An Experimental OFDM-Modem for the CENELEC B-Band

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Abstract. *In this paper a concept for a powerline communication system will be presented which utilizes the CENELEC B band for a bidirectional transmission to achieve a brutto bit rate of maximum 190 kbps. The proposed system uses the OFDM transmission technique which is known for its good performance in frequency selective channels as the one which can be found in the powerline environment. The aim of the presented experimental setup has been an approximation of the required processing capacity and the support of further studies of OFDM as a future powerline modulation technique.*

1 Introduction

Providing high-bit rate access to existing telecommunication networks is one of the challenging tasks of the next years in telecommunications. With the explosively growing demands for more bandwidth driven especially by Internet applications new ways to connect to the telecommunication backbone have to be found. One of the most promising candidates is the residential power circuit (RPC) which is available in nearly every room of the private premises. Moreover, only a very small region of the whole frequency band is currently being used. For that reason a strong interest exists in turning the "wasted" resources into additional bandwidth for communication applications.

In this paper a concept for a communication system will be presented which utilizes the RPC as a transmission medium. In contrast to known approaches for powerline communication systems that are based on the spread spectrum modulation techniques like the ones presented in [1][2] the proposed system employs the orthogonal frequency division multiplex (OFDM) modulation technique. The main advantage of this technique is the high bit rate efficiency and the ability to achieve this efficiency also in a multi path environment like the RPC.

In the following section we will briefly review the OFDM modulation technique and introduce the advanced multilevel differential amplitude phase modulation (DAPSK) which is used in the proposed system. This technique has the great advantage that a high spectral efficiency can be achieved without the overhead imposed by the channel estimation process required for a coherent transmission. Additionally time and frequency synchronization aspects will be discussed. The system parameters are derived in the fourth section by considering the physical channel, the medium access protocol as well as the desired applications.

2 The OFDM Transmission Technique

OFDM has raised a lot of attention as a modulation technique in mobile communication systems [3]. It has proven its ability to handle the problems that can occur in a radio environment: frequency selectivity of the channel, fast-fading caused by the time-variant channel impulse response and Doppler effect problems due to moving stations. The powerline channel only exhibits one of these properties which is the frequency selective transfer function. Thus, a good performance of this modulation techniques can be expected of OFDM in the powerline environment.

In the following we will discuss, besides some general OFDM system consideration, two important aspects of the proposed system: The sub channel modulation technique and time/frequency synchronization methods.

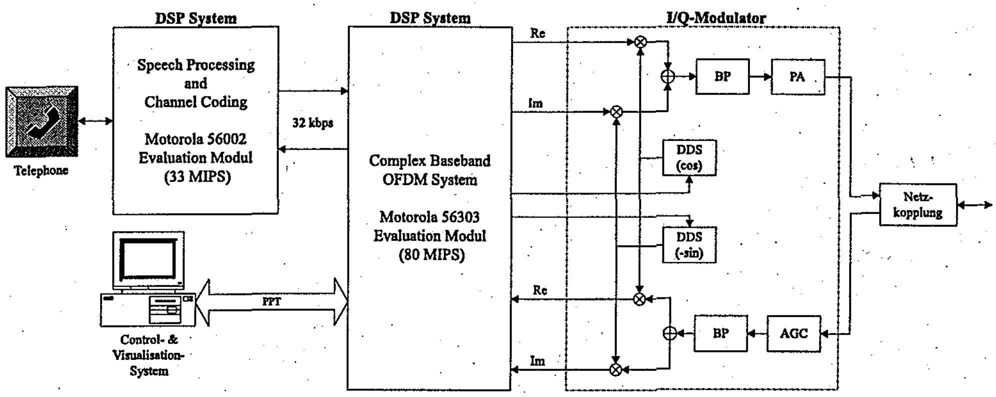


Figure 1: Structure of an OFDM transmission system

A. OFDM Transmission Technique

A main goal for a powerline communication system design should be a cost-effective solution. To reduce the system cost a full software realization of the system is desirable. By that means the number of components is minimized and a high flexibility of the system can be achieved.

