Performance Evaluation of Non–Coherent Transmission over Power Lines

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Abstract — **High–bit–rate communication over power lines is a promising solution to the last–mile problem. We examine the use of bandwidth–efficient, non–coherent multicarrier modulation as simple, flexible, and robust transmission scheme over power–line channels. Adaptive, requiring channel state information at the transmitter, and non–adaptive multicarrier modulation are discussed and assessed. The effects of moderate complex channel coding on both modulation schemes are pointed out by simulations.**

1 Introduction

The use of the power distribution grid to access the world–wide communications network has attracted much attention and has become a mature subject of research in the last few years. In order to combat the unfavorable transmission properties of power lines, of which frequency selectivity is the most distinct, the well–known multicarrier technique orthogonal frequency division multiplexing (OFDM), e.g. [1], is regarded as a favorite modulation scheme. Besides its ability to mitigate intersymbol interference, OFDM makes very efficient use of the allocated bandwidth possible [2]. If channel state information is available at the transmitter OFDM allows easy adaptation to the transmission channel via loading.

In this paper, we discuss the application of OFDM for non–coherent transmission over power lines. In particular, bandwidth efficient transmission schemes using adaptive and non–adaptive OFDM are designed and compared. For a typical example of a power–line communication channel, it is shown that loading is paramount in case of uncoded transmission, whereas the application of channel coding significantly reduces the performance gap between adaptive and non–adaptive OFDM.

2 Non–Coherent Transmission over Power Lines

As already well established, e.g. [3, 4, 5], the power–line communication channel can be described as frequency selective with relatively slow time variance over long periods of time. When transmitting over such channels, the transmitted signal undergoes severe distortion. In order to recover the conveyed information at the receiver, the use of some kind of equalization is mandatory. Generally, the complexity of equalization increases exponentially with the length p of the corresponding end–to–end discrete–time channel impulse response. However, by inserting a cyclic extension or guard interval of $D_{\mathrm{g}} \geq p$ samples every D samples at the transmitter, low complex frequency–domain equalization becomes possible at the receiver. Moreover, if the necessary time–frequency–domain transformations are done both at the receiver and at the transmitter, we arrive at the well–known OFDM [1], where the transmit signal is constructed in frequency domain. In this paper, we focus on the application of such multicarrier modulation techniques.

[1]This work was supported by iAd GmbH, Großhabersdorf, Germany.

Using OFDM, the actual channel is partitioned into D independent frequency non–selective subchannels (subcarriers) with complex transfer factors λ_v, $v = 1, 2, \ldots, D$, which are samples of the channel transfer function. If a number of subchannels is assigned to one communication link, frequency diversity can be utilized. In order to obtain a robust transmission scheme, which is insensitive against phase ambiguities and phase noise in the received signal, differential phase–shift keying (DPSK) across subcarriers and non–coherent reception are favorably applied. Of course, this presumes the transfer factors λ_v to change only slightly from index v to $v+1$.

In the following, adaptive and non–adaptive OFDM are compared. Hence, it is reasonable to assume that estimates of the amplitudes of the subchannel transfer factors are available at the receiver. Then, DPSK can be combined with amplitude modulation, called ADPSK, i.e., information is carried in the *phase difference* and in the *actual amplitudes* of two consecutively transmitted symbols, cf. [6]. As a natural extension of PSK constellations, here the transmitted symbols are taken from APSK constellations, consisting of $\alpha\beta$ points arranged on α arithmetically spaced concentric rings with radii $r_i = 1 + i \cdot \rho$, $i = 0, 1, \ldots, \alpha - 1$, increment ρ, and β equidistantly spaced phases. We specify the resulting transmission scheme by αADβPSK.

In order to increase power efficiency of OFDM transmission, moderate complex channel coding using convolutional codes and Viterbi decoding are applied. Channel coding is performed across OFDM subchannels, separately for each OFDM symbol. Binary coding and non–binary modulation are linked together by bit–interleaved coded modulation (BICM) [7, 8], which is simple and especially well suited for fading channels. Here, bit interleaving is restricted to and coding is terminated over one OFDM symbol.

3 Adaptive OFDM

Clearly, if the subchannel signal–to–noise ratio (SNR) is known at the transmitter side, transmit power and information can be appropriately assigned (loaded) to each subchannel. Thus, adaptive OFDM compensates for the amplitude $|\lambda_v|$ of the varying subchannel transfer factors λ_v.

