System Design Considerations for High data Rate Communications Over Multi-wire Overhead Power-lines

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***Abstract* – Broadband power-line communications over multi-wire overheard lines using Orthogonal Frequency Division Multiplexing (OFDM) is considered in this paper. From earlier investigations, it is known that this channel suffers with multipath fading and frequency selectivity. Nevertheless, the calculated channel capacity limit promises very high data rates over this channel, subject to simple fixes. Enhancement techniques, such as coding can help an OFDM system to achieve this limit as close as possible. The smart use of coding and power allocation in OFDM will be useful to get the desired performance at higher data rates. These theoretic facts are confirmed by means of computer simulations.**

Keywords - power-line communications, multi-wire overhead lines, capacity, OFDM, coding.

I. INTRODUCTION

The increasing interest in modern multimedia applications, such as broadband Internet, HDTV, etc. requires new access techniques for connecting private premises to a communication backbone. One promising technology, Broadband over Power-lines (BPL), intends to use the medium voltage power-line as a high speed digital data channel to connect a group of private users to a very high data rate fiber backbone. Since the power-line network is not designed for communication purposes, the channel exhibits unfavorable transmission properties. It is characterized by a frequency selective transfer function; attenuation increase with length and frequency, and severe narrowband interference [1].

The channel characteristics of medium voltage overhead power-line grids, a common situation in the USA, were investigated in details by the authors in [1]. The investigation showed that although the overhead power-line grids are very low in loss, they suffer from very deep fading caused by multipath. Mismatch at branches of power-line network reflects signals back and creates several signal paths from a transmitter to a receiver. In the same paper Shannon capacity limit of such channel has been investigated. It is shown that overhead power-line network has a very high capacity limit compared to other wireline structures such as cable or twisted pair.

In this paper, the well-known multicarrier technique, Orthogonal Frequency Division Multiplexing (OFDM), is considered as modulation scheme. By the application of OFDM, the most distinct property of power-line channel, its frequency selectivity, can be easily coped with. Moreover OFDM can make a very efficient use of allocated bandwidth [2]. We use an OFDM modulation system along with the channel introduced in [1] and evaluate the performance of such system over this channel. Furthermore, we investigate different ways that can improve the performance of overall communication system by means of coding and adaptive resource allocation.

In section II, a brief review of channel characteristics of our system is presented. Section III details the OFDM system. Simulation results and observations are demonstrated in section IV. Concluding remarks and references end the discussion.

II. OVERHEAD POWER-LINE CHANNEL MODEL AND ITS CAPACITY

Channel transfer function of a matched transmission power-line follows equations (1) and (2).

$$V(l) = H(f)V(0) \tag{1}$$

$$H(f) = e^{-\gamma(f)l} = e^{-\alpha(f)l} e^{-j\beta(f)l} \tag{2}$$

in which *v(0)* is the voltage at the source and γ is the propagation constant, α is the real part of the propagation constant, which is called attenuation constant and β, the imaginary part of the propagation constant, is called phase constant. To find the exact solution for γ at high frequencies with lossy ground return, several research efforts have been conducted since early last century. One of the most recent investigations in this area is done by D'Amore et al in [3]. By applying this method, the propagation constant of overhead power-lines can be carried out for frequencies of up to 100 MHz [1].

Channel transfer function of a matched transmission power-line follows equation (2). In the case of unmatched junctions, part of a propagating signal reflects back to the transmitter at branch junctions due to impedance mismatch and the remainder travels through [4]. Propagation along a wire follows equation (2), so one can easily express the multipath network channel model as:

$$H(f)=\sum_{i=1}^{N} g_i e^{-\alpha(f)d_i} e^{-j\beta(f)d_i} \qquad (3)$$

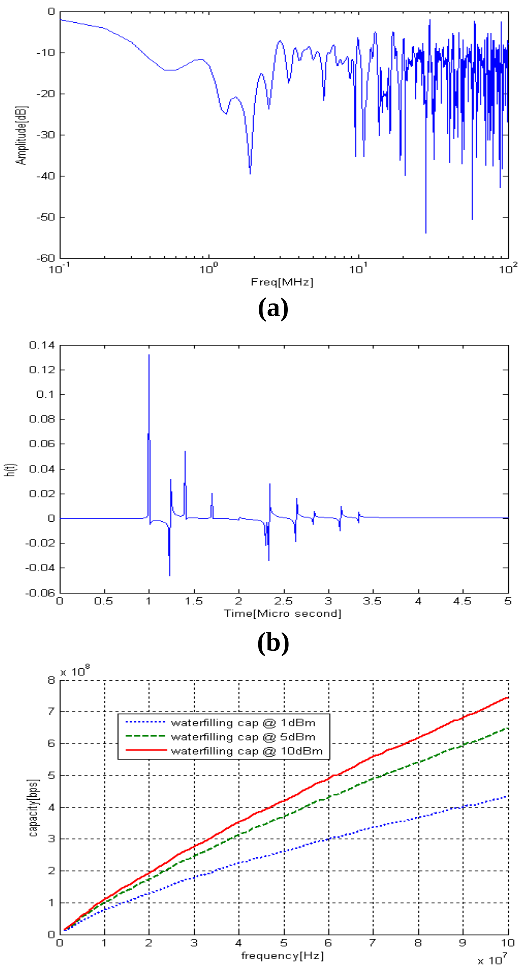
where N is the number of significant arrived paths at the receiver, d_i is the length of ith path and g_i is the weighting factor of the ith path, where g_i is very well defined in [5].

Using the mentioned method, we simulate the complex network shown in [1]. In this network, we have three branches between a transmitter and a receiver, which are by 1Km apart. Each end of these branches is an open-circuit, so reflection factor at each end is unity. Also, we have assumed the transmitter and receiver impedance are matched to that of the line. Channel frequency and impulse responses of this system are shown in Fig.-1(a) and (b). Our simulation results show 12 paths are dominant and from Fig.-1 (b), 12 pulses with different arrival times are distinguished. The maximum delay spread of this channel is approximately 3 microseconds. Fig.-1(c) illustrates channel capacity limits of this channel. For evaluation of channel capacity, we chose a uniform -105 dBm/Hz as a representative of average background noise spectral density level. Referring to [6], this value is a conservative average estimate of practical background noise level for MV power lines. According to this figure, the average capacity in this network with a 10 dBm launched transmit power level at 50 MHz band is about 400 Mbps.

III. OFDM SYSTEM

Multi-carrier modulation has long been known as an efficient modulation scheme for bandlimited channels [7]. OFDM is considered as one of the most promising modulation methods for power-line communications [8]. Besides its high spectral efficiency, OFDM has some favorable properties, which can be utilized properly in order to mitigate harsh characteristics of power-line channels.

The basic idea of OFDM is to split a high rate data stream into a number of lower rate streams and transmit these streams simultaneously, and in parallel over a number of orthogonal subcarriers. The orthogonality of subcarriers guarantees that the streams do not interfere with one another. It is possible that subcarriers lose their orthogonality due to multipath or channel non-stationary behavior. In this case, sub-carriers interfere with one another and cause inter-carrier interference (ICI). A very general block diagram realization of an OFDM system is depicted in Fig.-2.



(a)

(b)

(c)

Fig.-1 (a) Frequency and (b) impulse response of an overhead power-line network and (c) its associated capacity limit

Each data stream is sent in one subchannel, so that each has its own coherence bandwidth. If the bandwidth of transmitted signal is less than coherence bandwidth of the channel, inter-symbol interference (ISI) is eliminated on that channel. Lower data rate streams have lower bandwidth and therefore, if we choose enough subcarriers, we will be able to have very low-rate parallel data streams in each such that each subchannel will be ISI free. To avoid ISI almost completely, a guard time interval needs to be added to each OFDM symbol. Guard time interval needs to be longer than the delay spread of the overall channel. Also, in the guard time, the OFDM symbol should be cyclically extended in order to avoid ICI [9].