The lower spectral density of noise disturbances at higher frequencies will probably lead to a selection of a high frequency bandpass system. In such a case only a complex baseband implementation on a digital signal processor is sensible since otherwise extremely high sampling rates are required. The output of the digital baseband system is shifted to the desired frequency region using an analog quadrature modulator. The structure of such a setup is shown in Figure 1.

A characteristic feature of OFDM is the division of the incoming data stream into N streams which are modulated in parallel. The bit rate of each sub channel will be reduced by a factor of N compared to the input bit rate limiting the influence of the channel response on the transmitted symbol. To completely avoid inter-symbol-interference (ISI) the transmit symbol is periodically extended by a guard interval. If additionally the orthogonality of the transmitted sub channel signal is preserved by an appropriate sub carrier spacing equal to the inverse duration of the OFDM symbol and a precise frequency synchronization the transmitted symbol of sub channel k can be obtained at the receiver. The influence of the channel is reduced in this case to a complex scaling factor $H_k(n)$ and an additive noise component. The received symbol of sub channel k is given by

$$R_k(n) = H_k(n)S_k(n) + N_k(n). \tag{1}$$

B. Sub channel Modulation

For the demodulation process an estimate of the channel transfer factors $H_k(n)$ is required unless a differential modulation technique is employed. In that case the information is contained in the quotient of two succeeding symbols. The modulation is executed by multiplying the data symbol with previous transmitted symbol

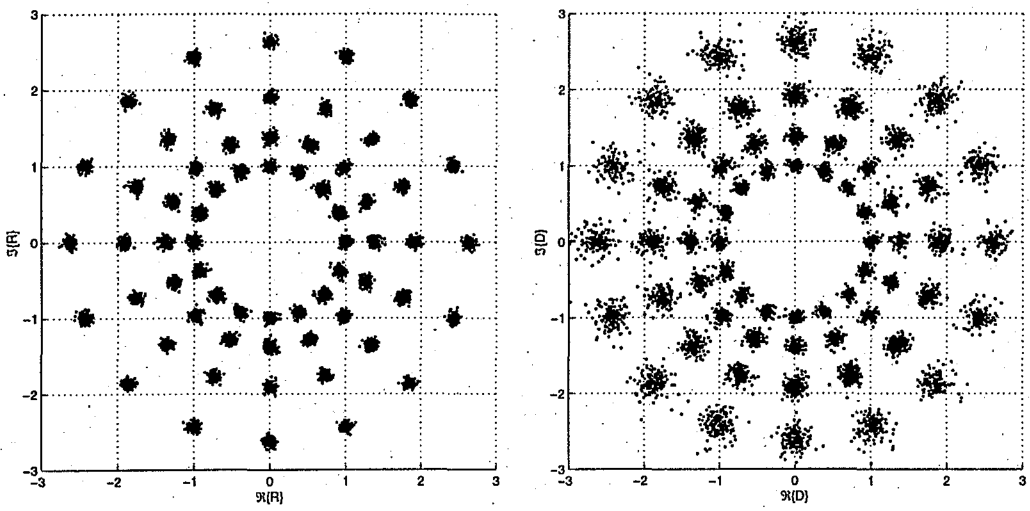
$$S_k(n) = S_k(n-1)\, D_k(n). \tag{2}$$

In the proposed system an enhanced differential modulation technique, the differential amplitude phase shift keying (DAPSK), is introduced [4]. This technique performs a differential modulation of the phases as well as of the amplitudes by mapping information to a signal set given by

$$D_k(n) \in \{a^A e^{j\Delta\phi P} | A \in \{0, \ldots, N_a - 1\}, P \in \{0, \ldots, N_p - 1\}\}. \tag{3}$$

Table 1: Optimized DAPSK constellations

M	2	4	8	16	32	64	128
N_a	1	1	1	2	2	4	4
N_p	2	4	8	8	16	16	32
a	-	-	-	1.8	1.45	1.38	1.21



(a) Received 64-DAPSK symbols

(b) Demodulated 64-DAPSK symbols

Figure 2: 64-DAPSK properties in an AWGN channel

The mapping of amplitude bits and phase bits can be performed separately. The distribution of the inputs bits to phase and amplitude information depends on the constellation size. Optimized values for different number of bits per symbols are given in Table 1. The differential modulation is performed by a multiplication as shown in equation (2) but in this case operation has to be performed modulo N_a. The main advantage of this technique is that even with large constellation sizes good results can be obtained. In contrast the conventional DPSK performance is degraded for constellations with more than 16 points because of the signal points located too close on one circle.

