14th European Signal Processing Conference (EUSIPCO 2006), Florence, Italy, September 4-8, 2006, copyright by EURASIP

TRANSMIT AND RECEIVE ANTENNA SUBSET SELECTION FOR MIMO SC-FDE IN FREQUENCY SELECTIVE CHANNELS

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ABSTRACT

Antenna (subset) selection is a feasible scheme to reduce the hardware complexity of Multiple-Input Multiple-Output (MIMO) systems. Studies of antenna selection schemes are typically based on channel capacity optimizations employing frequency flat channel models, which are inconsistent with MIMO systems employing spatial-multiplexing. Such systems aim to offer a high data-rate transmission, so that the channel is usually of frequency selective nature. In this contribution we study antenna subset selection at transmitter- and receiver-side for the MIMO Single Carrier (SC) scheme with Frequency Domain Equalization (FDE) in frequency selective channels. As an alternative selection metric the signal quality of the MIMO equalizer output is used.

1. INTRODUCTION

Current and future wireless applications (e.g. digital video/audio broadcast, video telephony, virtual reality, premium multimedia data services) demand high quality and high data-rate links in wireless communication networks in indoor and outdoor environments. Systems with multiple antennas at the transmitter-side and at the receiver-side, so called MIMO systems, are seen as a key technology to fulfill these demands, without occupying additional expensive signal bandwidth. MIMO systems can offer higher spectral efficiency at the expense of additional analog and digital hardware, yielding additional costs, power consumption, and space requirements.

High data-rate systems typically require a signal bandwidth that is higher than the channel coherence bandwidth, so frequency selective fading degrades the quality of the communication link. Two signaling schemes are widely accepted to mitigate the effect of frequency selectivity with reasonable complexity for equalization in indoor and in outdoor environments. The first is the well-known Orthogonal Frequency Division Multiplexing (OFDM) scheme, which uses multiple carriers to transmit the data at lower rates in parallel, and the second is the Single Carrier with Frequency Domain Equalization (SC-FDE) scheme, which employs a high rate single carrier transmission [1].

As of today SC-FDE is only deployed in IEEE 802.16 [2] as an alternative scheme and may also be deployed for broadband CDMA techniques [3]. Nevertheless, SC-FDE is gaining more and more interest, because SC signaling is a proven technology that can relax certain drawbacks of OFDM transmission (e.g. inefficient usage of power amplifiers caused by the high Peak-to-Average-Power-Ratio of transmission, sensitivity to phase noise and frequency offsets), while SC-FDE inherits OFDM's advantages (e.g. robustness against multipath, efficiency by using the Fast Fourier Transform (FFT) algorithm) [4]. OFDM is widely studied in combination with MIMO systems, whereas MIMO SC-FDE systems are studied less often.

Antenna selection or antenna subset selection is motivated by the reduction of the required complexity of analog radio hardware and of the digital processing hardware. This generally yields a reduction of power consumption, which is especially relevant for mobile devices. In addition, antenna (subset) selection allows for significant gains in performance and capacity by exploiting diversity at the transmitter- and/or the receiver-side.

As first indication for the hardware requirements of a MIMO chip, the following information for a system-on-chip (SoC) integrated SISO Wireless LAN transceiver [5] can be used. A die area of 41 mm^2 in a standard 0.18μm CMOS technology is reported, where 72 percent of the chip is digital logic. In transmit mode, the power dissipation is 180mA at 1.8V and in receive mode power dissipation is 175mA at 1.8V. In [6] the demands and challenges of MIMO transceiver Radio Frequency Integrated Circuit (RFIC) are reported. The RFIC integrates two complete radio paths on the same chip and it is reported that the isolation and the calibration of the different transmit or receive paths is especially challenging. This creates complications such as higher integration densities, but also limits the number of analog frontends for a given die area. Hence, antenna subset selection is a feasible candidate for reducing hardware complexity and savings of die area.

