i,n,\ell}|n=0,...,N_s-1\}$ with spreading factor $N_s$; $c_{i,n,\ell}$ denotes the $n^{\text{th}}$ chip of the sequence that spreads the data symbols transmitted by user $\ell$ during the $i^{\text{th}}$ symbol interval. Note that the spreading sequence does not depend on the carrier index $k$ : the same spreading sequence is used on all $N_c$ carriers. The $N_s$ components of the spread data symbol $a_{i,k,\ell}$ are denoted $\{b_{i,k,n,\ell}=a_{i,k,\ell}\, c_{i,n,\ell}|n=0,...,N_s-1;k \in I_c\}$. The components $b_{i,k,n,\ell}$ are serially transmitted on the $k^{\text{th}}$ carrier of an orthogonal multicarrier system, i.e., the data symbols are spread in the time-domain. The modulation of the spread data symbols on the orthogonal carriers is accomplished by means of an $N_F$-point inverse fast Fourier transform (inverse FFT). In order to avoid that channel dispersion 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 $s_{i,m,n,\ell}$, with

$$s_{i,m,n,\ell} = \frac{1}{\sqrt{N_F + N_p}} \sum_{k \in I_c} b_{i,k,n,\ell}\, e^{j2\pi \frac{km}{N_F}} \qquad m = -N_p, ..., N_F - 1 \tag{1}$$

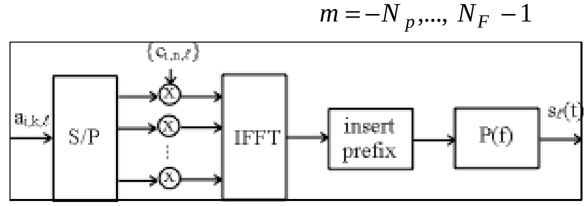


Figure 1: MC-DS-CDMA transmitter for a single user

The transmitter feeds the samples $s_{i,m,n,\ell}$ at a rate $1/T=(N_F+N_p)N_sR_s/N_c$ to a square-root raised-cosine filter $P(f)$ with rolloff $\alpha$ and impulse response $p(t)$, yielding the continuous-time transmitted complex baseband signal $s_\ell(t)$, given by

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

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 ($N_c \leq (1-\alpha)N_F$). The carrier index $k$ corresponds to the carrier frequency $k/(N_FT)$. Assuming $N_c$ to be odd, the set $I_c$ of carriers actually used is given by $I_c=\{0,...,N_c/2-1\}\cup\{N_F-(N_c/2-1),...,N_F-1\}$. For $N_p<<N_F$, the corresponding carrier spacing $\Delta f$ and system bandwidth $B$ can be approximated by $\Delta f=1/(N_FT) \cong (N_s/N_c)R_s$ and $B=N_c\Delta f\cong N_sR_s$.

When several users are active, each user transmits to the basestation a similar signal $s_\ell(t)$. In order to separate the different user signals at the receiver, each user is assigned a unique spreading sequence $\{c_{i,n,\ell}\}$, with $\ell$ denoting the user index. In this contribution, we consider orthogonal sequences, consisting of user-dependent Walsh-Hadamard 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 $N_s$. 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 $\ell$ reaches the basestation through a dispersive channel with transfer function $H_{ch\ell}(f)$ that depends on the user index $\ell$ (see figure 2.a). We assume that the timing phase of the transmitter and the time delay introduced by the channel are included in the transfer function $H_{ch\ell}(f)$. The output of the channel is affected by a carrier phase error $\phi_\ell(t)=2\pi\Delta F_\ell t+\phi_\ell(0)$, where $\Delta F_\ell$ denotes a small carrier frequency offset ($|\Delta F_\ell T|<<1$). The basestation receives the sum of the signals transmitted by the different users, disturbed by an additive white Gaussian noise (AWGN) process $w(t)$, with uncorrelated real and imaginary parts, each having a power spectral density of $N_0/2$. The contribution from each user is affected by a different carrier frequency offset $\Delta F_\ell$, as each user signal is upconverted by a different carrier oscillator.

