OFDM VS WAVELET-OFDM AND CIRCULAR WAVELET-OFDM IN HIGH SPEED COMMUNICATION OVER POWER LINES

Łukasz Zbydniewski[1], Tomasz Zieliński[2]

AGH University of Science and Technology, Department of Telecommunications, Kraków, Poland,
[1]e-mail: zbydniew@kt.agh.edu.pl
[2]e-mail: tzielin@agh.edu.pl

Abstract: *This paper presents results from simulations of classic non-prefixed Wavelet-OFDM and its circular version called Circular Wavelet-OFDM using a cyclic prefix. Both modulators have been compared with standard OFDM multicarrier techniques in the high speed power line communication environment. Circular Wavelet-OFDM, as a hybrid modulation scheme lying between Wavelet-OFDM and OFDM, has all advantageous of non-prefixed Wavelet-OFDM, additionally solving problem of equalization in the same way as in prefix-based OFDM. The main purpose of this article is focused on investigation of robustness of the mentioned above modulation schemes to colored noise, narrowband interference and, additionally, to impulsive disturbances. Statistically reliable calculation of BER performance is done by means of statistical modeling of three types of power line channels having different quality and by using statistical models of disturbances.*

1 Introduction

Orthogonal Frequency Division Multiplexing (OFDM) was adapted to many future communication systems due to its simple and elegant implementation resulting from usage of cyclic prefix, IFFT/FFT based modulator and demodulator [1]. However, OFDM is commonly believed to have a poor spectral characteristic because of relatively high side lobes of adjacent carriers. This is the main reason of proposing the alternative multicarrier modulation schemes for communications purposes. One of the well known is Discrete Wavelet MultiTone (DWMT), also recently proposed for high-speed communications over power lines under the name of Wavelet-OFDM [2]. The mentioned here main OFDM's drawbacks can be overcome by using specially designed filters. Unfortunately, the Wavelet-OFDM system do not use a guard interval what causes many difficulties with channel equalization [2] that are usually solved by computationally intensive solutions.

The high speed power line communication has to face with many technical and regulatory obstacles but it seems to be an interesting alternative to the in-door wireless multimedia streaming due to the fact that it can ensure, both, very high bit throughput and desired quality of service (QoS) [2]. However, in order to fully exploit the PLC advantages, it is first necessary to reduce destructive influence of a harsh power line environment on the bit throughput [1, 3]. A performance comparison of OFDM and Wavelet-OFDM modulators/demodulators in power line environment has been already widely studied in many research papers [2, 4, 5] pointing out advantages of both approaches. But, in our opinion, in these papers the influence of real power line channels and their typical disturbances for overall system performance has not been investigated in satisfactory way and, therefore, question concerning usefulness of different modulators in PLC environment is still open.

This paper addresses investigation of PLC application aspects of three modulators: OFDM, Wavelet-OFDM [2, 5] and Circular Wavelet-OFDM [6], a special case of the real circular Gabor transform modulator [7, 8]. Especially, we will present a new critical look on Wavelet-OFDM robustness to narrowband interferences. We will show that simple OFDM can achieve better results in conditions assuming high level of colored noise in the background. Furthermore, the OFDM is more susceptible to burst impulsive disturbances for which application of Wavelet-OFDM seems to be beneficial. In turn, Circular Wavelet-OFDM with an easy equalization and reduced spectral side lobes is somewhere in the middle and it is also suitable for practical applications in some circumstances.

The paper has the following structure. In sections 2 and 3 we present short description of modulators used in our simulations unfolding also the difference between classical and circular version of the Wavelet-OFDM as well as between OFDM. In section 4 we describe the simulation parameters for tested modulators and present results from simulations with: additive white Gaussian noise, colored noise, narrowband interferences and impulsive disturbances. Finally, in the last section, we conclude our research.

