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The Doppler Spread – Gaining Diversity for Future Mobile Radio Systems

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Abstract— **In this paper the trade-off between time diversity and the inter-carrier interference (ICI) in an OFDM based MC-CDMA system is discussed. Our approach is to partially shift each spectrum of an OFDM symbol at the transmitter by using different phase shifts in the time domain at different antennas after the OFDM modulation. The summary signal at the receiver has a wider Doppler spectrum as the result of different uncorrelated Rayleigh fading channels. This leads to an artificially increased selective time channel transfer function, which is more favorable for the channel decoder at the receiver. The trade-off between Doppler diversity and ICI is found at about 9% maximum Doppler spread of the subcarrier distance for flat fading channels and frequency selective fading channel models. The distance to the independent Rayleigh channel bound by applying an MMSE detector is less than 2 dB for convolutional coding and about 2 dB for turbo coding at a BER of 10^{-3} for flat fading channels. For frequency selective fading channels this approaches to less than 1 dB to the independent Rayleigh channel bound.**

I. INTRODUCTION

Severe Doppler spread can significantly degrade the performance of a wireless OFDM based multi-carrier system. By using the cyclic prefix the individual subcarriers in an OFDM system are orthogonal in a time invariant multipath channel. The orthogonality is destroyed when the channel is time variant and its characteristics are changing throughout the duration of an OFDM symbol. The variances can be modelled by the Doppler spread. The Doppler spread is the difference in Doppler frequencies between different channel paths. A common Doppler shift can be corrected, as it is a fixed frequency offset [1]. The Doppler spread reduces the useful energy in each subcarrier and introduces inter-carrier interference (ICI). Both effects decrease the SNR at the receiver.

Proposed future mobile wireless systems [2] increase the subcarrier distance that were imposed in the past by the maximum speed of the mobile users. The new subcarrier distances can be exploited by a broader Doppler spectrum. In this paper we identify the Doppler spread as a transmitter time diversity source for an OFDM (in particular MC-CDMA) based wireless system. The trade-off between time diversity on the one hand and the combination of leaking signal energy into adjacent subcarriers and ICI on the other hand is discussed.

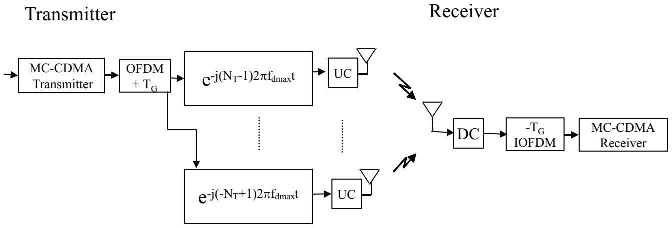

Fig. 1. MC-CDMA downlink system with N_T transmit antennas applying Doppler diversity.

The paper is organized as follows. Section II introduces the time diversity approach by broadening the Doppler spectra. Section III establishes the system model and its parameters for a proposed fourth generation scheme [2]. As an example a downlink MC-CDMA system is presented. In Section IV simulation results are discussed for the wider Doppler spectra. Section V summarizes and concludes this paper.

II. DOPPLER DIVERSITY

In [3], [4], [5] several diversity techniques are investigated for OFDM systems. They focus on exploiting frequency diversity as current systems adjust the subcarrier spacing to the maximum velocity of mobile users. In contrast the Doppler diversity approach uses time diversity and is explained in more detail in the following section. Additional constraints resulting from the local oscillator are briefly discussed from the simulation results at the end of this section.

A. Transmitter Doppler Diversity

Fig. 1 shows an N_T-transmitter antenna system applying MC-CDMA with Doppler diversity. The data stream is transmitted through an MC-CDMA system. After the OFDM modulation, the signal is split equally on N_T transmit antennas.

Before transmitting the signals, on each antenna the signal is multiplied by an exponential phase shifting function. This can be described by

$$s_{t,l}(t) = s(t) \cdot \phi(t,l) \tag{1}$$

with

$$\phi(t,l) = e^{-j\cdot(N_T-1-2\cdot l)\cdot 2\pi f_{dmax} t}, \text{ with } l = 0, ..., N_T - 1, \tag{2}$$

where $s_{t,l}(t)$ is the signal transmitted at the l'th antenna, f_{dmax} is the maximum Doppler spread of the channel and t is a time discrete coefficient. The "UC" unit represents the upconversion of the signal. The signal is then transmitted through a multipath channel. At the receiver the signal is downconverted by the "DC" unit. After the removal of the guard interval T_G the signal is fed into an MC-CDMA receiver applying a convolutional or a turbo channel decoder.