Optimally, in order to approach capacity, on the additive white Gaussian noise (AWGN) channel the transmit power is loaded according to the water–filling rule [9]. However, in [10] it is shown that for typical flat fading channels even without water–filling almost the entire capacity can be utilized. Similar results in terms of simulated bit error rate (BER) can be found in [11]. Moreover, in power–line communications (PLC) for frequencies above 148.5 kHz the average power spectral density might become limited [12] rather than the average transmit power. Consequently, we do not regard loading of power and concentrate on the adaptation of rates. For this, we fix, both, the desired transmission rate R_T in bit/s and a maximum tolerable overall bit error rate BER_T, and try to minimize the transmit power, and thus, the transmit power spectral density. Since in PLC exact values for the allowed power spectral density cannot be given yet, this procedure seems to be appropriate.

Before running a loading algorithm, a connection between BER, required SNR, and loaded rate has to be established for non–coherent ADPSK over the AWGN channel. Based on the results in [13] on BER of non–coherent on–off signaling and DPSK transmission the BER of non–coherent ADPSK can be estimated analytically. The resulting curves for BER over E_s/N_0 (E_s: received signal energy, N_0: one–sided noise power spectral density) are presented in Figure 1. Here, αAβPSK constellations, whose ring spacing is optimized for minimum BER, with up to 64 signal points are regarded as practicable. Additionally, simulated BER curves are plotted to verify the preciseness of the BER estimation. Unfortunately, the analytical expressions are rather intricate and do not provide a key for a simple loading algorithm. Hence, we have to resort to the corresponding analytically approximated BER curves in Figure 1.

A closer look on the curves in Figure 1 reveals gaps of approximately 3 dB as in coherent QAM transmission.

Therefore, loading algorithms designed for coherent transmission as e.g. [14, 15] might be a good choice even for non–coherent transmission. However, here we will use a recently published and very efficient algorithm by Piazzo [16]. Given λ_v, R_T, BER_T, and E_s/N_0 required for BER_T by the different constellations, i.e., one sample of each BER curve, the algorithm minimizes the transmit power and delivers the rates R_v in bit/symbol, $v = 1, 2, \ldots, D$, of the OFDM subchannels. The results obtained with this algorithm are very similar to results from a much more complex, but optimum greedy approach similar to the Hughes–Hartogs algorithm [1]. Thus, it is very well suited for the present situation.

When combining adaptive OFDM with channel coding, loading is also based on the BER curves of uncoded ADPSK. In this way, the reliability of decoder input data is expected to be almost equal for all subchannels.

4 Non–Adaptive OFDM

The availability of (perfect) channel state information at the transmitter is rather demanding with respect to channel estimation algorithms. A more robust transmission system does not need to rely on channel state information at the transmitter. Then, non–adaptive OFDM with only a single signal constellation is used. If adaptive OFDM is restricted to loading the rate, in terms of achievable channel capacity, adaptive and non–adaptive OFDM are identical [10]. For approaching channel capacity with non–adaptive OFDM, a large signal constellation in combination with powerful low–rate codes has to be applied. However, powerful low–rate coding close to channel capacity is difficult in practice.

In order to obtain design criteria for non–adaptive OFDM, the cutoff rate R_0 of the associated channel is regarded as a common measure of performance when applying convolutional coding [17]. To determine R_0 of the channel corresponding to non–adaptive OFDM with differential encoding and channel coding across subcarriers, the concatenation of OFDM transmitter, actual channel, and OFDM receiver is modeled as an equivalent slowly "time"–varying, frequency non–selective fading channel [5]. Like in mobile OFDM communication, cf. e.g. [18], the Rayleigh fading model is applicable to a certain extent [5] to PLC, too. Thus, the cutoff rate R_0 for non–coherent ADPSK transmission over Rayleigh fading, with constant fading gain over two consecutive symbols, and BICM, cf. also [8], is calculated. Figure 2 gives R_0 over $\bar{E}_\mathrm{s}/N_0$ ($\bar{E}_\mathrm{s}$: average received signal energy) for signal constellations carrying up to 6 bit/symbol. Surprisingly, the R_0 curves intersect.[2] Hence, judging from the cutoff rate analysis, combining large APSK constellations with low rate convolutional codes is not a suited strategy for non–adaptive, non–coherent OFDM and BICM. Depending on the target rate in bit/subcarrier, signal constellation and code rate have to be chosen appropriately.