The differential demodulation requires a calculation of the quotient of to succeeding symbols to retrieve the transmitted symbol. This technique requires that the channel transfer factors between these two symbols are correlated ($H_k(n) \approx H_k(n-1)$). Then the demodulated symbol can be written as

$$\tilde{D}_k(n) = \frac{R_k(n)}{R_k(n-1)} = \frac{S_k(n-1)D_k(n)H_k(n) + N_k}{S_k(n-1)H_k(n-1) + N_k(n-1)} \approx \frac{S_k(n-1)D_k(n)H_k(n)}{S_k(n-1)H_k(n)} = D_k(n). \qquad (4)$$

As can be seen from figure 2 (a) the constellation points located on the inner circles are disturbed more by the additive noise than the points with larger amplitudes. This leads to a BER that is not independent from the amplitude ring of the constellation point. After calculating the quotient of two succeeding symbols the noise distribution is transformed so that the same disturbances appear for small and great amplitude values again as depicted in figure 2 (b). From this plot decision levels could be derived which are not located at the arithmetic mean but at the geometric mean between the neighbouring amplitude levels. The numerator as well as the denominator are disturbed by the additive noise leading to a slight decrease of approximately 2 dB in the system performance of a DAPSK system. But this degraded performance can be accepted when the

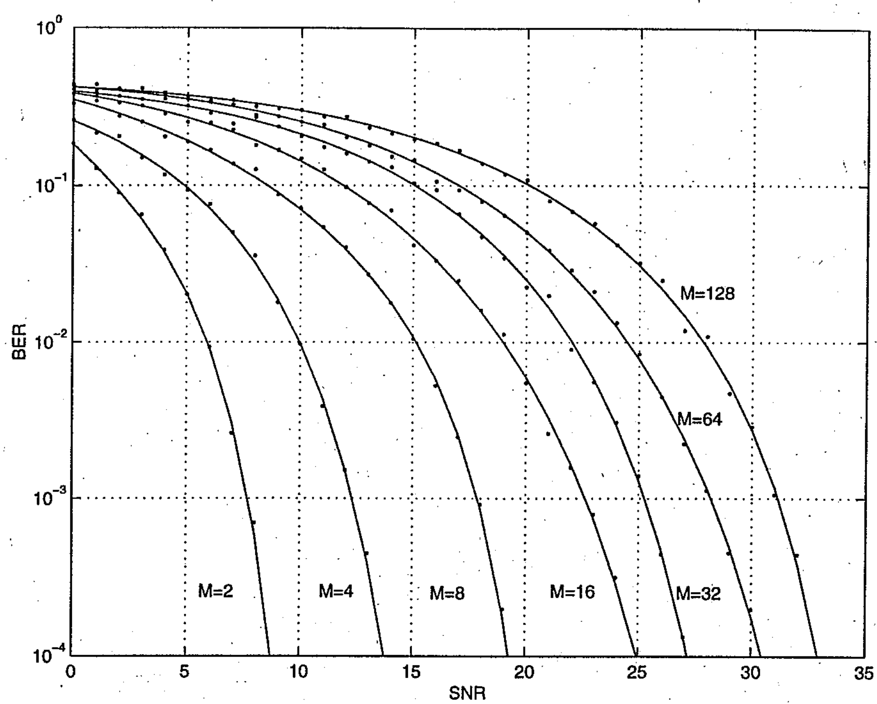


Figure 3: BER of DAPSK

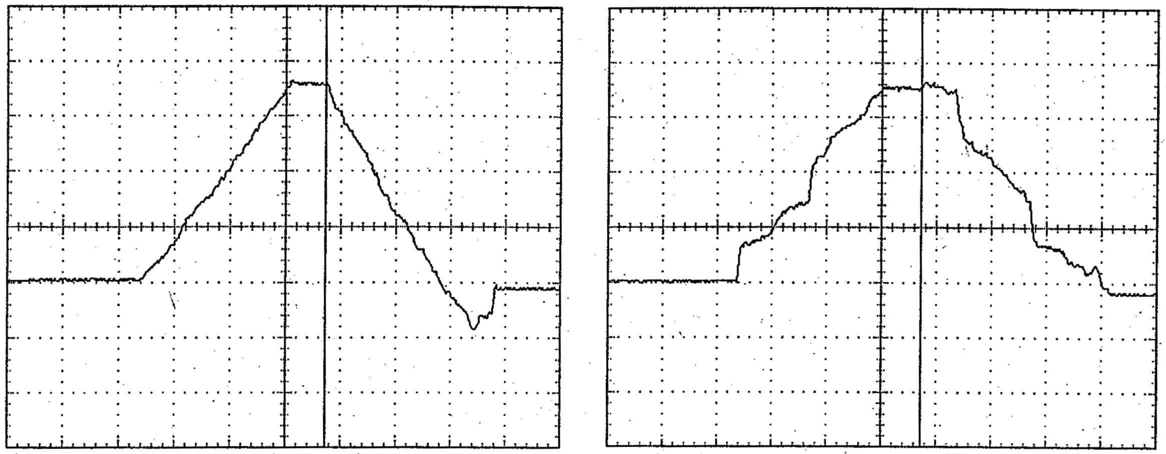
gain in the bit rate is considered. All sub channels utilized for the channel estimation process in a coherent transmission system now can be used for the transfer of data bits. In Figure 3 simulation results of different constellation sizes are depicted. The time domain signal of an OFDM transmission is normally distributed with variance σ. If the power of the time domain signal is equal to σ^2 the signal power per subchannel can be calculated due to energy preserving properties of the FFT.

$$\sigma^2 = P = \sum_{k=0}^{N} P_k \approx N \cdot P_k \tag{5}$$

For the 116 $dB\mu V$ restriction in the CENELEC B band a spectral density of the transmit signal of approximately 0 dB(mW) can be used. With a typical transfer function of an in-door environment signal-to-noise ratios of 30 dB can be expected. With these SNR values constellations mith $M = 64$ can be used at moderate bitrates.

C. Time and Frequency Synchronisation