In Fig. 2 the broadening effect of the Doppler spectrum is visualized for a rectangular spectrum. The exponential function at the transmitter causes the Doppler spectrum of the channel transfer function to be shifted by half of its bandwidth. For a three-dimensional scattering environment [6], [7] the Doppler spectrum has a rectangular shape. The rectangular shape is shifted by a phase shift $\phi(t,l)$ differently for each antenna. Finally at the receiver all shifted rectangular Doppler spectra are placed next to each other. The receiver cannot separate the different rectangular Doppler spectra and has to deal with one broad rectangular Doppler spectrum. f_{dmax} itself depends on the maximum possible Doppler spread in the wireless scenario. The maximum possible shift in this scenario depends on the number of antennas.

Applying any other function be capable of broadening the spectrum of the Doppler at the transmitter would also cause a more selective time fading channel. The increased time selectivity of the fading channel leads to a more favorable distribution of the errors caused by the channel transfer function. This is exploited by the convolutional or the turbo channel decoder at the receiver.

B. Synchronization and Velocity Estimation Aspects

In this section aspects regarding the synchronization and the estimation of the Doppler spread are briefly mentioned.

In [8] the effect of a large Doppler spread on the local oscillator is analyzed. For a two path Rayleigh distributed channel model the authors showed that the synchronization performs worse if both paths have the same power loss. The possible gain for the synchronization in case of different power losses of the signal paths is not noticeable [8] for Doppler spreads below 10% of the subcarrier spacing. In this paper the proposed Doppler spread for gaining time diversity is about 10% of the subcarrier spacing.

The Doppler spread is historically used for velocity measurements [9]. The estimation of the broaden Doppler spread effects the velocity vector estimation. In [10] a maximum-likelihood (ML) estimator and a suboptimal one are compared in respect to the convergence of the tracking of the Doppler spread. For a low and high Doppler spread the performance is similar. The broaden Doppler spectrum at the receiver leads to a falsified velocity estimation. This could be easily adjusted by feeding side information about the broadening factor from the transmitter (e.g. how many shifts have been done).

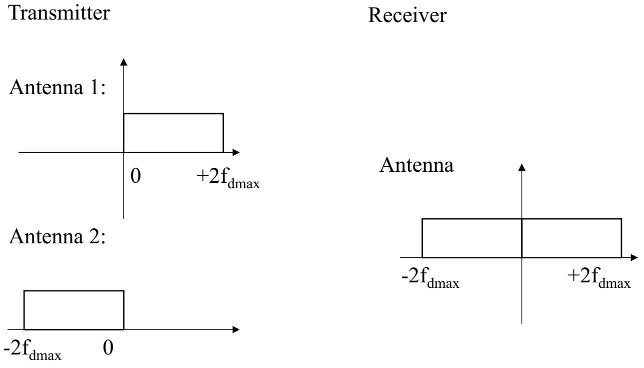

Fig. 2. The Doppler spectrum is broaden by a different phase shift at each transmitter antenna for $N_T = 2$.

III. MC-CDMA SYSTEM

In this section the system parameters of the used MC-CDMA system and the channel models that are used for the simulations are introduced.

A. System Parameters

Fig. 3 represents the block diagram of the downlink MC-CDMA system. At the transmitter side, there is a binary source for each of the K users. This is followed by a convolutional (rate $= \frac{1}{2}$, with memory 6) or a turbo channel encoder (mother code rate $= \frac{1}{3}$, punctured for code rate $= \frac{1}{1}$). The codebits are interleaved by a random codebit interleaver. The symbol mapper (MOD) assigns the bits to complex-valued data symbols according to different alphabets, like PSK or QAM with the chosen cardinality. A serial-to-parallel converter allocates the modulated signals to M data symbols per user. Each of the M data symbols is spread with a Walsh-Hadamard sequence of the length $L, (L > K)$ and is multiplexed. All modulated and spread signals are combined and form one user group. There are Q user groups which are interleaved by a symbol (LxMQ block) interleaver. The interleaved symbols are OFDM modulated and cyclically extended by the guard interval. The resulting OFDM symbols are transmitted over the multipath channel and additional white Gaussian noise is added. The same data symbols are allocated to each antenna. The total transmit power of the N_T antennas is normalized and independent of the number N_T. At each antenna element l the signal is shifted differently by $e^{-j\cdot(N_T-1-2\cdot l)\cdot 2\pi f_{dmax} t}$

according to (1). Then the shifted symbols are upconverted and transmitted over a multipath channel.