5 Performance of Adaptive vs. Non–Adaptive OFDM over Power Lines

5.1 Parameters and Loading

For the performance comparison of non–coherent adaptive and non–adaptive OFDM exemplary a typical power–line channel with a transmission bandwidth of 1 MHz is used. The channel transfer function $H(f)$ has been obtained from the parameter model according to [3, Table 4]. Its amplitude transfer function $|H(f)|$, shown in the lower part of Figure 3, is dominated by a deep notch at about 1.18 MHz. Within the transmission bandwidth $D = 256$ OFDM subcarriers are located, where, for simplicity, all subcarriers are allowed to be active. Since the guard interval has to be of the same size for both adaptive and non–adaptive OFDM, its dimension is of no

[2]A similar observation for coherent transmission is reported in [8].

interest with respect to performance comparison. Data rates of about $R_{\mathrm{T}} = 1$ Mbit/s and $R_{\mathrm{T}} = 2$ Mbit/s are desired to provide fast network access.

As a data rate of $R_{\mathrm{T}} = 1$ Mbit/s and a transmission bandwidth of 1 MHz require a rate of 1 bit/subcarrier[3] in case of non–adaptive OFDM, and according to the cutoff rate analysis in Figure 2, 2AD4PSK with code rate $R_c = 1/3$ is appropriate. Beside this, also 4AD16PSK with $R_c = 1/6$ is simulated, because this scheme is suggested from capacity considerations assuming optimum coded modulation. Correspondingly, for $R_{\mathrm{T}} = 2$ Mbit/s, 2AD8PSK with $R_c = 1/2$ and 4AD16PSK with code rate $R_c = 1/3$ are chosen. Convolutional codes with 64 states and generator polynomials from [19] are applied. For metric calculation and decoding see [20].

For adaptive OFDM convolutional coding of rate $R_c = 3/4$ and $R_c = 1/2$, respectively, is performed. On the one hand, a lower code rate leads to a larger coding gain. On the other hand, the lower the code rate the less flexible loading becomes as more code bits have to be assigned to the OFDM subcarriers. Thus, there is a tradeoff between coding and loading, when restricting the maximum size of constellations. An example of rate loading is given in the upper part of Figure 3. $R_{\mathrm{T}} = 2$ Mbit/s and a code rate of 1/2 are assumed. The target BER prior to channel decoding is chosen to be $\mathrm{BER}_{\mathrm{T}} = 10^{-3}$. Noteworthy, the loading results change only marginally if $\mathrm{BER}_{\mathrm{T}}$ is varied. As can be seen from Figure 3, subcarriers with relatively large amplitude transfer factor are loaded with large signal constellations, whereas subcarriers located at the notch are not used for transmission at all.

5.2 Simulation Results

Since we assume average transmit power spectral density and not power to be limited, in the following BER is plotted versus $\bar{E}_{\mathrm{s}}/N_0$, which is measured at the receiver side in case of constant transmit power spectral density. Noteworthy, this is also true in case of adaptive OFDM and unused subcarriers (see upper part of Fig. 3).

First, simulation results of adaptive and non–adaptive OFDM with non–coherent ADPSK over power lines without channel coding are discussed. The curves for BER over $\bar{E}_{\mathrm{s}}/N_0$ in Figure 4 illustrate clearly the enormous gains of about 10 dB in power efficiency due to loading. Without loading, the high bit error rates in severely attenuated subchannels dominate the overall BER.

Next, in Figure 5 the simulation results are presented for OFDM and channel coding with several code rates and a transmission rate of $R_{\mathrm{T}} = 1$ Mbit/s. A comparison of the BER curves of the adaptive system without coding ($R_c = 1$) and the non–adaptive system with coding ($R_c = 1/6, 1/3$) shows that channel coding is a much more appropriate mean to average the subcarrier SNRs than loading, which has to be done at the transmitter. If loading is combined with channel coding, adaptive OFDM becomes superior to non–adaptive OFDM. Here, adaptive OFDM with the powerful rate 1/2 code outperforms the system with the weaker rate 3/4 code. In the case of convolutional coded non–adaptive OFDM, 2AD4PSK with $R_c = 1/3$ yields a better performance by about 1.8 dB than 4AD16PSK with $R_c = 1/6$ as predicted by the associated cutoff rates. Overall, applying channel coding, a performance gain of loaded OFDM of about 1 dB at $\mathrm{BER} \approx 10^{-5}$ remains.