2 OFDM modulator

The block diagram of the OFDM transmultiplexer is presented in fig. 1. Symbol W denotes the NxN inverse FFT matrix $\mathbf{W}(n,k) = \exp(2\pi kn/N)\sqrt{N}$ where $k, n = 0,1,\ldots, N-1$ (k – frequency index, n – time index), matrices **T** and **R** stand for addition and subtraction of cyclic prefix having M samples:

$$\mathbf{T} = \begin{bmatrix} \mathbf{0}_{Mx(N-M)} \mid \mathbf{I}_M \\ \mathbf{I}_N \end{bmatrix}, \quad \mathbf{R} = \begin{bmatrix} \mathbf{0}_{NxM} \mid \mathbf{I}_N \end{bmatrix} \qquad (1)$$

and E_0 is a diagonal matrix of channel frequency equalizer:

$$\mathbf{E}_0 = diag\left(\frac{1}{H\left(\frac{2\pi k}{N}\right)}\right), \quad k = 0, 1, ..., N-1 \qquad (2)$$

with $H(.)$ denoting a channel frequency response. P/S and S/P stand for parallel-to-serial conversion and vice versa.

The following matrix input-output relation describes the entire system:

$$\hat{\mathbf{u}} = \mathbf{E}_0\left(\mathbf{W}^{*\mathrm{T}}\mathbf{R}\mathbf{H}_{lin}\mathbf{T}\mathbf{W}\right)\mathbf{u} \qquad (3)$$

in which $\boldsymbol{H}_{lin}$ is a matrix representing linear convolution with a channel impulse response $\boldsymbol{h}$. If this response is shorter than the cyclic prefix then the following equality is satisfied:

$$\mathbf{W}^{*\mathrm{T}}\mathbf{R}\mathbf{H}_{lin}\mathbf{T}\mathbf{W} = diag\left(H\left(\tfrac{2\pi k}{N}\right)\right), \quad k = 0, 1, ..., N-1 \quad (4)$$

resulting in perfect channel equalization: $\hat{\mathbf{u}} = \mathbf{u}$.

3 Wavelet-OFDM-like modulators

Wavelet-OFDM is an alternative multicarrier modulation scheme which has been proposed for power line communication standard [9]. It is equivalent to Discrete Wavelet MultiTone signaling [10]. The general idea is to replace discrete Fourier transform with wavelet transform [10]. However, in practice usually the cosine-modulated filter banks (extended lapped orthogonal transforms) are used [10, 11]. Wavelet-OFDM modulator does not use any guard interval in the form of a cyclic prefix and can apply perfect or near-perfect reconstruction filters banks. Detailed information about used in Wavelet-OFDM equalization can be found in [12].

Circular Wavelet-OFDM (Circ Wav-OFDM) [6] is a special form of the Wavelet-OFDM in which the filter bank works in circular manner inside each OFDM data frame and the cyclic prefix is used what enables simple FFT-based channel equalization. One can conclude that in Circ Wav-OFDM single OFDM time slot with many frequency lags is replaced by higher number of time slots but with smaller number of frequency lags. The Circ Wav-OFDM can be viewed as a real-value cosine-modulated circular Gabor modulator [7, 8] enabling efficient time-frequency tiling inside each frame.

A general block diagram of Circ Wav-OFDM signaling scheme is presented in fig. 2. Operation are performed in the same way as in OFDM but Fourier matrix **W** is replaced by matrix **F** representing a modified discrete cosine transform (MDCT). Additionally, after synthesis and before analysis, input data are processed circularly for each data frame. Our implementation allows using four configurations: 2 × 1024, 4 × 512, 8 × 256 and 16 × 128 (number of time slots × number of frequency slots). Perfect reconstruction filters are used in two first cases and near-perfect ones in the remaining two. More information can be found in [6].

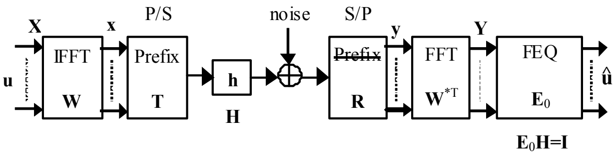

Fig.1. OFDM modulator block diagram.

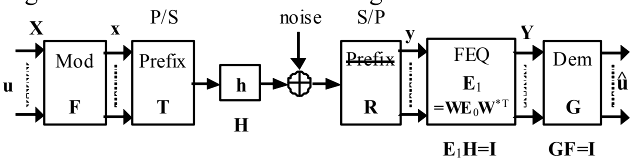

Fig.2. Circular Wavelet-OFDM modulator block diagram.

