Linear block codes for frequency selective PLC channels with colored noise and multiple narrowband interference

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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 [1] 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 are presented for measured PLC channels.

I. INTRODUCTION

Channel capacity considerations are promising relatively high capacities for PLC channels [2]. So, the use of broadband 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 (Fig. 1), 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 are presented in [1]. One feature of these codes is to cope with fading effects of the transmission channel. According to [2] usually one characteristic of PLC channels is frequency selective fading. In the following, is shown that these codes can be used as a basis for efficient PLC coding.

The outline of the paper is as follows: Section II comprises a short description of the considered class of linear space-time block codes. Based on these codes the new block code for PLC channels is presented in Section III; in Section IV simulation results for coded OFDM on PLC channels are shown.

II. SPACE-TIME CODE

Wireless mobile communication systems often suffer from severe fading of the communication channels. This can affect the performance of the transmission. By using space time codes and antenna arrays at the transmitter and / or at the receiver it is not only possible to cope with these fading effects but also to utilize the additional capacity of a Multiple Input Multiple Output (MIMO) communication channel [1], [4]. Fig. 2 a) shows an example for a linear space-time block code according to [1]. These codes are originally developed for wireless mobile communication systems. Because of the design these codes are independent from the used modulation alphabet and can easily be adapted to the requests of the transmission, for example to differ-

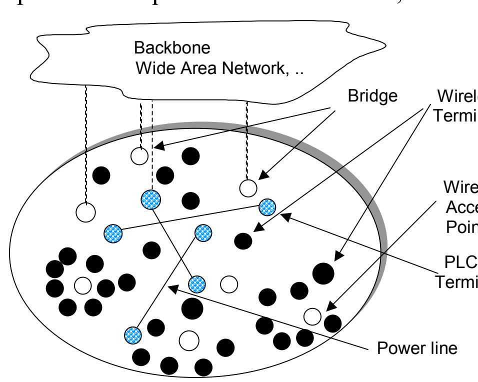

Fig. 1. Heterogeneous network

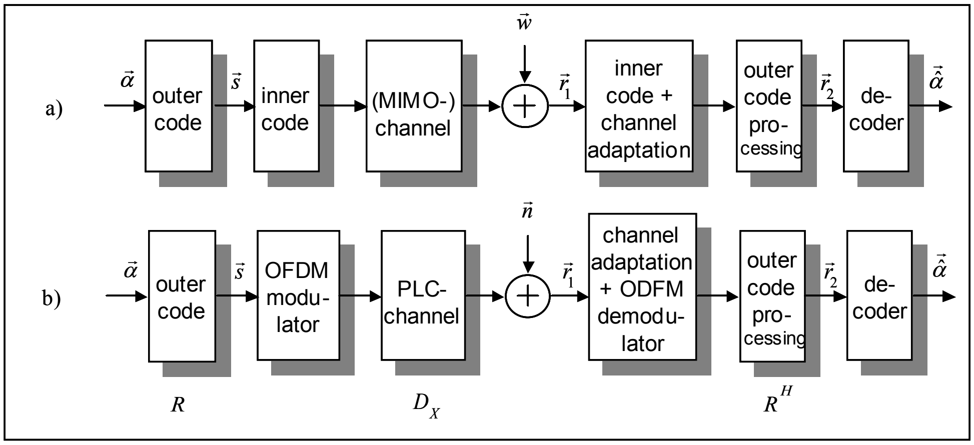

Fig. 2. Linear space-time block code (a), coded OFDM (b)

ent node complexities, subnet structures or transmission channels. They consist of two concatenated but decoupled linear block codes, the inner code and the outer code. No a priori channel knowledge is required at the transmitter. Furthermore, the use of large block lengths is possible.