Simulation results for transmission of 2 Mbit/s are presented in Figure 6. Again, non–adaptive OFDM with channel coding is advantageous over adaptive OFDM without coding. In accordance with the cutoff rate analysis 2AD8PSK with $R_c = 1/2$ outperforms 4AD16PSK with $R_c = 1/6$ by about 1.3 dB. For maximum power efficiency, loading and error correcting coding are jointly applied. Here, coding with rate $R_c = 3/4$ turns out to be preferable to coding with rate $R_c = 1/2$. The reason is that for $R_c = 1/2$, due to the restricted choice of

[3]Here, roll–off and guard band are neglected. When taking both effects into account, either the data rate in Mbit/s is somewhat reduced or the modulation rate in bit/subcarrier has to be slightly increased.

constellations (not larger than 64 signal points), loading cannot be optimally done as indicated in the upper part of Figure 3. Finally, at $\mathrm{BER} \approx 10^{-5}$ the best adaptive system is about 1.5 dB superior to the best non–adaptive system.

6 Conclusions

In this paper, high rate transmission over power lines is considered. Multicarrier modulation, which is well suited for the frequency selective power–line channel, together with non–coherent reception, to become robust against phase ambiguities and phase noise, are applied. Both loading for adaptive OFDM and the design of non–adaptive OFDM are investigated.

Simulation results for a typical transmission scenario in PLC indicate that loading yields large gains (more than 10 dB in power efficiency) if transmission is done without channel coding. However, if convolutional coding with moderate complex Viterbi decoding is used, the performance of non–adaptive and adaptive OFDM becomes comparable. In case of channel coding, having no channel state information at the transmitter available accounts for a loss of about 1–2 dB in power efficiency of non–adaptive OFDM.

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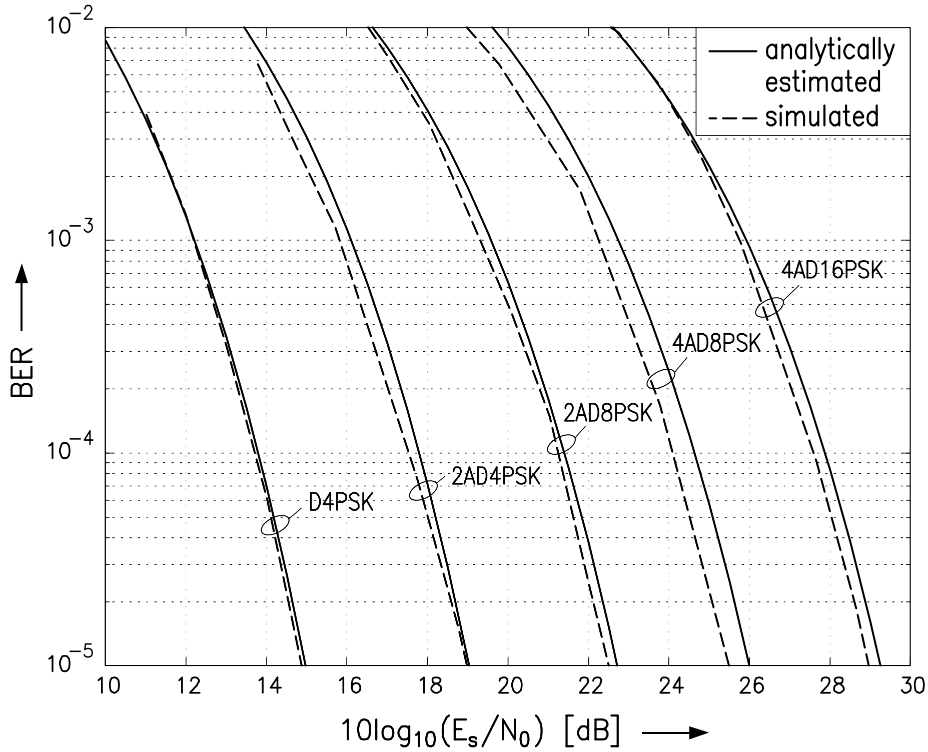