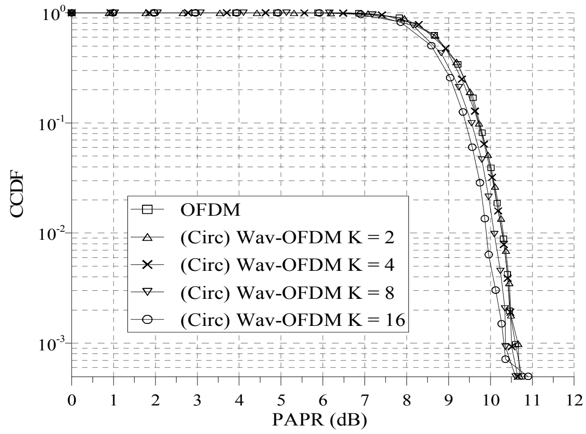

Fig.3. Complementary cumulative distribution function (CCDF) for circular and non-circular Wavelet-OFDM.

4 Simulation results and discussion

4.1 Setup of parameters

Three modulators have been compared: OFDM, Wavelet-OFDM and Circular Wavelet-OFDM. The simulations were performed for five scenarios of disturbances: additive white Gaussian noise, colored noise, narrowband interferences with and without colored noise and impulsive disturbances (two levels of colored noise have been assumed). Three types of PL channels have been simulated in order to add variety to transmission conditions (only mean values are presented below). Each channel had different constellation size for the QAM/PAM signaling. 256QAM/ 16PAM mapping was used for a “good” channel, 64QAM/ 8PAM – for a “medium” channel, and 16QAM/2PAM for a “poor” one. Therefore, the modulation was changing according to power line environment conditions. The random PL channel model presented in [13] was used. OFDM modulation had 2048 QAM symbols in one frame (the FFT size). In baseband simulations only 917 complex symbols were exploited. Wav-OFDM and Circ Wav-OFDM used 2*917 real PAM symbols. Sampling frequency was equal 62.5 MHz. Transmitters scaled energy of sent frames to the level of -70 dB [V^2/Hz].

4.2 PAPR analysis

The classical OFDM modulator suffers from a high peak

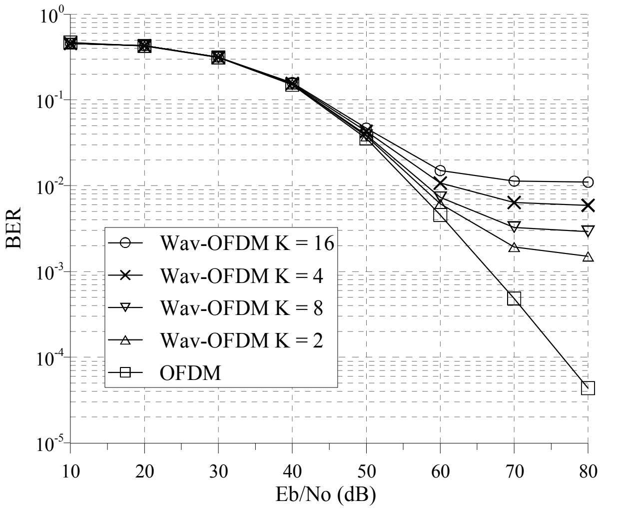

Fig.4. Wavelet-OFDM BER performance for AWGN noise.

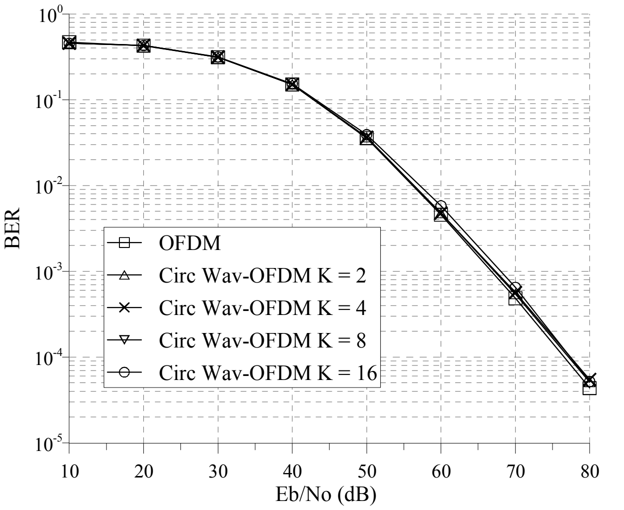

Fig. 5. Circular Wavelet-OFDM BER performance for AWGN noise.

