Spectral spreading by linear block codes for OFDM in Powerline Communications

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***Abstract*— Power Line Communication (PLC) uses the highly developed infrastructure of the electrical energy distribution network for data transmission. Measurements are showing that a broadband use of PLC channels is possible. So, PLC is of interest to future broadband communication systems. Such systems will be heterogeneous in several respects, for example relative to the used transmission channel but also relative to the complexity of the participant nodes. In [5] a new class of space-time block codes for radio channels is presented. These codes meet the requirements of future communication systems. They are highly flexible and can be adapted to the particular requests of the transmission.**

In this paper a PLC application of these codes is investigated. They are used as a basis for a scalable and efficient PLC channel coding scheme. This shows that this class of codes can be used as a generic coding scheme for heterogeneous networks. Alternatively, the PLC application can be considered as an example of the usage of the codes on a frequency selective channel with coloured noise. The applied linear block code optimally uses the diversity of the frequency selective channels in combination with OFDM. This leads to significant gains in performance in case of very frequency selective channels; for barely frequency selective channels or for an AWGN channel the performance is slightly better or not affected respectively. These performance results presented in this paper are based on measured PLC channels.

I. Introduction

Channel capacity considerations are promising relatively high capacities for PLC channels [4]. Thus, the use of broad-band PLC for future communication systems and access networks is an interesting option. These systems will be mostly wireless but the use of non-dedicated wired infrastructure, e.g. power lines, will help to reduce costs. This leads to heterogeneous networks, that are not only heterogeneous relative to the transmission channel (radio, power line, fibre, etc.) but also relative to the complexity of the participant nodes (number of antennas, complexity of the digital signal processing, etc.). A class of very flexible and adaptive codes is presented in [5]. One feature of these codes is to cope with fading effects of the transmission channel. According to [4], usually one characteristic of PLC channels is frequency selective fading. It is shown in the following that these codes can be used as a basis for efficient PLC coding.

II. A New Linear Block Code for PLC Channels

The new linear block code used in this paper has been developed for high rated wireless communication as a new class of *Space–Time Codes* [5][1][3]. On the transmitting side, the space-time codes consist of two components, the *outer*– ($\mathbf{C}_\mathrm{A}$) and the *inner* ($\mathbf{C}_\mathrm{I}$) code. Both of them are *linear block codes* which are determined by matrices. The channel is a Multiple Input Multiple Output (*MIMO*) communication channel which results from an antenna array at the transmitter and at the receiver and is described as matrix $\mathbf{X}$. The receiver consists of a matched channel adaption ($\mathbf{X}^H$) as well as an inner ($\mathbf{C}_\mathrm{I}^H$) and outer ($\mathbf{C}_\mathrm{A}^H$) code matched matrix. Finally, the code needs a decoder to estimate the transmit symbol vector $\hat{\vec{s}}$.

In this paper we will only consider the outer code because we focus on SISO channels, e.g. PLC–channels, and therefore we do not need the inner code. We identify the code with a matrix $\mathbf{C}$, which is orthonormal,

$$\mathbf{C} \cdot \mathbf{C}^H = \mathbf{I} \tag{1}$$

where $\mathbf{I}$ is the unit matrix. This property of the code matrix ensures the performance on an AWGN channel and the Euclidean distance. In [5] an efficient approach is described for the optimization of an orthonormal coding matrix for any given block length. However, in this paper we use another efficient approach to generate the code matrix. This calculation has two steps. In the first part we create the elements of the code matrix $c_{m,n} = \exp(j \cdot \phi_{m,n})$,

$\phi_{m,n} \in [0, \ldots, 2\pi]$, $m, n \in [1, \ldots N]$ as complex phasors which have an uniformly distributed random phase. In the second part we orthonormalize the code matrix using Gram-Schmidt orthonormalization. With these declarations we get the simplified system model shown in Figure 1.