In the literature most of the antenna (subset) selection schemes are based on the received input power [7] and [8] or on channel capacity studies [9] and [10]. A comprehensive overview about the active research in this area is given in [7] and [11]. As one can note, this research is mainly based on flat fading channel models. As stated in [7], schemes just based on the receiver input power are only valid for frequency flat channels and diversity schemes.

In [7] and [11] it is also stated, that in case of frequency selective channels antenna selection may not be feasible or useful. Therefore, the question arises as to how antenna selection can be valid for MIMO systems, which aim to provide higher data rates by using spatial multiplexing. Here typically the signal bandwidth is larger than the coherence bandwidth of the channel, so that the channel will be frequency selective.

Within this contribution we show that antenna subset selection is also motivated by the abilities of the equalizer. For

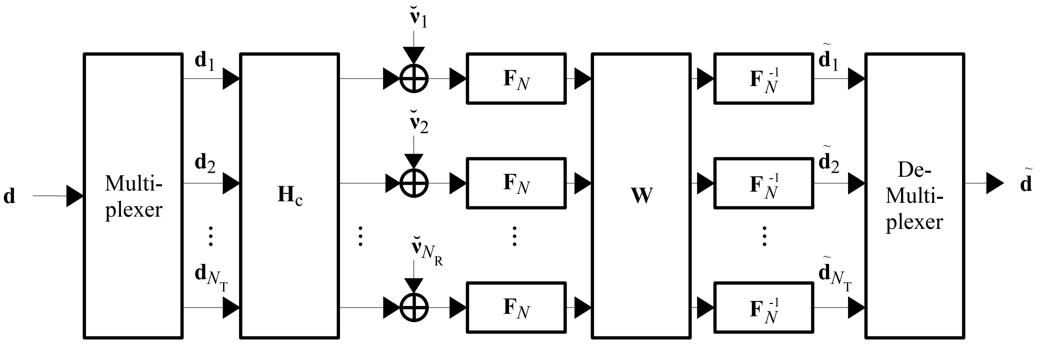

Figure 1: MIMO SC-FDE with Spatial Multiplexing for N_T Transmit and N_R Receive Antennas

our study we choose MIMO SC-FDE with spatial multiplexing as a signaling scheme. Nevertheless the similarities of SC-FDE and OFDM also allow re-using the techniques for OFDM-based systems. The antenna subset selection is done at the transmitter- and at the receiver-side, and the practical important linear receivers based on the Zero-Forcing (ZF) criterion and the Minimum Mean Square Error (MMSE) criterion are deployed.

2. SYSTEM MODEL OF ANTENNA SUBSET SELECTION IN MIMO SC-FDE

In the following we assume the transmission of N_T data blocks, each of size N, which are multiplexed to the N_T transmit antennas. This means we restrict our treatment on a single transmission interval, which will not affect the generality.

The mathematical system model for a MIMO SC-FDE with N_R receive antennas and N_T transmit antennas as given in Figure 1 can then be written as

$$\tilde{\mathbf{d}} = (\mathbf{D}_{\mathbf{F},N_\mathrm{T}})^{-1}\mathbf{W}\mathbf{D}_{\mathbf{F},N_\mathrm{R}}\mathbf{H}_\mathrm{c}\mathbf{d} + \tilde{v}, \qquad (1)$$