to average power ratio (PAPR) what is an important problem in practical applications. In particular, the A/D converters should have a linear output characteristic what imposes higher restrictions on their quality. Figure 3 presents the Complementary Cumulative Distribution function of amplitude (CCDF) versus PAPR what is directly related to unwanted out-of-band power. As one can see lower PAPR occurs for the modulator with more time slots, although, the difference is not significant.

4.3 Additive white Gaussian noise

Figure 4 depicts results obtained for the standard OFDM modulator and Wavelet-OFDM modulator working with four different time-frequency grids (K denotes the number of time slots corresponding to one OFDM frame). As we observe, problems with an equalization cause that BER curves for SNR higher than 50 dB start to split and the modulator with K = 2 performs better than the other ones but still worse than OFDM.

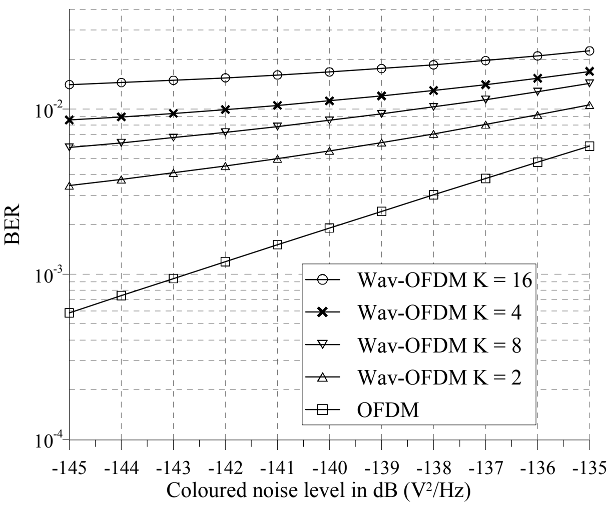

Fig.6. Wavelet-OFDM BER performance for colored noise.

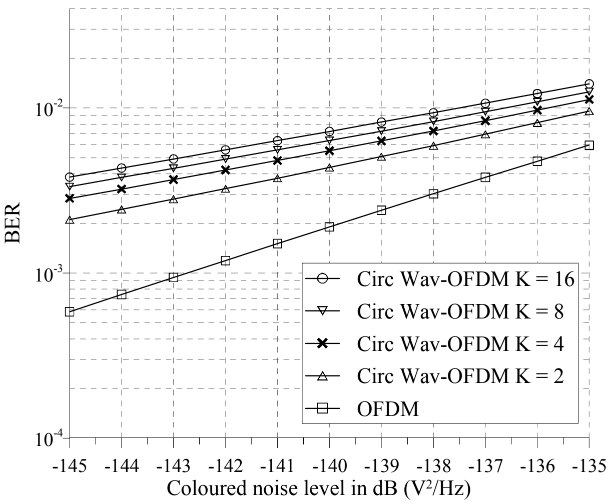

Fig.7. Circular Wavelet-OFDM BER performance for colored noise.

Different situation is observed in fig. 5 for four versions of the Circular Wavelet-OFDM modulator. The performance here is comparable depicting the same trend as above but in much smaller scale.

4.4 Colored noise

The colored noise is a characteristic feature of the PL transmission. In our simulation we have assumed that only the level of this noise is changing. Detailed information about this type of noise and its accurate specification can be found in [7, 14].