The adaptation to a MIMO radio channel (e.g. the adaptation to the applied number of transmit and receive antennas) and the decoupling of this channel and the outer code is done by the inner code. The inner code is optimized with respect to the variation of the instantaneous channel capacity conceived by the outer code. The outer code is optimized for diversity performance. It achieves a high diversity gain and an excellent performance in a fading environment even at code rate 1. As a result of the optimised diversity performance or because of interfering "spatial sub-channels" intersymbol interference (ISI) can arise [1]. This ISI has to be removed by a decoder using an ISI compensation method, for example a MMSE filter or a DFE structure. An efficient decoder for this class of space-time codes is presented in [3]. Due to the code concatenation the diversity performance optimization and the channel conditioning are decoupled. In [1] several different forms of code matrices are presented for the inner code; which form is used depends on the desired application: pure use of the "spatial sub-channels" of a MIMO channel to increase the data rate without increasing the bandwidth, pure use of transmit diversity to combat fading effects or use of joint transmit diversity and "spatial sub-channeling".

In this paper the outer code is used as a basis of a channel coding scheme for PLC channels (Fig. 2 b)). The inner code is not needed because the PLC channel can be considered as an example for a frequency selective Single Input Single Output (SISO) channel. The code matrix R, that is orthonormal, represents the outer code

$$R^H \cdot R = I$$

where I is the unit matrix; so the performance on an AWGN channel and the Euclidean distance are maintained. The matrix R is optimised for diversity. In [1] an efficient approach is described for the optimization of an orthonormal coding matrix for any given block length. For symmetry and complexity reasons a cyclic matrix R is used. Let the vector $\vec{h}$ with N components be the first row of matrix R ; to calculate $\vec{h}$ the parameterized approach

$$\vec{h}[n] = \frac{1}{\sqrt{N}} \sum_{k=1}^{N} \exp\left(j2\pi a_{cc} \frac{k-1}{N^2}\right) \cdot \exp\left(j2\pi \frac{(k-1)(n-1)}{N}\right)$$

is used (the inverse Fourier transform of a cyclic chirp filter) [1]. The cost function of the optimization is the maximum fading averaged pairwise probability of error. The parameter a_{cc} is determined in a way that the cost function is minimized for a given N.

III. A New Block Code for PLC Channels

PLC channels are in general characterized by frequency selective transfer functions and by coloured noise, partly because of strong narrowband interferences [2]. 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. No channel knowl-

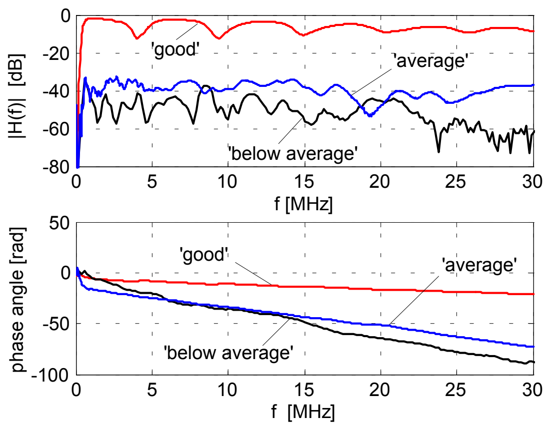

Fig. 3. Three measured PLC transfer functions (amplitude spectrum and phase angle)

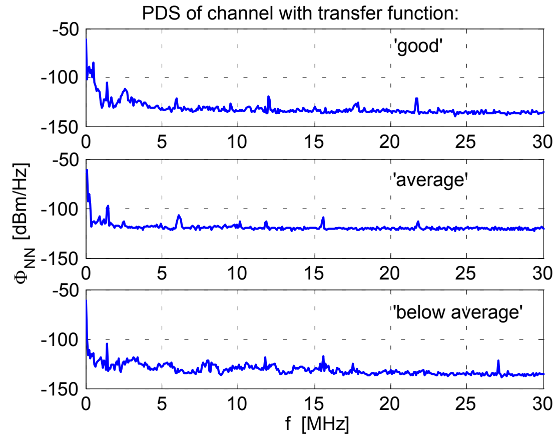

Fig. 4. Measured power density spectra (PDS) of the PLC channels in Fig. 3

edge is needed at the transmitter. Therefore such a code is especially suited for asymmetric channels or broadcast transmissions.