The division of data stream to several sub-carriers can be implemented easily using Inverse Fast Fourier Transform (IFFT). The match filtering of each sub-channel also is done by Fast Fourier transform (FFT). Further justification of this issue can be found in [9].

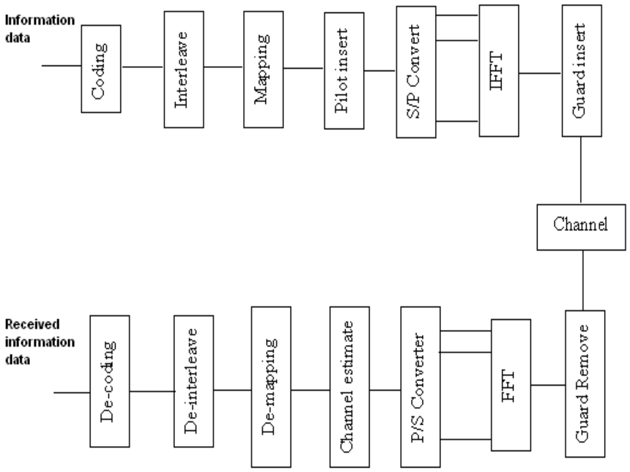


Fig.-2 General block diagram realization of an OFDM system

In the case of coherent detection system, which is the case in power-line communications, a channel estimate is also necessary. This estimate is important to identify the amplitude and phase reference of the mapping constellation in each subcarrier so that the complex data symbols can be demodulated, correctly. Channel estimation in OFDM can be done by insertion of some known symbols or pilot into the OFDM signal. These known symbols yield point estimates of the channel frequency response.

Similar to every other communication scheme, coding can be employed to improve the performance of overall system. Several coding schemes, such as block codes, convolutional codes and turbo codes have been investigated within OFDM systems in the literature.

Moreover, the deep fades in the frequency response of channel cause some groups of subcarriers to be less reliable than other groups and hence cause bit errors to occur in bursts rather than, independently. To solve this problem, several ways are considered in the literature. The easiest method is to use stronger codes for those faulty subchannels, if they are known. In the case that the subchannel situations are not known, an interleaving technique along with coding can guarantee the independence among errors by affecting randomly scattered errors.

IV. SIMULATION RESULTS AND DISCUSSION

For simulation purposes, we chose the channel impulse response shown in Fig.-1 to be characteristics of the medium under which our system is operating. The occupied bandwidth of the system is chosen to be 50 MHz. The capacity limit of this channel at 50 MHz with 10-dBm launch power is less than 400 Mbits/sec. The delay spread of the channel is 3 microseconds. To avoid ISI and lose less than a 0.5 dB due to guard interval insertion, we chose the OFDM symbol interval 9 times the delay spread, which is equal to 27 microseconds. The subcarrier spacing is now the inverse of 27-3=24 microseconds, providing 42 KHz. By considering 50 MHz bandwidth, at most we can use 1200 subcarriers. We designed a system with 1024 subcarriers and one known pilot channel for estimation. In each sub-channel QPSK modulation is used. Therefore, the overall bit rate will be equal to 1024*2*42 Kbits/sec= 90 Mbits/sec. The Bit Error Rate (BER) of this system versus Signal to-Noise-Ratio (SNR) is depicted in Fig.-3.

For comparison purposes, we simulated a single carrier communication system for the same channel with the same bit rate of 90 Mbits/sec. For this system, we used a linear LMS equalizer with 50 taps to mitigate the ISI. The performance of such a system is illustrated in Fig.-3, as well. It is seen from this figure that the single carrier scheme has a much worse performance than the OFDM system. By increasing the SNR, after some point, the single carrier system no longer improves the overall performance, whereas the OFDM system performance continues to improve. It is due to deep notches in the channel transfer function causing the linear equalizer to enhance the noise more than eliminating ISI [10]. Non-linear equalizer will be more useful in this kind of channel but still it needs many taps (more than 100) to cope with severe frequency selectivity of the channel.