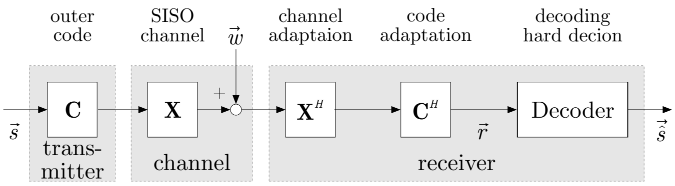


Fig. 1. System model for the SISO channel

III. THE SYSTEM MODEL

The OFDM system used in this paper should be dimensioned in such a way that the channel impact is only a scalar multiplication of the transmitted symbols $\hat{s}'_i$ with the complex transfer factors $H_{c,i}$ of the channel. So, the received symbol vector $\vec{r}'$ is given by

$$\vec{r}' = \mathbf{D}_{Hc} \cdot \vec{\hat{s}}' + \vec{n}' \tag{2}$$

where $\mathbf{D}_{Hc}$ describes the diagonal channel matrix with the complex transfer factor on the diagonal and $\vec{n}'$ is the additive coloured noise.

We used (2) and the system model from Figure 1 in order to investigate the block code. The channel adaptation

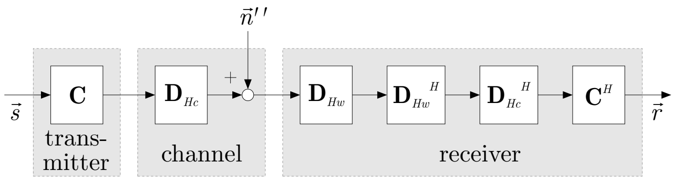


Fig. 2. System model for the linear block code and the OFDM

is dimensioned according to the matched filter principle, in this case the matched matrix. The matched matrix consists of a pre-whitening matrix $\mathbf{D}_{Hw}$ for the coloured noise, a matched matrix $\mathbf{D}^H_{Hw}$ for the pre-whitening matrix and a matched matrix $\mathbf{D}^H_{Hc}$ for the channel. The pre- whitening matrix can be realised as a diagonal matrix because the coloured noise is transformed into a white instationary noise. The outer code will be adapted to a hermitic code matrix $\mathbf{C}^H$. With these declarations the received vector $\vec{r}$ is:

$$\begin{aligned} \vec{r} &= \mathbf{\Lambda}_{ISI} \cdot \vec{s} + \mathbf{C}^H \cdot \mathbf{D}^H_{Hc} \cdot \mathbf{D}_{|Hw|^2} \cdot \vec{n}'' \\ &= \mathbf{\Lambda}_{ISI} \cdot \vec{s} + \vec{n} \end{aligned} \tag{3}$$

The notation $\mathbf{D}_{|Hw|^2} = \mathbf{D}^H_{Hw} \cdot \mathbf{D}_{Hw}$ means that the elements of the diagonal matrix will be calculated as square of the magnitude and $\mathbf{\Lambda}_{ISI} = \mathbf{C}^H \cdot \mathbf{D}_{|Hc|^2} \cdot \mathbf{D}_{|Hw|^2} \cdot \mathbf{C}$ describes the system matrix, which includes the dependence of the transmitter symbols on the receiver symbols which are influenced by the channel and the coding. Thus, $\mathbf{\Lambda}_{ISI}$ describes the intersymbol interference (ISI) of the receiver symbols.

The intersymbol interference, which has been constrained by coding, is the basis for the diversity gain; this is a kind of spectral spreading. If some transfer factors $H_{c,i}$ are strongly attenuated or even at zero, the intersymbol interference can be used to reconstruct the disturbed symbols. Figure 3 shows the system model from (3).

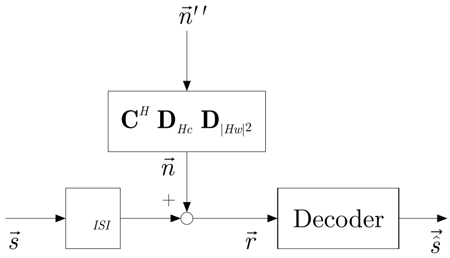


Fig. 3. Composite system model

To compensate this ISI, a decoder using an equalization method is needed. In [2] we presented a new method for intersymbol compensation. This method and a MMSE decoder will be used in this paper for ISI cancellation. The MMSE equalizer matrix is defined as:

$$\boxed{\mathbf{G} = (\mathbf{\Lambda}_{ISI} \cdot \mathbf{\Lambda}^H_{ISI} + \mathbf{R}_{nn})^{-1} \cdot \mathbf{\Lambda}_{ISI}} \tag{4}$$