Fig. 2 b) shows a system block diagram (baseband representation) of the used linear block code (the code matrix *R*) combined with OFDM. The vector $\vec{\alpha}$ is the transmitted symbol vector; $\vec{n}$ contains the samples of the colored PLC noise, $\vec{x}$ the samples of the PLC channel impulse response. The symbol vector $\vec{\alpha}$ is encoded with the code matrix *R* and then transmitted using OFDM modulation. The channel adaptation in Fig. 2 b) consists of a whitening filter $\vec{f}$ and of a matched filter adapted to the impulse response $\vec{x}$ of the PLC channel. The whitening filter transforms the coloured noise into white noise using the knowledge of the power density spectrum of $\vec{n}$.

Using inverse discrete Fourier transformation (iDFT) as a model for the OFDM modulator the received symbol vector $\vec{r}_1$ according to Fig. 2 b) and Fig. 5 can be derived as follows:

$$\vec{r}_1 = iDFT\{R \cdot \vec{\alpha}\} * \vec{x} + \vec{n}$$

where $*$ denotes (cyclic) convolution. Using discrete Fourier transformation (DFT) as a model for the ODFM demodulator the vector $\vec{r}_2$ is:

$$\vec{r}_2 = R^H \cdot DFT\{\vec{r}_1 * \vec{f} * \vec{x}^*\}$$

$$= R^H \cdot D_X^H \cdot D_F \cdot DFT\{iDFT\{R \cdot \vec{\alpha}\} * \vec{x} + \vec{n}\}$$

$$\vec{r}_2 = R^H \cdot D_X^H \cdot D_F \cdot (D_X \cdot R \cdot \vec{\alpha} + \vec{N}) \quad (1)$$

$$\vec{r}_2 = \Lambda_{ISI} \cdot \vec{\alpha} + \vec{n}_2 \quad (2)$$

The matrices D_X and D_F are diagonal with the elements of *DFT{*$\vec{x}$*}* (the discrete *transfer function* of the PLC channel) and *DFT{*$\vec{f}$*}* on the main diagonals.

The measured *transfer functions* of PLC channels show high differences in the average attenuation and the frequency selectivity of the attenuation [2]. Fig. 3 shows three examples of measured PLC transfer functions. They are roughly classified in the categories ‘good’, ‘average’ and ‘below average’. In Europe broadband PLC is restricted to frequencies between 1 MHz and 30 MHz. As a result of the attenuation PLC channels are frequency selective fading channels. In (2) the matrix D_X contains the fading coefficients. The power density spectrum (PDS) of a PLC channel is frequency selective too [2]. This is the reason why the matrix D_F can increase the frequency selective fading (Fig. 6). Fig. 4 shows examples of measured power density spec-

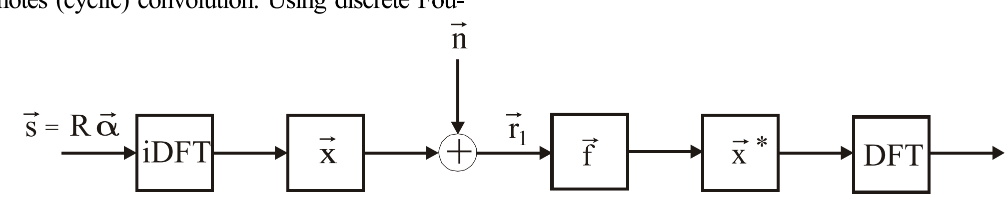

Fig. 5. Model: coded OFDM

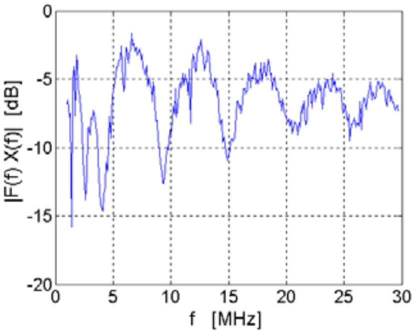

Fig. 6. Entire transfer function of PLC channel and whitening filter ('good' channel)