The resulting signal is applied to the receiver filter, which is matched to the transmit filter, and sampled at a rate $1/T$ (see figure 3). The receiver removes the cyclic prefix, and applies the remaining $N_F$ samples to an $N_F$-point FFT, followed by one-tap equalizers that scale and rotate the FFT outputs. We denote by $g_{i,k,n}$ the coefficient of the equalizer, operating on the FFT output with index k during the $n^{\text{th}}$ FFT block of the $i^{\text{th}}$ symbol interval. The resulting equalizer outputs are multiplied with the corresponding chip of the reference user's spreading sequence, and summed to yield the samples $z_{i,k}$ at the input of the decision device. Assuming a sufficient cyclic prefix length, no interference between successive FFT blocks is introduced. In this case, the sample $z_{i,k}$, used to make a decision about the symbol $a_{i,k,0}$, can be decomposed as

$$z_{i,k}=\sqrt{\frac{N_F}{N_F+N_p}}\sum_{\ell=0}^{N_u-1}\sum_{k'\in I_c}a_{i,k',\ell}I_{i,k,k',\ell}+W_{i,k} \qquad k\in I_c \tag{3}$$

where

$$I_{i,k,k',\ell}=\frac{H_{k',\ell}}{N_s}\sum_{n=0}^{N_s-1}g_{i,k,n}c^*_{i,n,0}c_{i,n,\ell}A^\ell_{i,k,k',n} \tag{4}$$

$$A^\ell_{i,k,k',n}=e^{j\phi_\ell(0)}e^{j2\pi\Delta F_\ell T(n+iN_s)(N_F+N_p)}D_{N_F}\left(\frac{k'-k}{N_F}+\Delta F_\ell T\right) \tag{5}$$

$$D_M(x)=\frac{1}{M}\sum_{m=0}^{M-1}e^{j2\pi mx}=e^{j\pi(M-1)x}\,\frac{\sin(\pi Mx)}{M\sin(\pi x)} \tag{6}$$

In (4), $H_{k,\ell}=H_\ell(mod(k;N_F)/(N_FT))/T$, where $mod(x;N_F)$ is the modulo-$N_F$ reduction of $x$, yielding a result in the interval $[-N_F/2,N_F/2]$. 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 (3) contains a useful component with coefficient $I_{i,k,k,0}$. 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 AWGN contribution is denoted $W_{i,k}$.

The equalizer coefficients are selected such that the coefficients $I_{i,k,k,0}$ of the useful component equal $1$, for $k\in I_c$. This yields

$$g_{i,k,n}=\frac{e^{-j\phi_0(0)}e^{-j2\pi\Delta F_0T(n+iN_s)(N_F+N_p)}}{H_{k,0}D_{N_F}(\Delta F_0T)} \tag{7}$$

From (4), (5) and (7), it follows that the one-tap equalizer compensates the scaling and the rotation of the useful component at the corresponding FFT output. However, this equalizer cannot eliminate the MUI and the ICI, i.e., $I_{i,k,k',0}\neq 0$ for $k'\neq k$, and $I_{i,k,k',\ell}\neq 0$ for $\ell\neq 0$.

## 2.2. Downlink MC-DS-CDMA

In downlink MC-DS-CDMA, the basestation broadcasts to all users the sum of the $N_u$ user signals $s_\ell(t)$ from (2). As shown in figure 2.b, this broadcast signal reaches the receiver of the reference user through a dispersive channel with transfer function $H_{ch}(f)$. The output of the channel is affected by a small carrier frequency offset $\Delta F$: $\phi(t)=2\pi\Delta Ft+\phi(0)$ with $|\Delta FT|<<1$. The contributions from all users are affected by the same frequency offset, because all user signals are upconverted by the same carrier oscillator at the basestation. Further, the received signal is disturbed by an AWGN process $w(t)$, whose real and imaginary parts are uncorrelated and have the same power spectral density $N_0/2$.