One of the most important parts of an OFDM system are the time and frequency synchronisation. Without time synchronisation it is not possible to process the received data because the symbol bounds cannot be identified. The start of a new OFDM symbols has to be detected with some accurance which is given by the remaining part of the guard interval. This goal can be achieved by correlation methods. Correlating the remaining guard interval with the corresponding part of the data symbol does not deliver the desired reliability when only one symbol is observed. Thus, an additional synchronisation symbol has to be used. This symbol consists of two identical half symbols and can be easily designed in the frequency domain by omitting every second carrier. If the synchronisation symbol should have the same energy like a normal data symbol then the signal constellation of each subchannels has to be scaled by a factor of $\sqrt{2}$. At the receiver



(a) Good post synchronisation symbol (b) Bad post synchonisation symbol

Figure 4: Example for influence of post synchronisation symbol

the metric

$$P(n) = \sum_{l=0}^{\frac{N}{2}-1} \left(r^*(n+l)r(n+l+\frac{N}{2}) \right) \tag{6}$$

is calculated to detect the start of the OFDM symbol [5]. $r(n)$ denotes the complex baseband time domain samples and N is the symbol length without the guard interval. When a synchronisation symbol is processed a constant maximum value for the duration of the remaining guard interval is calculated. The start of the symbol can then be selected at any arbitrary point within the detected plateau. Normally the absolute maximum

$$\hat{n} = \max_{n}\{|P(n)|^2\}. \tag{7}$$

is used as a criterion. To limit the noise influence on the detection process some filtering has to be applied. Furthermore false detection can occur depending on the correlation of the synchronisation symbol and the succeeding data symbol. The data symbol has to be selected carefully otherwise even under low noise conditions. If this symbol is designed so that only half the number of carriers of the second symbols are used for data transmission good results can be obtained. In Figure 4 (a) an example for a good symbol combination is shown. In Figure 4 (b) a bad symbol combination is depicted which leads to a false detection in a noise free channel. In both figures the bounds for a correct decision have been marked.
By utilizing an extra synchronisation symbol with the given properties this symbol can be used for a fine frequency synchronisation. The carrier frequency offset can be calculated by

$$\Delta f_c = \frac{1}{2\pi} \arctan \left\{ \frac{\Im\left\{\sum_{l=0}^{\frac{N}{2}-1} r^*(n+l)r(n+l+\frac{N}{2})\right\}}{\Re\left\{\sum_{l=0}^{\frac{N}{2}-1} r^*(n+l)r(n+l+\frac{N}{2})\right\}} \right\}. \tag{8}$$

Since in this setup numerical controlled oscilators are used and so only a frequency offset smaller than one carrier spacing has to be corrected.