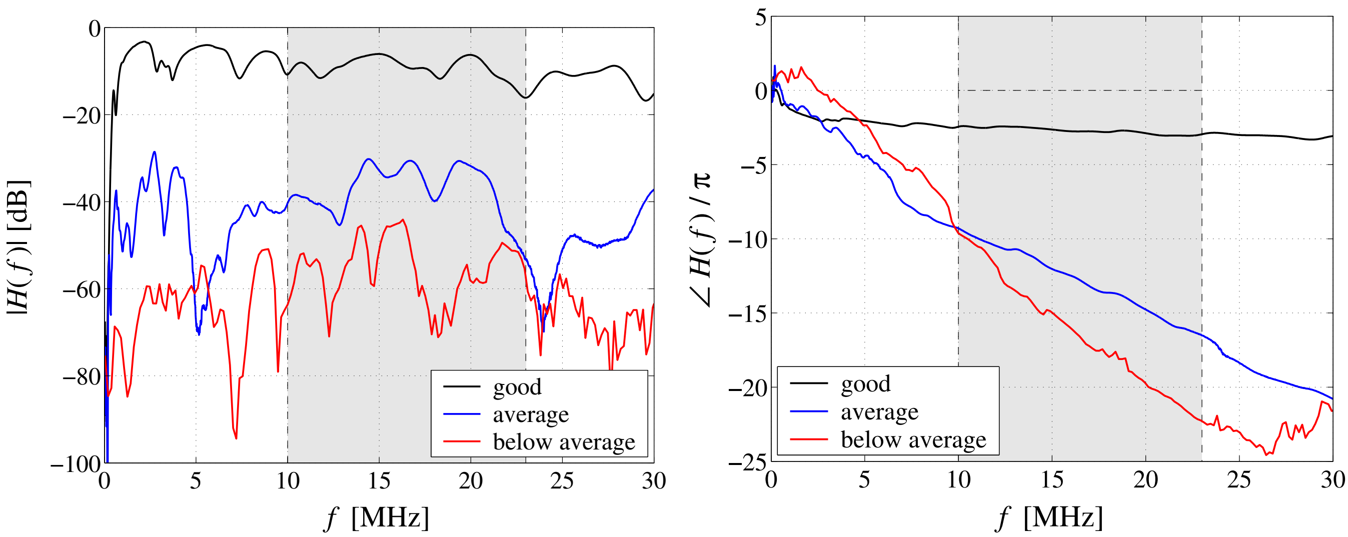
where $\mathbf{R}_{nn}$ is the autocorrelation matrix of the noise. Considering optimal whitening we obtain the autocorrelation matrix as:

$$\mathbf{R}_{nn} = \sigma^2_w \cdot \mathbf{\Lambda}_{ISI} \tag{5}$$

where σ^2_w is the noise variance.

IV. THE PLC CHANNEL

PLC channels are in general characterized by frequency selective transfer functions and by coloured noise, partly because of strong narrowband interferences [1][4]. OFDM modulation seems to be a good choice for broadband PLC because it is suitable for frequency selective channels. To combat the coloured noise a whitening filter can be used. This filter can increase the frequency selectivity of the transfer function. The applied linear block code - the outer code - optimally uses the diversity of frequency selective channels in combination with OFDM.



(a) amplitude spectrum

(b) phase angle

Fig. 4. Three measured PLC transfer function

No channel knowledge is needed at the transmitter. Therefore, such a code is especially suited for asymmetric channels or broadcast transmissions.

In this paper we use for the simulations three different channels, which contain the typical characteristics of powerline channels. In Europe broadband PLC is restricted to frequencies between 1 MHz and 30 MHz. Figure 4 shows the transfer function of the used channels. The measured transfer functions of PLC channels show high differences in the average attenuation and the frequency selectivity of the attenuation. They are roughly classified in the categories 'good', 'average' and 'below average'. The 'good' channel has a small attenuation and a slight frequency selectivity. The transfer function is measured at the same phase and at the same fuse, in the same room in a residential area. The 'average' channel shows a distinct average attenuation of approximately -40dB as well as strong fading with an attenuation up to -71dB. The phase shown in Figure 4(b) is nearly linear. The transfer function is measured at the same room but at different phases. The third channel, identified as 'below average', has an average attenuation of -65dB. The plugs of this channel are in different rooms and they are not connected at the same phase or at the same fuse.