with $\tilde{v} = (\mathbf{D}_{\mathbf{F},N_\mathrm{T}})^{-1}\mathbf{W}\mathbf{D}_{\mathbf{F},N_\mathrm{R}}\check{v}$, and where $\mathbf{d} = [\mathbf{d}_1, \mathbf{d}_2, \ldots, \mathbf{d}_{N_\mathrm{T}}]^\mathrm{T}$ describes the parallel transmitted data blocks, $\check{v} = [\check{v}_1, \check{v}_2, \ldots, \check{v}_{N_\mathrm{R}}]^\mathrm{T}$ contains the corresponding noise vectors, $\tilde{\mathbf{d}} = \left[\tilde{\mathbf{d}}_1, \tilde{\mathbf{d}}_2, \ldots, \tilde{\mathbf{d}}_{N_\mathrm{T}}\right]^\mathrm{T}$ are the equalized received data blocks, and the matrix $\mathbf{W}$ is the MIMO equalizer matrix. The matrices described by $\mathbf{D}_{\mathbf{Z},z} = \mathbf{I}_z \otimes \mathbf{Z}$ are block diagonal matrices with z times the matrix $\mathbf{Z}$ as elements. The operator '$\otimes$' indicates the Kronecker product. The elements of the $N \times N$ Fourier matrices $\mathbf{F}_N$ are defined as $[\mathbf{F}_N]_{n,\mu} = \frac{1}{\sqrt{N}}\exp(\mathrm{j}2\pi\frac{n\mu}{N})$, where n is the sample number and μ is the frequency tone number. $\mathbf{H}_\mathrm{c}$ is defined as a block matrix, containing all circular channel matrices $\mathbf{H}_{q,p}$ between the p-th transmit and the q-th receive antenna,

$$\mathbf{H}_\mathrm{c} = \begin{pmatrix} \mathbf{H}_{1,1} & \mathbf{H}_{1,2} & \ldots & \mathbf{H}_{1,N_\mathrm{T}} \\ \mathbf{H}_{2,1} & \mathbf{H}_{2,2} & \ldots & \mathbf{H}_{2,N_\mathrm{T}} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{H}_{N_\mathrm{R},1} & \mathbf{H}_{N_\mathrm{R},2} & \ldots & \mathbf{H}_{N_\mathrm{R},N_\mathrm{T}} \end{pmatrix}.$$

The circular channels can be obtained from the linear ones by Cyclic Prefix-based or Unique Word-based techniques, which modify the transmitted and the received signals.

Now let us assume we have only $K_\mathrm{T} < N_\mathrm{T}$ transmit RF modules and $K_\mathrm{R} < N_\mathrm{R}$ receive RF modules as shown in Figure 2. Then, the digital processing system model is reduced to a $K_\mathrm{R} \times K_\mathrm{T}$ MIMO SC-FDE system. In case of antenna subset selection we have $B_\mathrm{T} = \binom{N_\mathrm{T}}{K_\mathrm{T}} = \frac{N_\mathrm{T}!}{K_\mathrm{T}!(N_\mathrm{T}-K_\mathrm{T})!}$ possible selections at transmitter-side and $B_\mathrm{R} = \binom{N_\mathrm{R}}{K_\mathrm{R}} = \frac{N_\mathrm{R}!}{K_\mathrm{R}!(N_\mathrm{R}-K_\mathrm{R})!}$ possible selections at receiver-side. From this we can conclude, that we have $B = B_\mathrm{T} \cdot B_\mathrm{R}$ possible channel matrices $\mathbf{H}_\mathrm{c}^{(b)}$. Therefore, we modify (1) to be

$$\tilde{\mathbf{d}}^{(b)} = (\mathbf{D}_{\mathbf{F},K_\mathrm{T}})^{-1}\mathbf{W}^{(b)}\mathbf{D}_{\mathbf{F},K_\mathrm{R}}\mathbf{H}_\mathrm{c}^{(b)}\mathbf{d} + \tilde{v}^{(b)}, \qquad (2)$$

with $b = 0, 1, ..., B-1$.