Figures 6 and 7 present BER performance as a function of the colored noise level for Wav-OFDM and Circ Wav-OFDM modulators, respectively. The general trend is that modulators with a smaller number of time slots perform better. Only for Wav-OFDM, the modulator with 4 time slots performs worse than with 8 time slots. It can be explained as follows: the modulator's prototype filter for K = 4 has slightly worse performance since when circu-

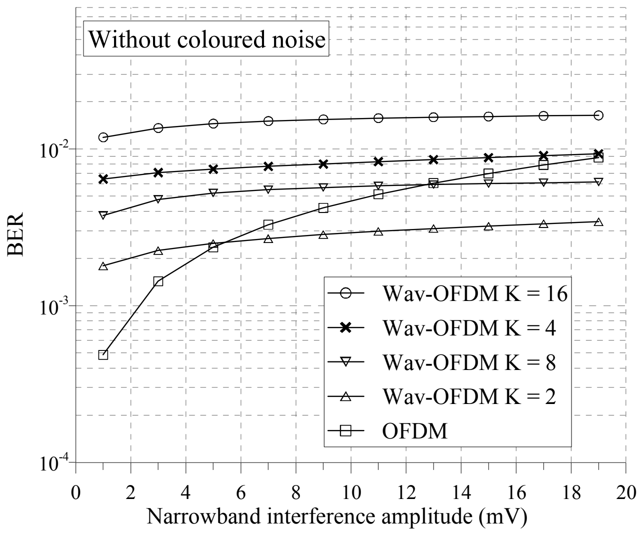

Fig.8. Wavelet-OFDM BER performance for narrowband interference without background colored noise.

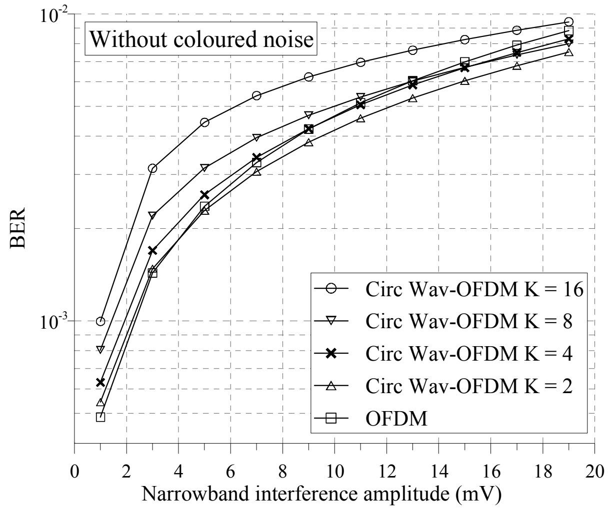

Fig.9. Circular Wavelet-OFDM BER performance for narrowband interference without background colored noise.

larity is not applied the design of this filter has higher importance.

4.5 Narrowband interference without colored noise

Initially, we performed simulations which do not include colored background noise, in order to investigate the susceptibility of modulators only to narrowband interferences. The common opinion is that the OFDM modulator has poor performance because of its relatively high spectral side lobes. This was the main reason for introduction of filter banks, e.g. in ADSL, because they have better spectral containment. In the reported research every transmission was performed with the use of 1024 random channels with 10 frames per channel. Additionally, narrowband interferences were changing their carrier frequencies linearly every 10-th frame and they were scanning every subcarrier of transmitted signal.

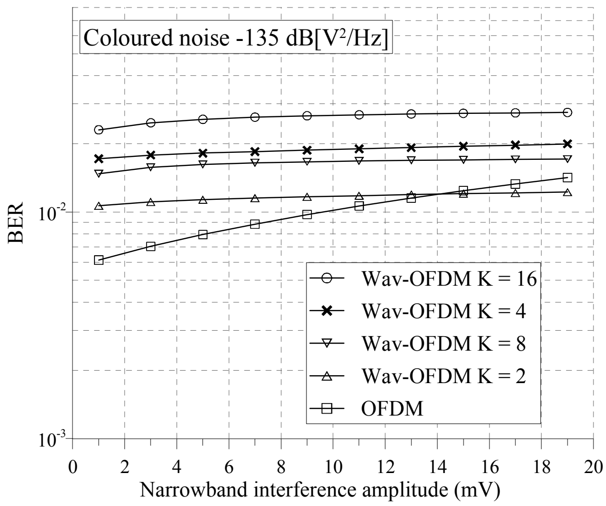

Fig.10. Wavelet-OFDM BER performance for narrowband interference with background colored noise at -135 dB [V^2/Hz] level.