Apart from the transfer function, the coloured noise, which is described by the power density spectrum, is also important. Figure 5 shows as example the measured coloured noise at the receiver for the average channel. The range for the transmission is marked grey. The Figure shows clearly the narrowband disturbances caused by radio stations. Higher frequencies show a decreasing of the interference power.

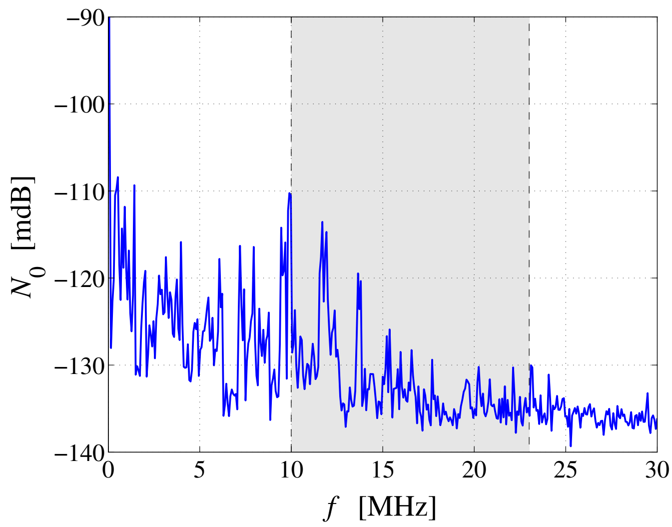


Fig. 5. Measured power density spectrum for the average channel

V. Simulation Results

For the simulation we assume that the PLC is combined with a wireless LAN (WLAN) that works according to the IEEE 802.11a standard. The interconnection between both networks is established through a gateway which should have a low complexity. This means that the gateway does not repack the data packet. The WLAN standard has defined a lot of different timing parameters such as the guard interval. The guard interval length depends of the multipath channel delay-spread and it must be greater than the expected spread of multipath delays. In [1] it was shown that the multipath channel delay-spread has a minimum of 0,4μs and a maximum of 1,5μs at the frequency band between 10MHz and 30MHz. To obtain the compatibility between the WLAN standard and the PLC application, we chose 1,6µs as the duration of the guard interval. This is equivalent to the double length of the standard. So, the symbol duration is 6,4µs and the whole symbol duration is 8µs. Because of the double length of the guard interval, it is necessary to double the number of carriers to get the same data rate as the IEEE 802.11a standard. Therefore, 104 carriers are required: 96 for the data and 8 as pilot carriers. The spacing between the carriers is $\Delta f = 1/T_s = 125\text{kHz}$ and the bandwidth is $B = 125\text{kHz} \cdot 104 = 13\text{MHz}$. For the simulation we use the frequency band that starts at 10MHz and was shown in Figure 4 and 5 with a grey background.

The coding uses two blocks with 48 carriers and the code rate 1 which is a compromise between complexity and diversity gain.

For the simulation we use the equivalent baseband system model. Perfect channel knowledge (measured transfer function and measured power density spectrum) as well as perfect time– and frequency synchronization at the receiver is assumed. The symbol alphabet is 4 QAM, which leads to a data rate of 24MBit/s. For the ISI cancellation we use the MMSE decoder and the MMSE cascade decoder which is presented in [2]. The MMSE cascade decoder works with two stages. The loss of signal-to-noise ratio, which results from the guard interval, is not considered in the simulation.

Figure 6 shows the symbol error rate (SER) versus E_s/N_0 at the receiver and versus the transmitting power. The partial images 6(a) and 6(b) show the symbol error rate for the 'good' channel. The performance of the coded OFDM with an ISI decoder according to [2] is much better than the performance of the coded OFDM with a simple MMSE filter for ISI compensation. The second stage of the MMSE cascade decoder obtains only a small improvement compared to the first stage. The 'good' channel property is the reason why the MMSE decoder has also a good performance. If we consider the necessary transmitting power, shown in Figure 6(b), we need 0,1μW to get a SER of 10^{-4} with the MMSE cascade decoder and we need 0,17µW for the same SER with the simple MMSE decoder.

The results of the simulation with the channel of 'average' attenuation, Figure 6(c) and 6(d), have a distinct degradation of the SER for both decoders. In this case, the performance of the MMSE cascade decoder is much better than the performance of the simple MMSE decoder. Furthermore, the second stage of the cascade decoder reaches a gain of 2dB for a SER of 10^{-4}. If we compare the essential transmitting power of the 'good' channel to the 'average' channel, partial image 6(d), we recognize that we need much more power to reach the same SER. For the SER 10^{-4} we need approximately 20µW with the MMSE cascade decoder and approximately 2,1mW with the MMSE decoder.