From (2) we can conclude, that an antenna subset selection affects $\mathbf{H}_\mathrm{c}^{(b)}$, $\mathbf{W}^{(b)}$, $\tilde{\mathbf{d}}^{(b)}$, and $\tilde{v}^{(b)}$. The effect on $\mathbf{H}_\mathrm{c}$, namely $\mathbf{H}_\mathrm{c}^{(b)}$, is due to the different channels seen. $\mathbf{W}^{(b)}$ is based on channel estimation. The noise $\tilde{v}^{(b)}$ is affected in two ways: by the receive antennas' different noise levels (caused by diversity of hardware) and by different equalizer matrices $\mathbf{W}^{(b)}$. The receiver output signal $\tilde{\mathbf{d}}^{(b)}$ is obviously effected by $\mathbf{H}_\mathrm{c}^{(b)}$, $\mathbf{W}^{(b)}$, and $\tilde{v}^{(b)}$. Additionally $\tilde{\mathbf{d}}^{(b)}$ is also affected by other hardware impairments not modeled here.

Note that a derivation of the MIMO ZF and MIMO MMSE equalizer matrix can be found in [12] and will therefore be omitted here.

3. APPROACHES BASED ON OPTIMIZING THE CHANNEL CAPACITY

The capacity of a MIMO frequency selective channel can be described by

$$C^{(b)} = \frac{1}{N}\sum_{\mu=0}^{N-1}\log_2\det\left(\mathbf{I}_{K_\mathrm{R}} + \frac{1}{K_\mathrm{T}}\left(\Lambda_\mathbf{a}^{(b)}\mathbf{H}_\mathrm{F}^{(b,\mu)}\right)^\mathrm{H}\left(\Lambda_\mathbf{a}^{(b)}\mathbf{H}_\mathrm{F}^{(b,\mu)}\right)\right) \qquad (3)$$

with

$$\mathbf{H}_\mathrm{F}^{(b,\mu)} = \begin{pmatrix} \left[\mathbf{H}_\mathrm{F}^{(b)}\right]_{\xi(\mu,1),\xi(\mu,1)} & \ldots & \left[\mathbf{H}_\mathrm{F}^{(b)}\right]_{\xi(\mu,1),\xi(\mu,K_\mathrm{T})} \\ \vdots & \vdots & \vdots \\ \left[\mathbf{H}_\mathrm{F}^{(b)}\right]_{\xi(\mu,K_\mathrm{R}),\xi(\mu,1)} & \ldots & \left[\mathbf{H}_\mathrm{F}^{(b)}\right]_{\xi(\mu,K_\mathrm{R}),\xi(\mu,K_\mathrm{T})} \end{pmatrix},$$

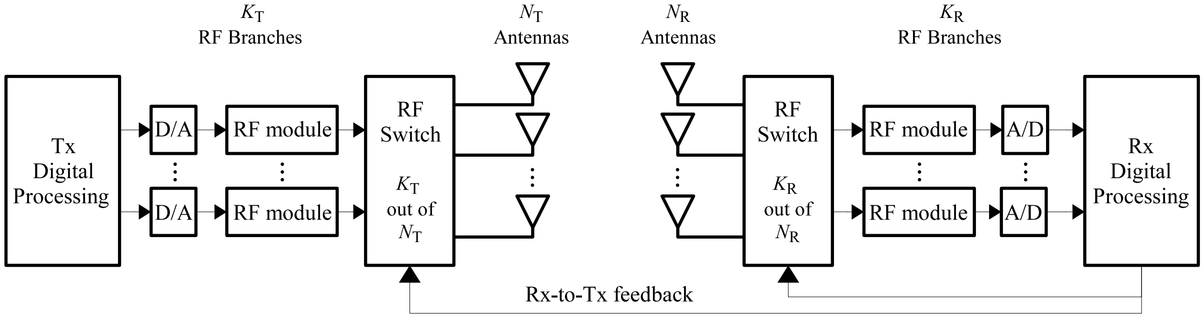

Figure 2: MIMO Communication System with Rx- & Tx-Side Selection

where $\xi(\mu,x) = \mu + 1 + N(x-1)$. The matrix $\mathbf{H}_\mathrm{F}^{(b)} = \mathbf{D}_{\mathbf{F},K_\mathrm{R}} \mathbf{H}_\mathrm{c}^{(b)} \mathbf{D}_{\mathbf{F},K_\mathrm{T}}^{-1}$ is a *block matrix* with the elements $\left[\mathbf{H}_\mathrm{F}^{(b)}\right]_{q,p} = \mathrm{diag}\left(\mathbf{F}\mathbf{h}_{q,p}\right)$, where $\mathbf{h}_{q,p}$ is a $N \times 1$ vector containing the linear channel impulse response between the p-th transmit antenna and q-th receive antenna of the corresponding selection.