The receiver applies a downconversion and the received symbols are shortened by the guard interval, OFDM demodulated and deinterleaved at the receiver. A demultiplexer identifies the user group of interest out of the Q different user groups and detects the signal of the desired user with an MMSE detector. The equalized signal is despread. Then all data symbols of the desired user are combined to a serial data stream. The symbol demapper maps the data symbols into bits, and calculates the log-likelihood-ratio for each bit based on the selected alphabet. The codebits are deinterleaved and finally decoded using soft decision algorithms. At the sink the bits are compared with the source bits and the errors are counted.

The system parameters that we use, allow the exploitation of the broaden Doppler diversity. The system parameters are presented in Table I and have been successfully implemented in a testbed [2].

TABLE I

MAIN SYSTEM PARAMETERS

Parameter	Characteristic/Value
Bandwidth	101.5MHz
Subcarriers	768
Subcarrier Spacing	131.836 kHz
Frames	48
Users	16
Data Symbols per OFDM Symbol	48
Spreading Factor	16
Data Modulation	4-QAM
Channel Coding (Convolutional/Turbo) rate	1/2
Channel Estimation	perfect

B. Channel Models

The simulations are based on a two-path and a twelve-path channel model with wide sense stationary uncorrelated scatterers (WSSUS). Table II shows the main channel properties of the two channel models. The twelve-tap channel model imposes more delay diversity in comparison to the two-tap channel model. The guard interval was chosen according to the channel model to ensure that no intersymbol-interference and ICI occur. The rate loss due to the guard interval was not taken into account.

IV. SIMULATION RESULTS

The Doppler spreads are given relatively to the subcarrier distance in percentage. The lower bound in all figures is based on the independent Rayleigh channel. It is used as a reference curve for all coding scenarios.

Each subcarrier and each OFDM symbol are independently identically distributed by Rayleigh fading. The independent Rayleigh channel provides the maximum diversity in time and frequency direction by providing the following issues:

TABLE II

MAIN CHANNEL PROPERTIES

Path	Path-Delay $[\mu s]$	rel. avg. Power $[dB]$	Fading-Char.	Doppler Spectr. Form
Channel A:				
1	0	0	Rayleigh	rect
2	10	-3	Rayleigh	rect
Channel B:				
1	0	0	Rayleigh	rect
2	16	-1	Rayleigh	rect
3	32	-2	Rayleigh	rect
4	48	-3	Rayleigh	rect
5	64	-4	Rayleigh	rect
6	80	-5	Rayleigh	rect
7	96	-6	Rayleigh	rect
8	112	-7	Rayleigh	rect
9	128	-8	Rayleigh	rect
10	144	-9	Rayleigh	rect
11	160	-10	Rayleigh	rect
12	176	-11	Rayleigh	rect

- Intersymbol- and intercarrier-interference does not occur.
- Fading on each subcarrier is independently and identically distributed in frequency and time direction.
- Fading is invariant in time during one OFDM symbol.

Fig. 4 presents the simulation results for channel A with convolutional coding. These results were obtained by varying the Doppler spread. For an increased Doppler spread of up to 11% of the subcarrier distance, the gain is still increasing. The performance approaches the lower bound by less than 2 dB at a BER of 10^{-4}.

Additional simulations have been made with another two tap channel model and a six times higher delay spread. There was no difference in the performance between channel A and the wider delay spread channel. The results are therefore not shown here.

Fig. 5 depicts the simulation results for channel A with turbo coding. The results demonstrate that the turbo decoder at the receiver can exploit the diversity gain more efficiently. However, the gain or the 'turbo' effect starts at 6 dB for BER below 10^{-3}. The gain through the Doppler diversity approach is more dominant for higher SNRs. The difference to the independent Rayleigh channel bound is nearly 2.5 dB.

For channel B the picture changes slightly. This channel type already has frequency diversity caused by the twelve taps or paths. Fig. 6 presents the channel B with convolutional coding. The performance increases until the Doppler spread $f_{d(Rect)}$ reaches 5%. Then the effect of ICI starts to dominate and the performance for higher Doppler spreads decreases.