The last two partial images 6(e) and 6(f), show the SER for the 'below average' channel. The SER of the 'average' channel (Fig. 6(c)) compared to the SER of the 'below average' channel (Fig. 6(e)) shows nearly the same SER. The 'below average' channel shows a performance that is a little bit better. Furthermore, the partial image 6(f) shows the necessary transmitting power to reach this performance. The MMSE cascade decoder requires approximately 2,5mW and the MMSE decoder approximately 11mW to achieve the SER of 10^{-4}.

VI. Conclusion

The presented linear block code leads to significant gains in performance even at code rate 1, because the coded OFDM profits from high diversity gains as a result of the frequency selectivity of the PLC channels, for those with a severe frequency selective attenuation as well as for those only slightly attenuated. This channel coding scheme is very efficient for typical PLC channels even using a MMSE decoder of very low complexity.

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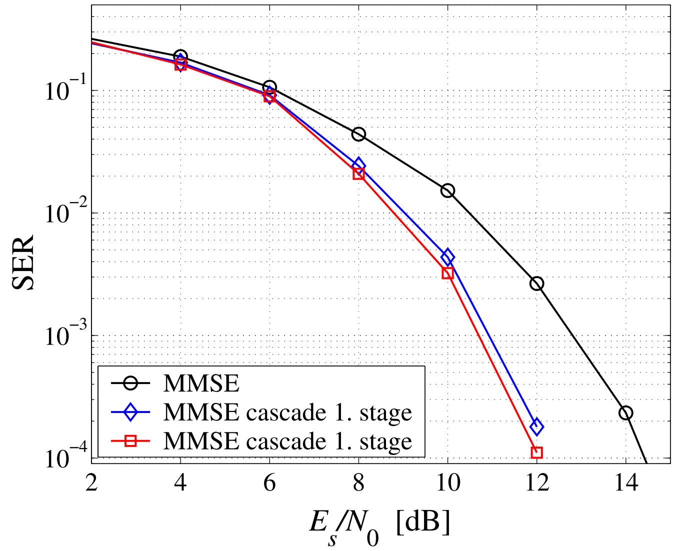
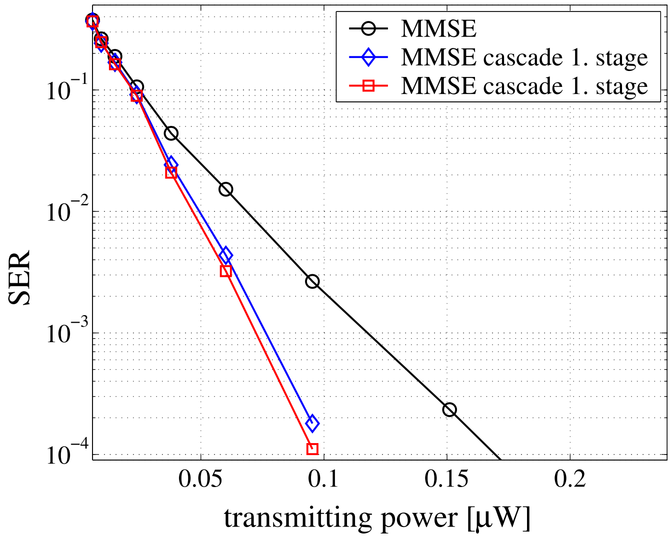
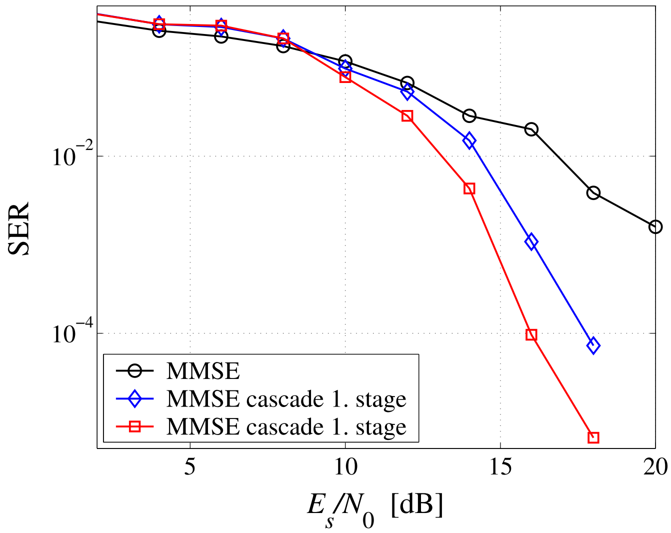