With help of $\Lambda_\mathbf{a}^{(b)} = \mathrm{diag}(\mathbf{a}^{(b)})$ the different average receive Signal-to-Noise Ratios (SNR) of the receive antennas of the selected antenna set b is modeled.

The vector $\mathbf{a}^{(b)} = \left[\sqrt{\rho_1^{(b)}}, \sqrt{\rho_2^{(b)}}, \ldots, \sqrt{\rho_{K_\mathrm{R}}^{(b)}}\right]^\mathrm{T}$ contains the square roots of the corresponding average receive SNRs ρ_k over all frequency tones μ.

Modification of (3) yields

$$C^{(b)} = \frac{1}{N}\sum_{\mu=0}^{N-1} \log_2 \det\left(\mathbf{I}_{K_\mathrm{R}} + \frac{1}{K_\mathrm{T}}\left(\mathbf{H}_\mathrm{F}^{(b,\mu)}\right)^\mathrm{H} \Lambda_\rho^{(b)} \mathbf{H}_\mathrm{F}^{(b,\mu)}\right), \tag{4}$$

where $\Lambda_\rho^{(b)} = \mathrm{diag}\left(\left[\rho_1^{(b)}, \rho_2^{(b)}, \ldots, \rho_{K_\mathrm{R}}^{(b)}\right]^\mathrm{T}\right)$.

The aim is to find the antenna set b, so that $C^{(b)}$ achieves its maximum. Note that b is selected for a transmission interval of at least length N.

As can be seen from (4) an excessive search and computationally complex calculations are required to find the optimum antenna set b in terms of channel capacity. The excessive search over B possible configurations motivates incremental and decremental methods as described in [9] and [10]. Nevertheless we will use an excessive search based on (4) as a reference and will refer to it as a "C-based" method.

In Figure 3 the achieved *Ergodic Capacity* $\mathrm{E}\left\{C^{(b)}\right\}$ is plotted over SNR ρ for a frequency flat Rayleigh fading channel with $L = 1$ tap (solid lines) and for a frequency selective Rayleigh fading channel with $L = 4$ taps (dotted lines).

The underlying symbol-spaced quasi-static MIMO channel model consists of tapped delay lines with $L = 1, 4$, or 15 taps. All coefficients have zero mean and are randomly chosen. The norm of the coefficients of each tapped delay line channel is set to 1 and the noise is i.i.d. with zero mean. For simplicity we assume here and in the following $\Lambda_\rho^{(b)} = \rho \mathbf{I}_{K_\mathrm{R}}$, which means the same average SNR ρ at all receive antennas, which is typically valid in a rich scattering environment.