Figure 1: *BER vs. E_s/N_0 of ADPSK over AWGN channel. Solid lines: analytical approximation. Dashed lines: simulation. From left to right: D4PSK, 2AD4PSK $\rho = 1.1$, 2AD8PSK $\rho = 0.6$, 4AD8PSK $\rho = 0.6$, 4AD16PSK $\rho = 0.3$.*

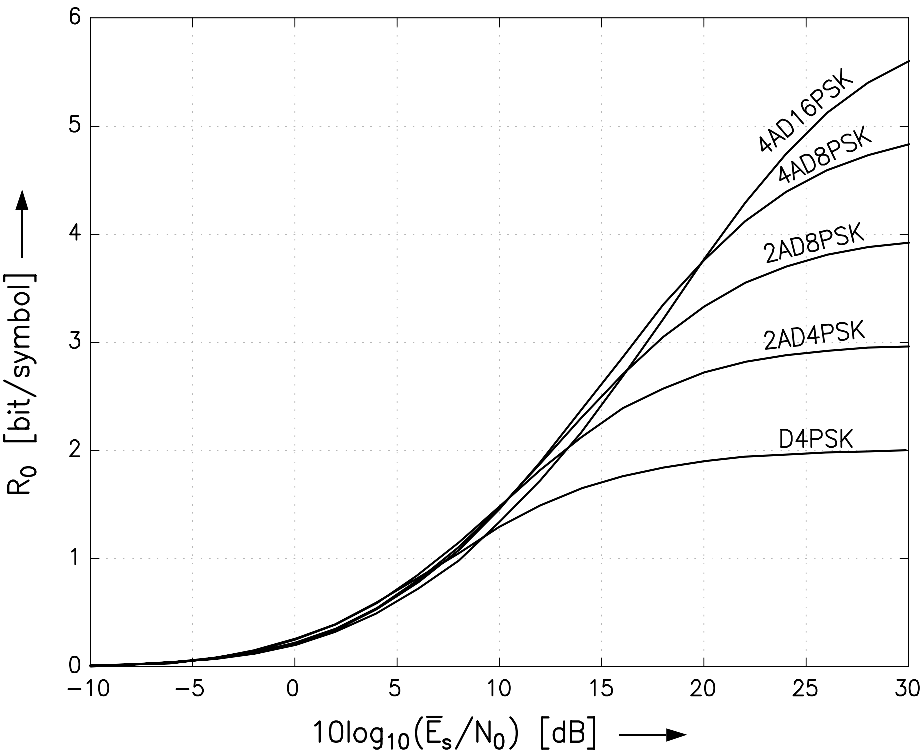

Figure 2: *Cutoff rate R_0 vs. $\bar{E}_s/N_0$. Non–coherent ADPSK and BICM over Rayleigh fading.*