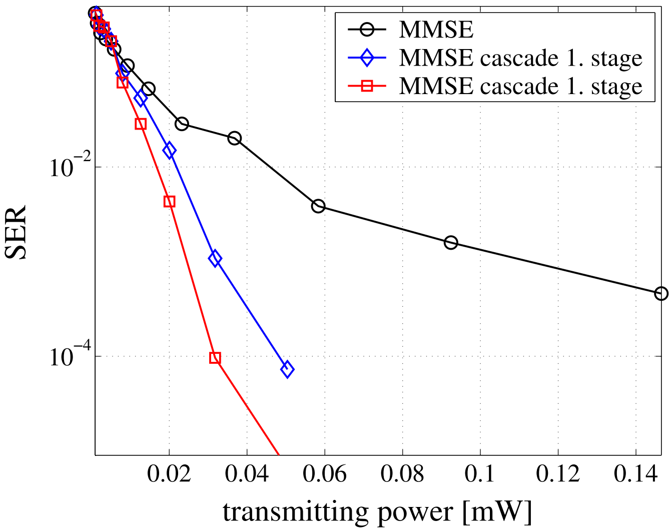
(a) SER, good channel



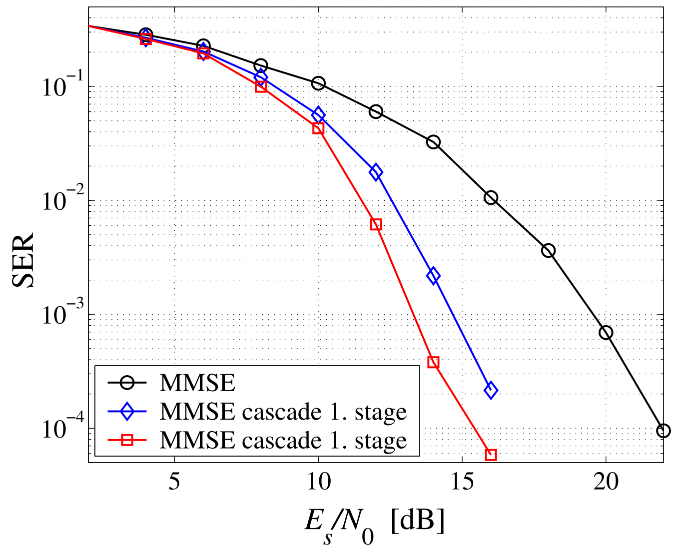
(b) transmitting power, good channel



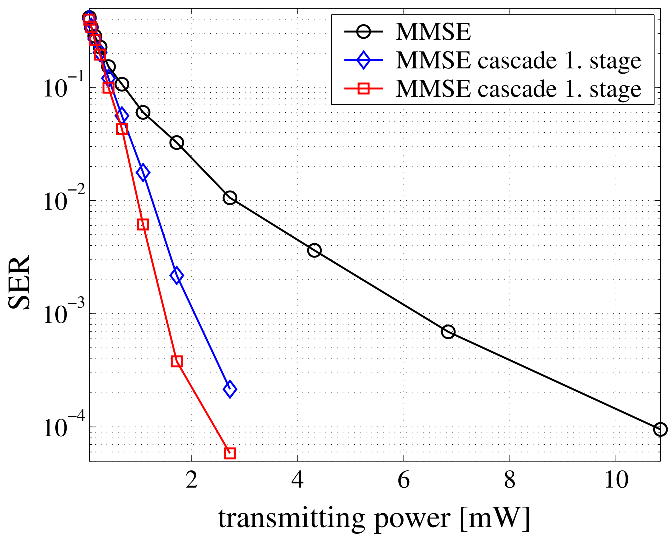
(c) SER, average channel



(d) transmitting power, average channel



(e) SER, below average channel



(f) transmitting power, below average channel

Fig. 6. SER versus E_s/N_0 and versus the transmitting power for the three measured transfer functions