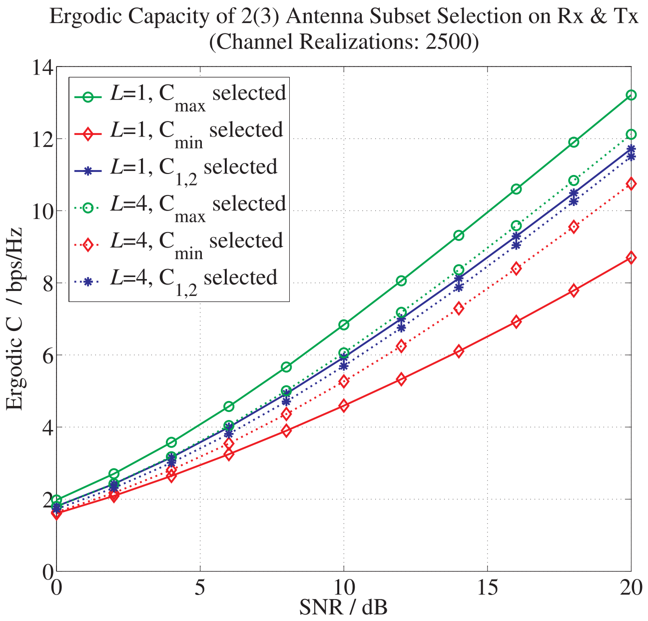

Figure 3: Ergodic Capacity Obtained by Selection (Max, Min, Fixed). $L = 1$ or $L = 4$. Same SNR on all Rx Antennas.

The curves labeled C_max represent the achieved ergodic capacity, whenever the antenna subsets that lead to a maximum capacity are selected. C_min represent the achieved ergodic capacity, whenever the antenna subsets that lead to a minimum capacity are selected (worst case). $C_{1,2}$ represents the achieved ergodic capacity, whenever the antenna 1 and antenna 2 at transmitter- and receiver-side are selected, so no adaptive selection is performed. From the frequency flat ($L = 1$) curves in Figure 3 it can be seen, that in terms of channel capacity adaptive antenna subset selection gives a reasonable improvement compared to a fixed selection. In case of a frequency selective channel with $L = 4$ taps, we observe that the curves for the ergodic capacity obtained by the different selection methods are becoming closer to each other. A result that is not included confirms a similar tendency for an $L = 15$ tap channel.

Also note, that the instantaneous capacities for frequency selective channels of the different subsets are very similar.

At a first glance this supports the statement of [7] and [11], that in case of frequency selective channels antenna selection may not be feasible or useful. However, this result also allows the question, ”Is channel capacity a suitable metric for antenna (subset) selection?”, because the capacities for different antenna subsets are, in the case of frequency selectivity, so close to each other, that such a selection can hardly be motivated.

4. APPROACH BASED ON EQUALIZER OUTPUT SIGNAL QUALITY

In the following we motivates antenna subset selection by the equalizer output signal quality, which includes the equalizer abilities. These abilities include equalization of the received signal and separation of the originally transmitted streams. We use known training sequences to decide which antenna subset can be used. One can, for example, use the training sequences for channel estimation as known sequences, which are required anyway, so that no additional overhead arises.

One possibility is to use the Euclidean distance between the equalizer output symbols $\tilde{\mathbf{d}}^{(b)}$ and the known transmit symbols $\mathbf{d}$

$$\Delta^{(b)} = \left|\tilde{\mathbf{d}}^{(b)} - \mathbf{d}\right|. \tag{5}$$

Alternatively, a decision-directed approach can be used, where the detected symbols $\hat{\mathbf{d}}^{(b)}$ are used instead of a known sequence. Here the quality of the detector will have an effect on the selection as well. Note, that the calculation of the Euclidean distance is for example already done in a Viterbi-decoder, which will also allow for sharing already implemented hardware.

The distortion of $\mathbf{d}$ has the power $P_\Delta^{(b)} = \mathrm{E}\left\{\left(\Delta^{(b)}\right)^2\right\}$.

A selection method can now be based on $P_\Delta^{(b)}$ or on the Signal-to-Distortion Power Ratio (SDR)

$$\delta^{(b)} = \frac{\mathrm{E}\left\{\left|\tilde{\mathbf{d}}^{(b)}\right|^2\right\}}{\mathrm{E}\left\{\left(\Delta^{(b)}\right)^2\right\}}. \tag{6}$$

The aim is to find the antenna subset b, which minimizes the distortion power $P_\Delta^{(b)}$ of the receiver output or maximizes the receiver output SDR $\delta^{(b)}$.