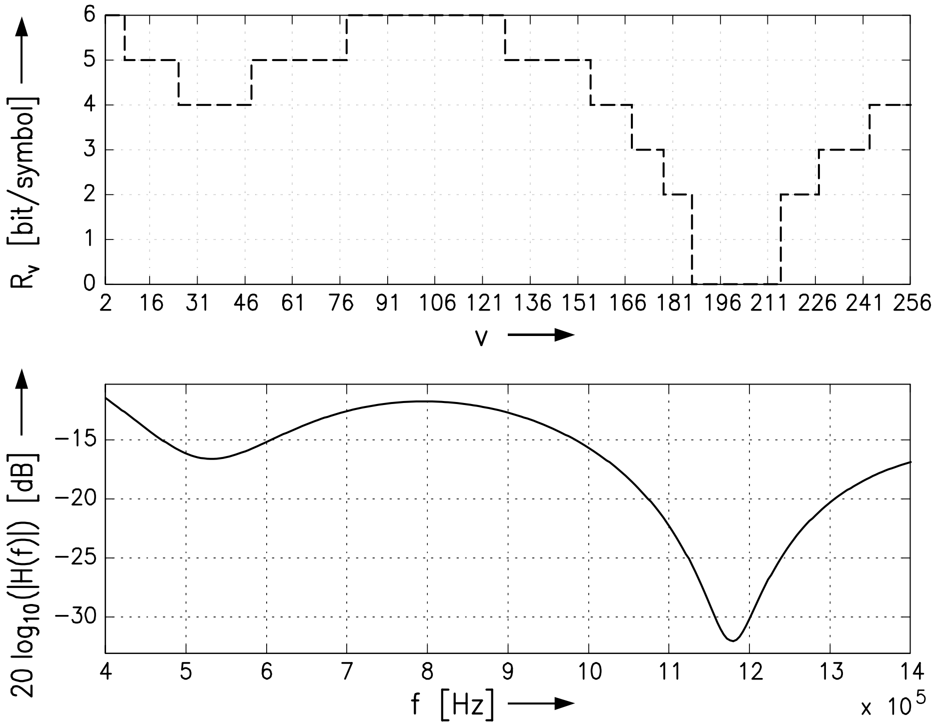

Figure 3: *Top: Assignment of rates R_v to subcarrier v with loading algorithm by Piazzo [16]. $R_\mathrm{T} = 2$ Mbit/s, $\mathrm{BER_T} = 10^{-3}$, $R_c = 1/2$. Bottom: Power–line channel amplitude transfer function $|H(f)|$ according to [3].*

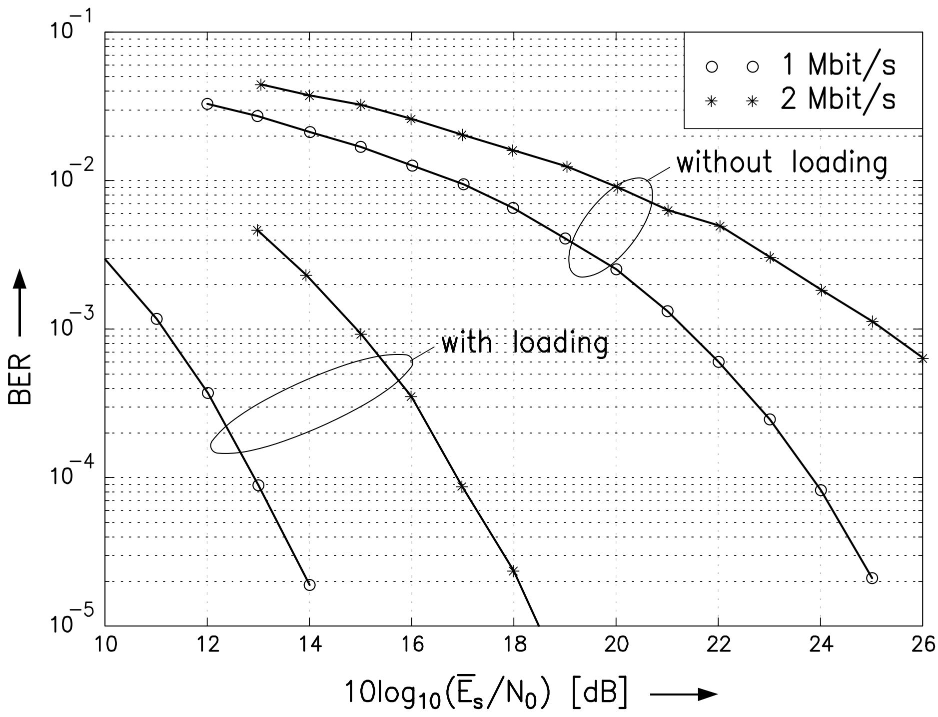

Figure 4: *BER vs. $\bar{E}_\mathrm{s}/N_0$ for adaptive and non–adaptive uncoded OFDM with non–coherent ADPSK over power lines.*