Fig. 7 illustrates the results for channel B with turbo coding. By applying turbo coding, the diversity gain could be even more efficiently exploited as it could be already seen for channel A. However, there is a performance gain by about

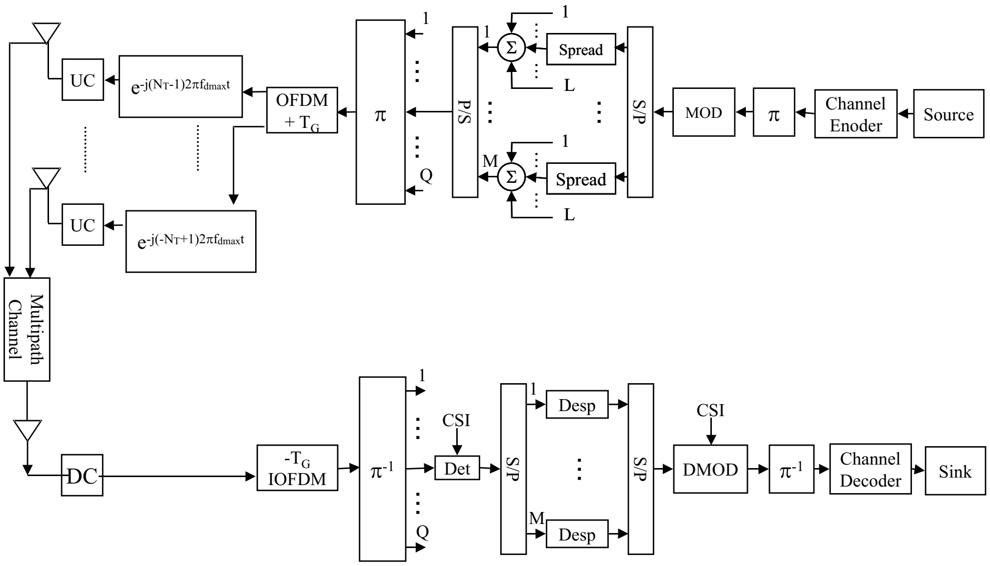

Fig. 3. The MC-CDMA system with Doppler diversity applying at the transmitter.

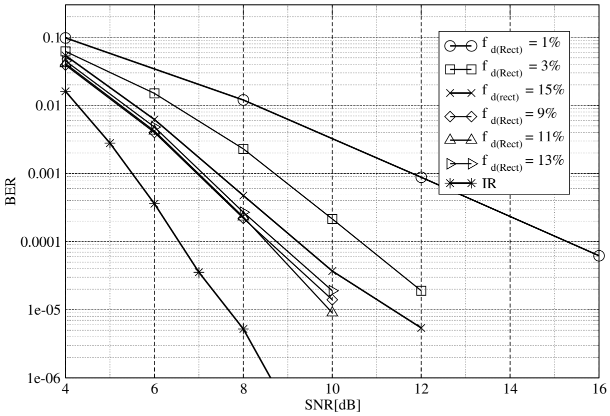

Fig. 4. Simulation results for channel A and convolutional coding with rate $\frac{1}{2}$.

2 dB by increasing the Doppler spread up to $f_{d(Rect)} = 9\%$. At a Doppler spread of 15% the performance is already reduced by the ICI to the performance results for a Doppler spread of 5%.

The Doppler spread causes a more selective time fading channel. Fig. 8 shows the possible performance gains with a turbo encoded system without the negative losses due to power leakage and intercarrier-interference. The channel model A suffers from missing frequency diversity. The performance loss for channel model A is about 3.2 dB in comparison to the independent Rayleigh channel bound for a Doppler spread of 15%. The results for the channel model B are approaching the independent Rayleigh bound by about 0.5 dB.

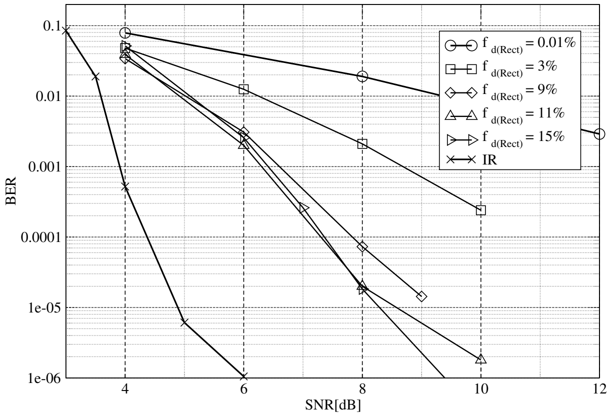

Fig. 5. Simulation results for channel A and turbo coding with rate $\frac{1}{2}$.