3 System Design Aspects

To determine an optimum set of parameters for an OFDM communication system a consideration of numerous partly contradictory demands is necessary. The selection of parameters depends strongly on the application and on the properties of the transmission channel in the considered frequency band. In the following aspects will be given that have influence on this selection process. Even if in this case of a very small transmission band OFDM does not exhibit its full perormance, the same decisions like in a wide band system have to be taken. From the chosen parameters finally an estimation of the achievable bitrate will be given.

A. Application Requirements and Regulations

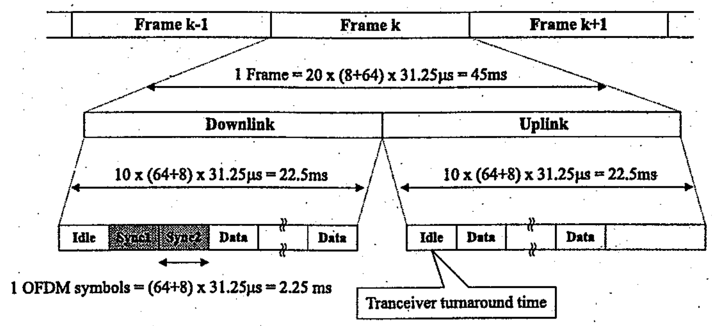
A number of demands are given by the performance which is required for the proposed application. Also regulations like the EN 50065 have to be obeyed when choosing the system paramenters. In the proposed system the CENELEC B band will be used which is located between 95 kHz and 125 kHz. In this band no restriction apply concerning the use or access technique. Also the level of the transmit signal can be relatively high. By the decision for this band the bandwidth B is limited to 30 kHz. In such a small bandwidth system a bidirektional transmission is only sensible when a time-division-duplex system (TDD) is used. Otherwise either an echo cancellor or filtering is required to seperate the two directions. Additionally, for the proposed speech transmission system the processing delay has to be limited. If the delay is to large the comprehensibility of the speech transmission is degraded and the quality of the transmitted data will not be acceptable. In this case we have limited the transmission delay τ_d to 50 ms. Besides the delay the required bitrate is an important factor. For the proposed setup an ADPCM speech codec with 32 kbps should be used. A bit error rate of 10^{-4} can be accepted for speech transmission.

B. Transmission Channel and OFDM Inherent Requirements

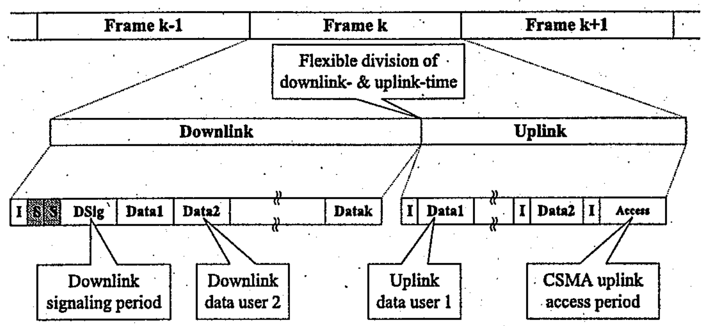
In order to select an appropriate guard interval the length of the impulse response of the channel has to be considered. The extent of the RPC network of several hundred meters let us expect a delay due to multipath propagation of not more than 5 μs. In the case of the proposed system this value is much smaller than the sampling time. So only the system inherent impulse response has an influence on the guard interval length. With the mentioned assumptions the coherence bandwidth of the channel is much bigger than the whole transmission band and so the selection of the carrier spacing also has no influence on the system design. But these two factors become very important when the sampling frequency of the system will be increased in future studies. For an efficient implementation of the DFT algorithm a number of taps should be chosen which is a power of two. Moreover, with an increasing number of subcarriers the efficiency of the transmission can be improved. As already mentioned the bandwidth of each subchannel has to be much smaller than the coherence bandwidth of the channel. For a high bitrate system a high enough number of carriers has to be used. On the other hand long symbols lead to an increased processing delay which should be limited in real-time applications like the proposed speech transmission. Furthermore only a reduced number of subchannels can be used for the data transmission in order to allow a reduced effort for analog interpolation filters.