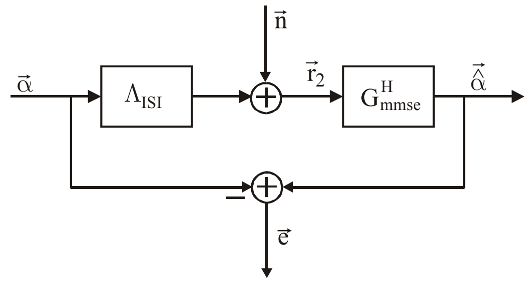

Fig. 7. MMSE decoder

tra of the PLC channels in Fig. 3.

The fading in D_X (and in D_F) introduces ISI because the orthonormality of R is destroyed as can be seen in (1). The ISI included in the received signal is linear and represented in (2) by the matrix Λ_{ISI}. The ISI has to be compensated because otherwise the performance could be heavily affected. A maximum likelihood decoder is optimal for interference compensation, but due its high complexity it is often not suitable for the practical use. In [3] an efficient scalable decoder is presented that has a much lower complexity. Moreover linear methods can be used, e.g. a MMSE detector. These linear methods have a very low complexity but generally - compared to the maximum likelihood decoder - a weak performance too. Fig. 7 shows a system block diagram of a MMSE decoder [5]. The received symbol vector $\vec{r}_2$ is multiplied with the MMSE matrix G^H_{mmse}. This matrix is calculated using the knowledge of Λ_{ISI} at the receiver and employing the mean squared error (MMSE) criterion to minimize

$$\min\{\ \vec{e} = G^H_{mmse} \cdot \vec{r}_2 - \vec{\alpha}\ \}.$$

As the code can be described as a linear block code the additional use of error-detecting and error-correcting codes (not in the scope of this paper) is not hindered.

IV. Simulation Results

For the simulation results presented in this section a block length of 32 coded symbols is used. The coded symbols are transmitted over measured PLC channels at code rate 1 using an OFDM system. The PLC channels are modelled using a measured transfer function and a measured power density spectrum (PDS). Perfect knowledge of the transfer function and of the noise power density spectrum of the channel is assumed at the receiver.

For the considered PLC channels (Fig. 3) each OFDM sub-channel has a bandwidth of 100 kHz. Our measurements show durations of the channel impulse response of up to 3 µs, so a symbol duration of 10 µs seems possible; the OFDM guard time should be about 3 µs. Additional aspects of the OFDM system are out of the scope of this paper and not considered in the simulations. Using the frequency range of 1 MHz – 28.8 MHz 9 blocks of block length 32 can be simultaneously transmitted over the OFDM system. For 'frequency interleaving' the first coded block of 32 symbols uses sub-channel 1 for the first symbol, sub-channel 10 for the second symbol, sub-channel 19 for the third symbol, …, sub-channel 280 for the 32-th symbol; the second block uses the sub-channels 2, 11, 20, …, 281; etc.

In Fig. 8 and Fig. 9 simulation results of two channels of Fig. 3 are presented: the channel with the transfer function 'below average' and the channel with the transfer function 'good' respectively. The symbol error rate (SER) of 4-QAM versus E_b/N_0 at the receiver is shown. The performance of the coded OFDM with an ISI decoder according to [3] is much better than the performance of the coded OFDM with a simple MMSE filter for ISI compensation; and the OFDM with this decoder performs better than the uncoded OFDM. For the channel of the category 'below average' a symbol error rate of SER = 1 e (-4) is reached at E_b/N_0 = 14 dB using the decoder according to [3], this means a transmitting signal power of about 4.8 mW in this case. In the case of the 'good' channel this SER is found for E_b/N_0 = 12 dB; because of the low attenuation and of the low noise power (less than 4 e (-8) W) of this channel this means a much lower transmitting signal power (only about 4 e(-6) W).