To use this method, it is required to pass the training sequences through the equalizer, which is normally not done. This will not occupy additional hardware, because the equalizer is already implemented, but it may be required to deploy some additional buffer units, due to the early usage of the equalizer and the caused latency. This latency may be equal to the one caused by the C-based approach, which also requires additional calculations and has to wait for the channel estimation results.

Note that the SDR-based method provides the following benefits: the decision is only based on the signal quality seen by the decoder, so all effects that cause a loss of signal quality (e.g. synchronization errors, channel estimation errors, spatial correlation, hardware effects) are inherently considered. In addition, only simple calculations or already implemented equalizer functions are required.

5. COMPARISON

With help of Monte-Carlo simulations we compare the C-based and SDR-based methods in terms of their BER performance over SNR, when ZF or MMSE equalizers are employed. We use the quasi-static MIMO channel model as described in section 3 and assume that the channel is static for the 10 transmitted data blocks per antenna. We choose a system with $N_\mathrm{T} = 3$ transmit antennas and $N_\mathrm{R} = 3$ receive antennas. Both methods will choose a subset of $K_\mathrm{T} = 2$ at the transmitter-side and of $K_\mathrm{R} = 2$ at the receiver-side. The feedback for the selection at the transmitter is assumed to be error-free and without delay. The data block-length N is 64 and a cyclic prefix of 16 is used. The data symbols are 16-QAM modulated. The overall transmit power is normalized to 1 and we assume the same received SNR at all antennas. Perfect channel knowledge and perfect synchronization is assumed.

In Figure 4 the performance of the MIMO SC-FDE system with ZF-Equalizer for different selection methods in a 1-tap (frequency flat) MIMO channel is shown. As it can be seen the C_max-based and SDR$_{max}$-based show basically the same performance.

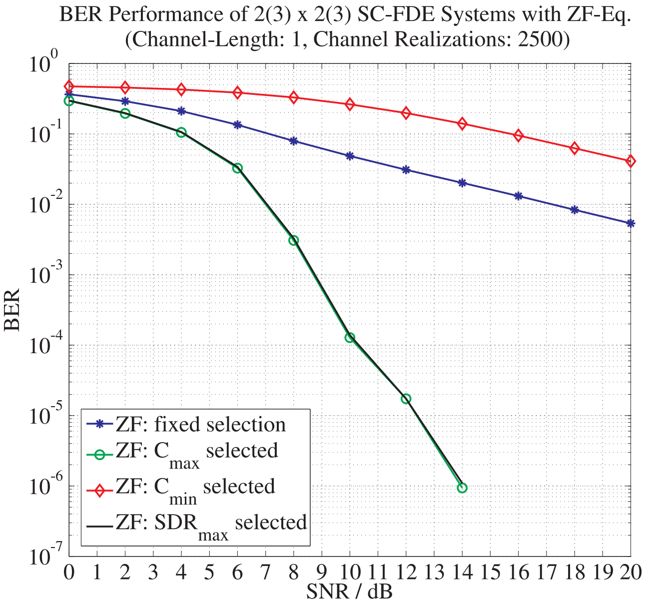

Figure 4: MIMO ZF SC-FDE under Different Selections with $L = 1$ Channel Tap.

Figure 5 shows the BER performances with ZF and MMSE equalizers in a 4-tap frequency selective MIMO channel. Here it becomes visible that the SDR-based method clearly outperforms the C-based methods by 5-6 dB at BER 10^{-3} for the ZF equalizer and 2-3 dB for the MMSE equalizer. Interestingly the SDR-based curve for the ZF-Equalizer almost reaches the performance of the MMSE-Equalizer. This can be explained as follows. The SDR-based method employs the signal quality at the equalizer output. ZF equalizers generally suffer from noise amplification if the channel is frequency selective. Noise amplification contributes to the distortion power at the equalizer's output, so that the SDR-based approach will try to choose subsets that will show no or just reduced noise amplification. Thereby, it will make use of transmit and receive diversity offered by the subset selection to mitigate the noise amplification. The MMSE equalizer also gains from this diversity compared to the fixed selection.