Similarly as in uplink MC-DS-CDMA, the received signal is applied to the receiver from figure 3, in order to detect the data symbols transmitted to the reference user ($\ell=0$). Assuming a sufficient cyclic prefix length, the sample $z_{i,k}$ at the input of the decision device can be represented as in (3). The quantities $I_{i,k,k',\ell}$ are given by (4), with $H_{k,\ell}$, $f_\ell(0)$ and $\Delta F_\ell T$ substituted by $H_k = H(mod(k;N_F)/(N_F T))/T$, $f(0)$ and $\Delta FT$, respectively. As in the uplink, the samples $z_{i,k}$ are decomposed into a useful component, intercarrier interference (ICI), multi-user interference (MUI) and noise. The equalizer coefficients, that are selected such that the coefficients $I_{i,k,k,0}$ of the useful component equal $1$, are given by (7), with $H_{k,0}$, $f_0(0)$ and $\Delta F_0 T$ substituted by $H_k$, $f(0)$ and $\Delta FT$. The resulting equalizer not only compensates for the scaling and rotation of the useful component, but also eliminates the MUI (i.e., $I_{i,k,k',\ell}=0$ for $\ell \neq 0$). However, this equalizer cannot eliminate the ICI.

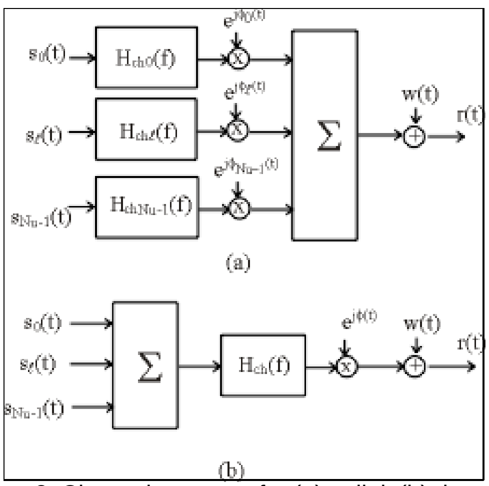


Figure 2: Channel structure for (a) uplink (b) downlink

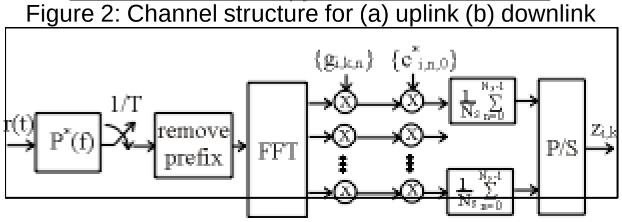


Figure 3: MC-DS-CDMA receiver structure

## 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 useful component ($P_U$) to the sum of the powers of the intercarrier interference ($P_{ICI}$), the multi-user interference ($P_{MUI}$) 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

$$SNR_k(\Delta \mathbf{F}T) = \frac{\frac{N_F}{N_F+N_P} P_{U_k}}{P_{N_k} + \frac{N_F}{N_F+N_P}\left(P_{ICI_k} + P_{MUI_k}\right)} \tag{8}$$

where $\Delta \boldsymbol{F}=(\Delta F_0,\Delta F_1,\ldots,\Delta F_{Nu-1})$. In (8), the powers of the useful component, ICI, MUI and noise are given by

$$\begin{aligned} P_{U_k} &= E_{s_{k,0}} \\ P_{ICI_k} &= \sum_{\substack{k'\in I_c \\ k'\neq k}} E_{s_{k',0}} \left|\frac{H_{k',0}}{H_{k,0}}\right|^2 \frac{X_{k,k',0}}{X_{0,0,0}} \\ P_{MUI_k} &= \frac{1}{N_s-1}\sum_{\ell=1}^{N_u-1}\left(\sum_{k'\in I_c} E_{s_{k',\ell}}\left|\frac{H_{k',\ell}}{H_{k,0}}\right|^2 \frac{X_{k,k',\ell}}{X_{0,0,0}}\right) Y_\ell \\ P_{N_k} &= \frac{N_0}{\left|H_{k,0}\right|^2 X_{0,0,0}} \end{aligned} \tag{9}$$

with

$$\begin{aligned} X_{k,k',\ell} &= \left|D_{N_F}\left(\frac{k'-k}{N_F} + \Delta F_\ell T\right)\right|^2 \\ Y_\ell &= \left(1 - \left|D_{N_s}\left(\left(N_F + N_p\right)\left(\Delta F_\ell - \Delta F_0\right)T\right)\right|^2\right) \end{aligned} \tag{10}$$