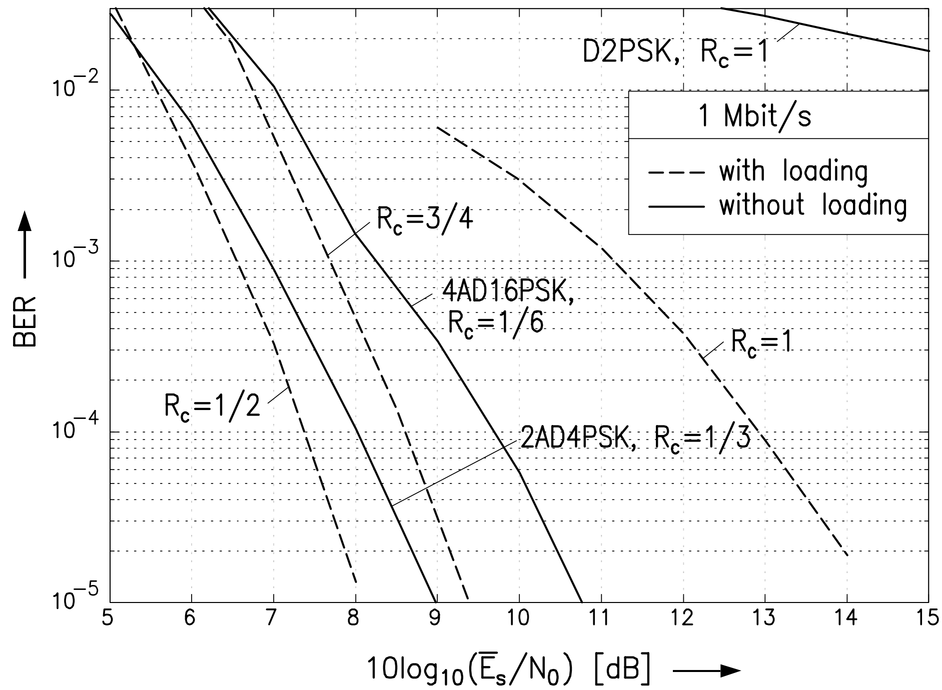

Figure 5: *BER vs. $\bar{E}_\mathrm{s}/N_0$ for adaptive and non–adaptive coded OFDM with non–coherent ADPSK over power lines. Data rate $R_\mathrm{T} = 1$ Mbit/s.*

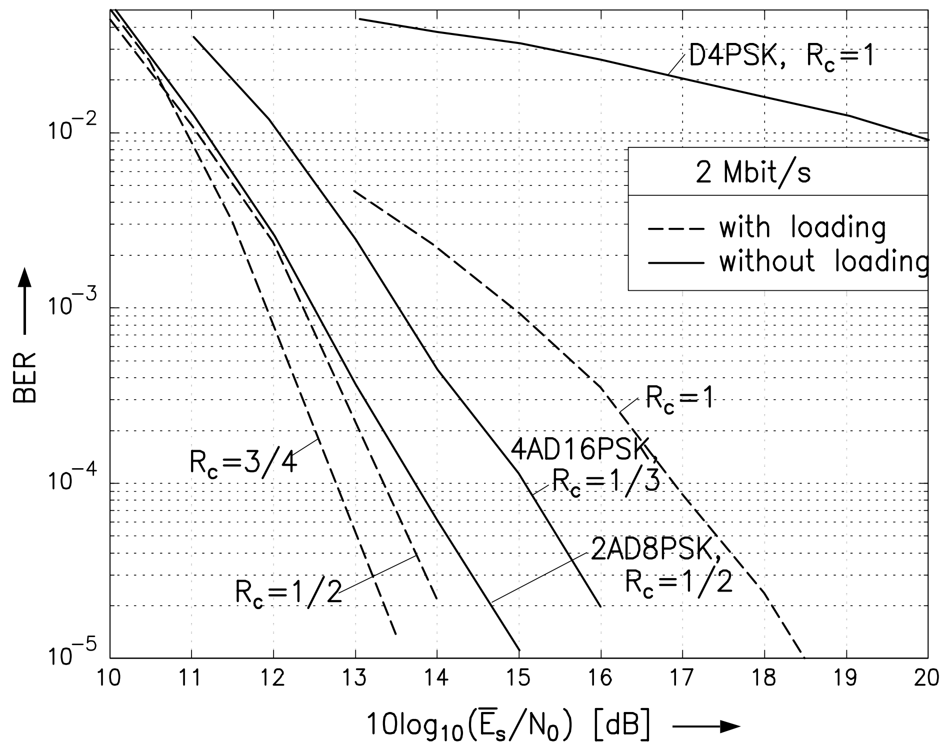

Figure 6: *BER vs. $\bar{E}_\mathrm{s}/N_0$ for adaptive and non–adaptive coded OFDM with non–coherent ADPSK over power lines. Data rate $R_\mathrm{T} = 2$ Mbit/s.*