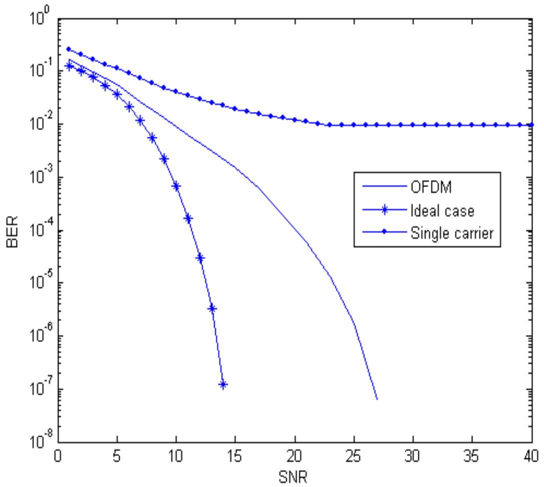


Fig.-3 Performance comparison of multi-carrier and single-carrier systems.

In Fig.-3, the ideal case that has all the intersymbol and interchannel interference removed has been plotted as a benchmark for comparison purposes. This performance will be achieved if the receiver has a complete knowledge of the channel impulse response and uses this knowledge for alleviating ISI.

As it is mentioned before, coding can help to improve the overall performance of the system. Two convolutional codes are investigated for this OFDM system: one “lower-rate” code with the coding rate of 0.5 and one “higher-rate” code with coding rate of 0.75. We simulated our OFDM system with these two codes over the channel and the results are depicted in Fig.-4. It is shown in this figure that the stronger code with the smaller coding rate has a better performance with the drawback of losing data rate. The system with a code rate of 0.5 has a data rate of 45Mbits/sec, whereas the other system that employs a code rate of 0.75 can operate at a 67Mbits/sec data rate.

To increase the data rate, we can use modulation schemes with more levels. By increasing the levels, signal points in the modulation constellation become closer to one another, thereby the probability of communication error increases. In Fig.-4 is plotted the performance of a system which uses 16 QPSK modulation without coding. Although, the data rate in this modulation scheme is twice the data rate of the system we investigated before (i.e. QPSK modulation), this system needs more transmitted power (SNR) to achieve the same bit error rate that the lower data rate system achieves at a less SNR value.

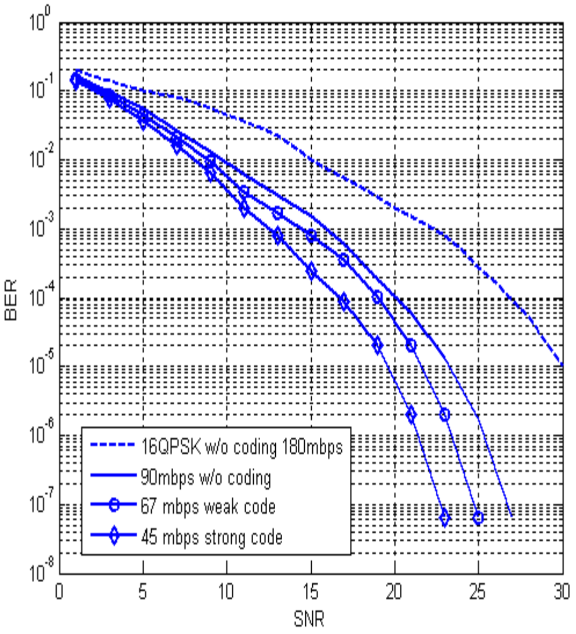


Fig.-4 Performance comparison of OFDM systems with different coding schemes and higher modulation levels