In (9), $E_{s_{k,\ell}}=E[|a_{i,k,\ell}|^2]$ denotes the symbol energy transmitted on carrier $k$ by user $\ell$. The MUI power from (9) represents an average over all possible assignments of the orthogonal spreading sequences to the users. In the absence of carrier frequency offsets ($\Delta \boldsymbol{F}$ = 0), the SNR (8) 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 carrier frequency offset is defined as $Deg_k = 10log(SNR_k(0)/SNR_k(\Delta \boldsymbol{F}T)$.

In order to clearly isolate the effect of the carrier frequency offsets, we assume that the channels are ideal and all users have the same energy per symbol on each carrier (i.e., $|H_{k,\ell}|=1$ and $E_{s_{k,\ell}}=E_s$ for $k \in I_c$, $\ell=0,\ldots,N_u-1$). In this case, the degradation is given by

$$Deg_k = -10\log\left(X_{0,0,0}\right) + 10\log\left(1 + SNR(0)\left(\sum_{\substack{k\in I_c \\ k'\neq k}} X_{k,k',0} + \frac{1}{N_s-1}\sum_{\ell=1}^{N_u-1}\left(\sum_{k\in I_c} X_{k,k',\ell}\right)Y_\ell\right)\right) \tag{11}$$

where $SNR(0)=(N_F/(N_F+N_p))(E_s/N_0)$. The summation over $k'$ in (11) ranges over the set $I_c$ of $N_c$ modulated carriers. A simple upper bound on the degradation is obtained by extending in (11) this summation over all $N_F$ available carriers, i.e. $k'=0,\ldots,N_F-1$. This yields

$$Deg \le -10\log\left(X_{0,0,0}\right) + 10\log\left(1+SNR(0)\left(1-X_{0,0,0}+\frac{1}{N_s-1}\sum_{\ell=1}^{N_u-1}Y_\ell\right)\right) \quad (12)$$

which is independent of the carrier index $k$. This upper bound is reached when all carriers are modulated ($N_c=N_F; \alpha=0$). When $\alpha>0$, the upper bound (12) yields an accurate approximation for the actual degradation on carriers near the center of the signal band.

### 3.2. Downlink MC-DS-CDMA

As in uplink MC-DS-CDMA, the performance is measured by the SNR defined in (8). The powers of the useful component, the intercarrier interference, the multi-user interference and the noise are given by (9), with $H_{k,\ell}$ and $\Delta F_\ell T$ substituted by $H_k$ and $\Delta FT$, respectively, for $\ell$ = 0, 1, ..., $N_u$-1. In this case, it follows from (6) and (10) that $Y_\ell=0$. This expresses that, in contrast with uplink MC-DS-CDMA, MUI is absent in downlink transmission (see (9)). The degradation of the SNR is defined in a similar way as in the uplink (with $H_{k,0}=H_k$ and $\Delta F_0=\Delta F$). For given $N_F$ and $\Delta FT$, this degradation is independent of the spreading factor $N_s$ and of the characteristics of the other users.

To clearly isolate the effect of the carrier frequency offset, we consider the case where the channel is ideal ($|H_k|=1,\ k \in I_c$), and the energy per symbol is the same for all carriers and all users ($E_{s k,\ell}=E_s$ for $k \in I_c$, $\ell=0,...,N_u-1$). The resulting degradation is given by

$$Deg_k = -10\log\left(X_{0,0}\right) + 10\log\left(1+SNR(0)\left(\sum_{k'\in I_c}X_{k,k'}-X_{0,0}\right)\right) \quad (13)$$

with

$$X_{k,k'} = \left|D_{N_F}\left(\frac{k'-k}{N_F}+\Delta FT\right)\right|^2 \quad (14)$$

As in uplink transmission, an upper bound on the degradation is obtained by extending the summation over $k'$ in (13) over all $N_F$ available carriers, yielding

$$Deg \le -10\log\left(X_{0,0}\right)+10\log\left(1+SNR(0)(1-X_{0,0})\right) \quad (15)$$

which is independent of the carrier index $k$. The upper bound (15) is only a function of $SNR(0)$ and $X_{0,0}$. This upper bound is reached when all carriers are modulated ($N_c=N_F; \alpha=0$). For $\alpha>0$, the upper bound yields an accurate approximation for the actual degradation on carriers near the center of the signal band.