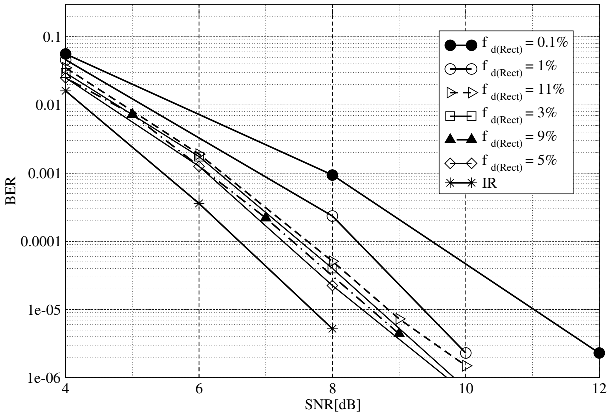

Fig. 6. Simulation results for channel B and convolutional coding with rate $\frac{1}{2}$.

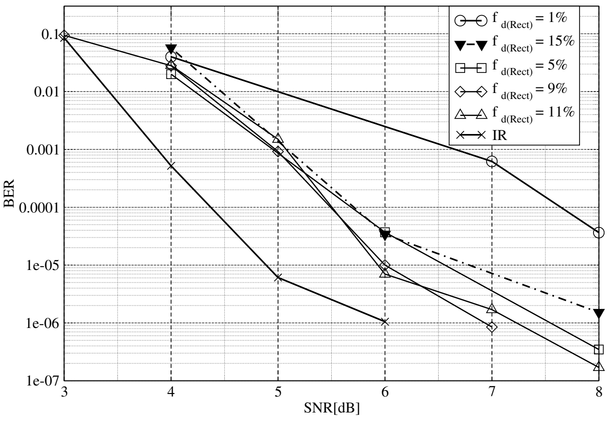

Fig. 7. Simulation results for channel B and turbo coding with rate $\frac{1}{2}$.

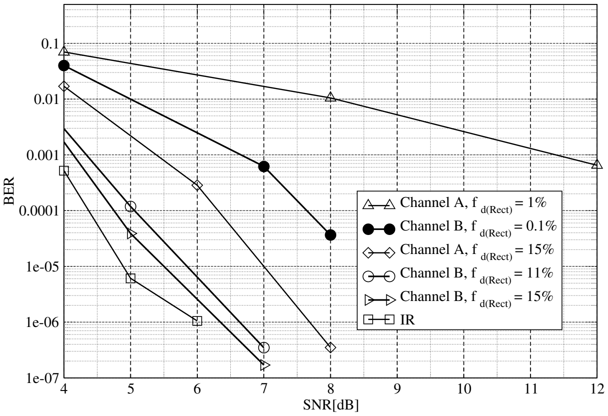

Fig. 8. Simulation results for channel A and B and turbo coding with rate $\frac{1}{2}$. All results just show the possible diversity gain, without the losses due to the ICI effect.

V. SUMMARY

The Doppler diversity method could be easily and cost efficiently implemented at the transmitter, as we are focusing on the downlink.

The simulation results prove that the Doppler diversity is especially exploitable by the channel encoder in environments not offering multipath diversity. These scenarios could be local hotspots or urban regions where users ask for high-rate data transmissions in a nearly static environment. For an MC-CDMA system applying convolutional or turbo channel coding, broadening the Doppler spectrum introduces a gain by more than 3 dB at a BER of 10^{-2} for flat channels, like the channel model A.

The gain reduces at lower Doppler spreads, if the channel model itself offers frequency selective fading in comparison to a less frequency selective channel. Rural areas, where a dozen Rayleigh faded signal paths arrive at the receiver within 20% of the OFDM symbol time already offer multipath diversity. The gain with Doppler diversity is about 1 dB at a BER of 10^{-3} for convolutional coding and nearly 2 dB for turbo coding.

The improvement is independent of the delay spread, which is also a major diversity source for multicarrier systems applying coded OFDM [3], [4]. In addition to the time diversity scheme presented in this paper the transmitter could apply a frequency diversity scheme, like cyclic delay diversity (CDD). CDD could be used especially for higher SNRs, where the ICI gets more dominant in comparison to channel noise. Therefore a combination of both techniques could improve the system performance by making it more independent of the channel characteristics itself. The bound would be the independent Rayleigh channel performance results.

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