As we discussed earlier, not all the subchannels experience the same deterioration. Some of the subchannels are in very deep nulls and some are operating in medium or low loss conditions. For this reason, it is more appropriate to use stronger enhancement schemes, like strong codes or transmitted power increments on these subchannels rather than utilizing the same scheme on all of them. For example, in our channel we defined those subchannels that the amplitude of their frequency response is less than –20 dB as “weak” subchannels. There are 344 such subchannels out of 1024. We investigated three communications scenarios in order to improve the performance of our system. In the first scenario we employed the lower-rate code only on weak subchannels and left the remaining subchannels without coding. The second scenario was similar to the first one with the difference that the higher-rate code was used on the less problematic subchannels. For the third scenario, we used the same coding schemes as in the second scenario but for weak subchannels the transmitted power was twice the transmitted power of other subchannels. The performance of these three systems are shown in Fig.-5 along with the performance of the system, which uses the strong code on all subchannels with the same transmitted power on all sub-channels. Performance of the first system is slightly worse than the case that we used the same code for all subcarriers, but the data rate of this system is equal to 75Mbit/sec, which is much greater than the former case. The second scenario improves the system performance by 1 dB and its performance is almost similar to the system with strong code on all subchannels, but with a data rate equal to 60 Mbits/sec. For the third scenario, SNR is defined as the ratio of the average of transmitted power levels on sub-channels over the noise power. Fig.-5 shows the third scenario has a 2.5 dB improvement over the second scenario with the same data rate. This is due to smart use of power and codes for appropriate sub-channels.

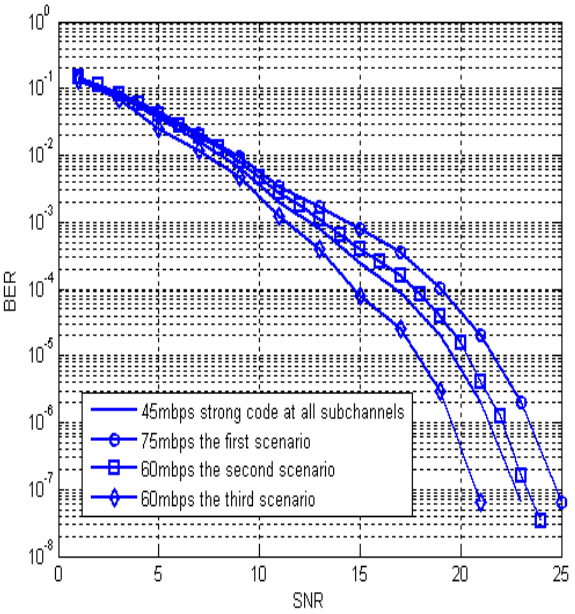


Fig.-5 Performance comparison of OFDM systems for optimum use of power and coding enhancements

V. CONCLUSIONS

In this paper, we investigated performance of OFDM systems for high data rate transmission over multi-wire overhead power-lines. The channel characteristics and capacity limit were obtained in earlier research. Simulation results show that the OFDM transmission link, added with a bit allocation for pilot, is required to cope with the channel fading. It is shown single carrier schemes need very complex non-linear equalizers to have an acceptable performance. Linear equalizers were also considered in the simulations and it was seen from the results that these equalizers enhance noise more than eliminating ISI, due to deep nulls in the channel characteristics function.

Coding enhances the overall system performance. The drawback is in a loss of effective data rate.

Not all OFDM sub-channels experience the same channel deterioration. For this reason, it is admissible to use more cautious communication techniques on these sub-carriers. By this method, it is possible to achieve higher data rates and better performance for an OFDM system. However, the complexity of the system is increased. Therefore, in designing an OFDM based Broadband Power-line (BPL) modem, based on data rate needs and system complexity, appropriate transmitted power and code allocation on sub-carriers should be selected.

Acknowledgements

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