Fig. 11 shows the performance over the PLC channel of Fig. 10 for the same boundary conditions as Fig. 7 and Fig. 8 except for other OFDM parameters. The block length still is 32, but the bandwidth of a sub-channel is 300 kHz. The used frequency range is 10 MHz – 19.6 MHz. This means a low attenuation, low noise and low frequency selectivity for the considered PLC channel (Fig. 9). So, the performance of the uncoded OFDM is

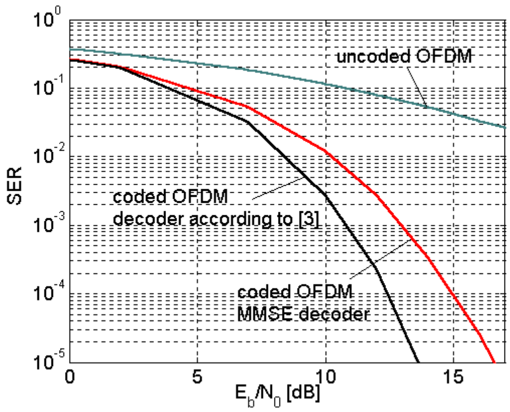

Fig. 8. Performance for PLC channel with transfer function 'good'

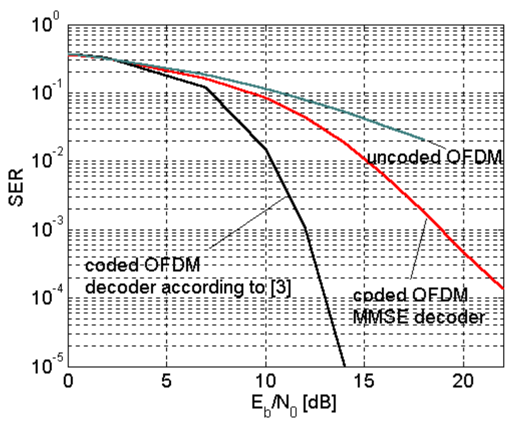

Fig. 9. Performance for PLC channel with transfer function 'below average'

better as in Fig. 8 and Fig. 9. But there is still a clear performance gain for the coded OFDM.

V. Conclusions

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.

So, in a heterogeneous network the same code can be used for different subnets, for example a wireless mobile subnet and a PLC subnet. In addition, these results show that the linear block codes presented in [1] can be combined with

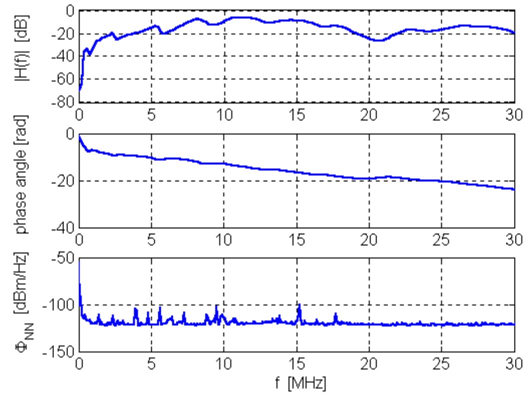

Fig. 10. Measured PLC channel (amplitude spectrum and phase angle of the transfer function, PDS)

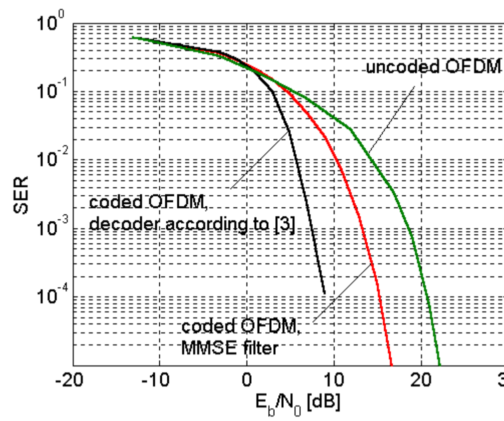

Fig. 11. Performance for the PLC channel in Fig. 9; block length 32; used frequency range 10 –19.6 MHz

OFDM in case of frequency selective channels (also in colored noise).

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