Figure 6 shows similar results for the 15-tap channel. The

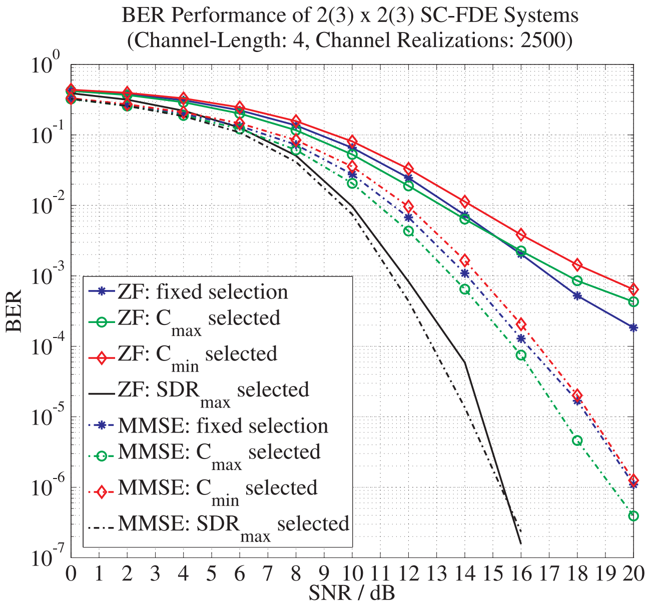

Figure 5: MIMO SC-FDE with ZF/MMSE Equalizers under Different Selections with $L = 4$ Channel Taps.

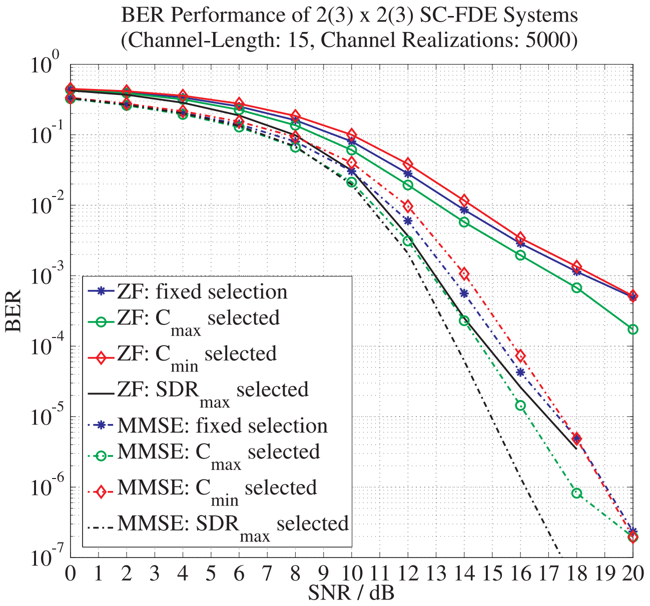

Figure 6: MIMO SC-FDE with ZF/MMSE Equalizers under Different Selections with $L = 15$ Channel Taps.

curves are becoming closer, but there is still a significant gain of approximately 5 dB at a BER of 10^{-3} for the SDR-based method compared to fixed selection in case of the ZF equalizer.

6. CONCLUSION

Within this contribution we acknowledged that antenna subset selection can provide a significant gain in BER performance, even in frequency selective channels, if the signal quality of the equalizer output is used as an antenna subset selection metric. This performance gain can be obtained by using already implemented and shareable hardware.

7. ACKNOWLEDGEMENT

This work is funded by the *Deutsche Forschungsgemeinschaft* (DFG) under the project title “Analytische und experimentelle Untersuchung von mehrteilnehmerfähigen Mehrantennen-Systemen mit niederratiger Rückkoppelung” (KA 1154/15).

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