## 4. Comparison of Degradations in Uplink and Downlink MC-DS-CDMA

When the frequency offset $\Delta F$ in downlink transmission is the same as the frequency offset $\Delta F_0$ for the reference user in uplink transmission, it follows from (9) that the powers of the useful signal, the ICI and the noise in downlink transmission are the same as in uplink transmission. Hence, the degradation in the uplink is larger than in the downlink, because MUI is absent in the latter.

Let us assume that all carrier frequency offsets are within the interval $[-F_{max},F_{max}]$, where $F_{max}$ is restricted to be smaller than the carrier spacing, i.e., $F_{max}<\Delta f=1/(N_F T)$. For small $x$, the approximation $\sin(\pi x) \cong \pi x$ holds, such that $|D_M(x)| \cong \sin(\pi Mx)/(\pi Mx)$ (see (6)). Hence, when $N_F >> 1$, $X_{0,0,0}$ from (10) and $X_{0,0}$ from (14) are essentially functions of $N_F\Delta F_0 T$ and $N_F\Delta FT$, respectively. In uplink transmission, we consider the case where $N_u >> 1$ and the frequency offsets $\Delta F_\ell$ for $\ell > 0$ are uniformly distributed in the interval $[-F_{max},F_{max}]$; in this case (12) reduces to

$$Deg \le -10\log\left(X_{0,0,0}\right) + 10\log\left(1 + SNR(0)\left(1-X_{0,0,0}+\frac{N_u-1}{N_s-1}\bar{Y}\right)\right) \quad (16)$$

where

$$\bar{Y} = 1-\frac{1}{2F_{\max}T}\int_{-F_{\max}T}^{F_{\max}T}\left(\frac{\sin(\pi N_s(N_F+N_P)(x-\Delta F_0 T))}{N_s\sin(\pi(N_F+N_P)(x-\Delta F_0 T))}\right)^2 dx \quad (17)$$

Note that $\bar{Y}$ still depends on $\Delta F_0$. In the following we look for the values of $\Delta F$ and $\Delta F_0$ that maximize (15) and (16), respectively, and compare the corresponding maximum degradations.

The bound (15) on downlink degradation is a decreasing function of $X_{0,0}$. Taking into account (14), the condition $|\Delta FT| < 1/N_F$ and the behavior of the function $|D_M(x)|$ (see (6)), it follows that the maximum value of (the bound on) the degradation (15) occurs when $|\Delta F|$ assumes its maximum value, i.e., $|\Delta F|=F_{max}$. This maximum degradation is given by (15), with

$$X_{0,0} = \left|\frac{\sin(\pi N_F F_{\max}T)}{N_F\sin(\pi F_{\max}T)}\right|^2 \quad (18)$$

For given $N_F\Delta FT$, the maximum degradation does not depend on the spreading factor.

The bound (16) on uplink degradation is decreasing with $X_{0,0,0}$ but increasing with $\bar{Y}$. A similar reasoning as for downlink transmission shows that $X_{0,0,0}$ is minimum for $|\Delta F_0|=F_{max}$. Moreover, it turns out that $\bar{Y}$ is maximum for $|\Delta F_0|=F_{max}$. Hence, the maximum uplink degradation is given by (16), with

$$X_{0,0,0} = \left|\frac{\sin(\pi N_F F_{\max}T)}{N_F\sin(\pi F_{\max}T)}\right|^2 \quad (19)$$

$$\bar{Y} \cong 1-\frac{1}{2F_{\max}N_F T}\int_0^{2F_{\max}N_F T}\left(\frac{\sin(\pi N_s x)}{N_s\sin(\pi x)}\right)^2 dx \quad (20)$$

where the approximation in (20) holds for $N_F >> N_P$.