C. Synchronisation and Protocol Requirements

As described in section 2 the synchronisation is performed within two symbols for each transmitted data packet. This overhead can be reduced if one system acts as a master system. This system measures the delay of the received uplink data and transmits a timing-advance information to the slave system. With this information the slave station, which has adapted its carrier frequency to the one of the master, transmits its data packets only separated by a transceiver turn-around interval. By this means the overhead can be reduced to two synchronisation symbols per frame plus an idle symbol between each change of the direction of the data transmission. The timing of a peer-to-peer system is depicted in Figure 5 (a).
This frame structure can be easily expanded to a dynamic TDMA structure as it is shown in Figure 5 (b). Like in the previous structure all slave systems have to synchronise their carrier frequency to the one of the



(a) Bidirectional Transmission



(b) Multiple Access Transmission

Figure 5: Structure of a TDD OFDM transmission burst

master station. The master station again calculates all timing-advance information and transmits it to the slaves in the downlink signalling period following the synchronisation symbols. The signalling period also contains timeslot allocations for the up and downlink and information concerning the start of the uplink access period.

In our proposed system the suitability of this access technique for multiple access systems with low bitrates for home-automation applications will be part of further studies.

D. Estimation of the Achievable Bitrate

In the following we will give an estimation for the achievable bitrate of our experimental system based on the system parameters given in Table 2. The experimental setup is based on a Motorola 56303 eveluation board. This board offers a sampling frequency f_S of 32 kHz with an oversampling codec. Only the carriers located within the 30 kHz bandwidth are used and also the carrier at DC is omitted so that the number of used carriers N_U is 57. To get a good efficiency a FFT length N_C of at least 64 is selected. With a guard interval length N_G of 8 the overhead is reduced to max. 12.5%. Assuming the same number of bits in all subchannels - no bitloading is employed - the maximum bitrate is given by

$$R_{brutto} = \frac{f_S}{N_G + N_C} \sum_{k=1}^{N_U} b_k = b_k \frac{N_U f_S}{N_G + N_C} \approx b_k \cdot 25 \; kbps. \qquad (9)$$

Table 2: Used system parameters

Sampling frequency	32 kHz
Bandwidth	30 kHz
FFT-Length	64
Guard Interval length	8
Used carriers	57
Data symbols per packet	10
Separation of direction	TDD

with the number of bits per subchannel b_k.
This bitrate is reduced by a factor of two for a bidirectional TDD transmission. Additionally, the overhead introduced by the synchronisation symbols has to be considered. With theses restrictions a netto bitrate R_{netto} per direction for a bi-directional peer-to-peer transmission of

$$R_{netto} = b_k \cdot \frac{1}{2} \cdot \frac{18}{22} \cdot R_{brutto} \approx b_k \cdot 10\ kbps \tag{10}$$

can be achieved. If an average number of bits per subchannel b_i of 4 can be guaranteed at the desired BER then bitrate will allow the desired data transmission. An additional convolutional coder with a coderate of 0.8 can be employed for a slight performance improvement.

4 Conclusion

A concept for an OFDM based communication system for the residential power circuit has been proposed. OFDM offers the possiblity to achieve high data rates over frequency selective channels. To limit the system overhead an enhanced differential modulation technique is employed which outperforms the conventional DPSK and does not require a channel estimation for demodulation. A robust synchronisation technique has been proposed which allows a fast and reliable time and frequency synchronisation. An estimation of the maximum achievable bitrate has been given on the basis of a derived parameter set for the CENELEC B band. This system is currently implemented on a Motorola fixed-point DSP to verify the calculations and for the purpose of further studies of the powerline enviroment.

References

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