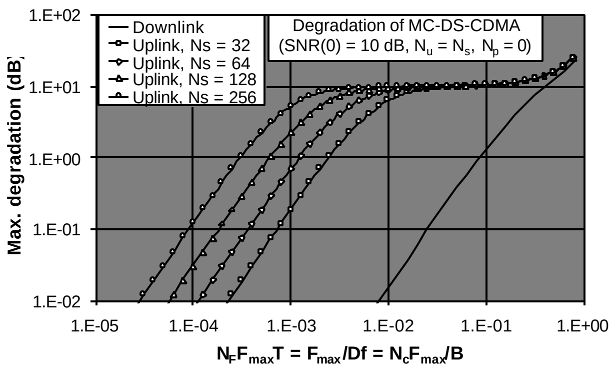


Figure 4: Maximum degradation caused by carrier frequency offset

Assuming $N_u = N_s$, the maximum uplink and downlink degradations at SNR($0$) = 10 dB are shown in figure 4 as a function of $F_{max}/Df = N_F F_{max} T = N_c(F_{max}/B) = (N_c/N_s)(F_{max}/R_s)$, for several values of the spreading factor $N_s$.

- For given SNR($0$), the downlink degradation depends only on the ratio $F_{max}/Df$. Hence, for given $F_{max}/B$, this degradation increases with the number ($N_c$) of carriers. Stated otherwise, for given $F_{max}/R_s$, the degradation increases with the ratio $N_c/N_s$. In order to obtain small degradations, the carrier frequency offset must be kept small as compared to the carrier spacing of the multicarrier system, i.e., $F_{max} << Df$. In this case, the degradation is essentially proportional to $(F_{max}/Df)^2 = (N_F F_{max} T)^2 = (N_c F_{max}/B)^2 = ((N_c/N_s)(F_{max}/R_s))^2$.
- We observe that the maximum degradation is much larger in the uplink than in the downlink. This indicates that the uplink degradation is dominated by the MUI. For $F_{max} >> Df/(2N_s)$, we have $\overline{Y} \cong 1$ (see (20)), in which case the maximum uplink degradation (16) depends only on the ratio $F_{max}/Df$. In this region the curves in figure 4 coincide for different values of $N_s$; for given $F_{max}/B$ or $F_{max}/R_s$, the corresponding degradation increases with $N_c$ or $N_c/N_s$, respectively. A small degradation can be obtained only when $F_{max} << Df/(2N_s)$. As compared to the downlink, this condition on $F_{max}$ is more stringent by factor of $2N_s$. For $F_{max} << Df/(2N_s)$, the degradation is essentially proportional to $(N_s F_{max}/Df)^2 = (N_s N_F F_{max} T)^2 = (N_s N_c F_{max}/B)^2 = (N_c F_{max}/R_s)^2$; in this region, the ratio between uplink and downlink degradation is proportional to $N_s^2$.

## 5. Conclusions

In this contribution, we have investigated the effect of carrier frequency offsets on uplink and downlink performance of MC-DS-CDMA with orthogonal spreading sequences. Our conclusions can be summarized as follows.

- In the uplink, carrier frequency offsets give rise to a reduction of the useful signal power and to the occurrence of ICI and MUI. In the downlink, MUI is absent. Hence, frequency offsets cause a larger degradation in the uplink than in the downlink.
- In both the uplink and the downlink, the degradation strongly increases with the ratio $F_{max}/Df$ of maximum frequency offset to carrier spacing.
- For given $F_{max}/Df$, the degradation in the downlink does not depend on the spreading factor $N_s$. Achieving a small degradation requires $F_{max}/Df << 1$, in which case the degradation is proportional to $(F_{max}/Df)^2$.
- For given $F_{max}/Df$ and assuming a fully loaded system ($N_u = N_s$), the degradation in the uplink increases with the spreading factor $N_s$. Achieving a small degradation requires $F_{max}/Df << 1/(2N_s)$, which condition is much more stringent than in the downlink, especially when the spreading factor is large. The corresponding degradation is larger than in the downlink, by a factor that is proportional to $N_s^2$.

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