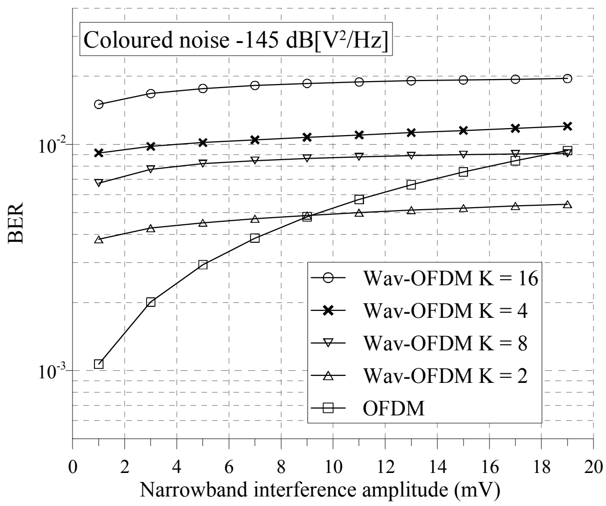

Fig.11. Wavelet-OFDM BER performance for narrowband interference with background colored noise at -145 dB [V^2/Hz] level.

Figures 8 and 9 show the obtained BER performance for Wavelet-OFDM and Circular Wavelet-OFDM, respectively. Small amplitudes work to OFDM advantage over two tested modulators. Only for higher level of narrowband interferences we observe their slight superiority.

4.6 Narrowband interference with colored noise

To make our simulations more realistic and adequate to the real PL channel model, we additionally embedded a received signal in a colored noise. Results for Wav-OFDM are presented in figures 10 and 11 for two levels of the colored noise equal -135 dB [V^2/Hz] and -145 dB [V^2/Hz], respectively. The same transmission scenario was chosen for Circ Wav-OFDM – see figures 12 and 13. We observe that colored noise also works to OFDM benefit regardless the type of Wav-OFDM modulator.

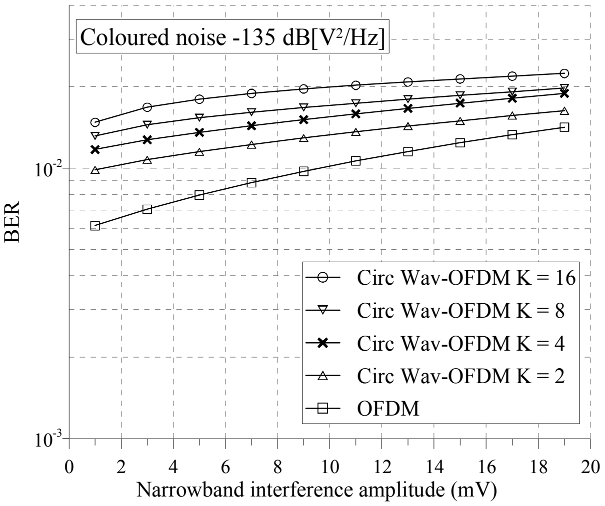

Fig.12. Circular Wavelet-OFDM BER performance for narrowband interference with background colored noise at -135 dB [V^2/Hz] level.

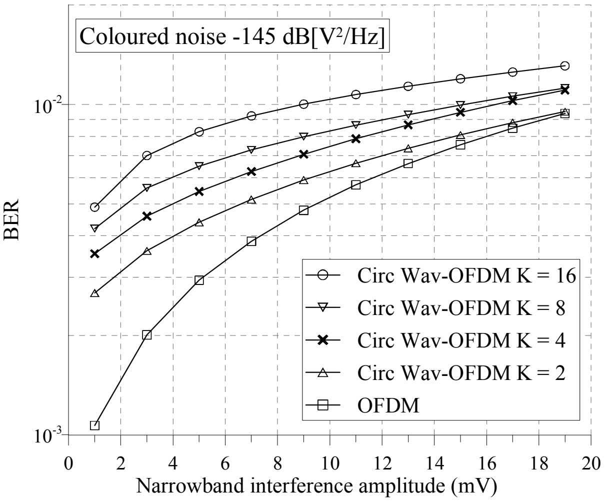

Fig.13. Circular Wavelet-OFDM BER performance for narrowband interference with background colored noise at -145 dB [V^2/Hz] level.

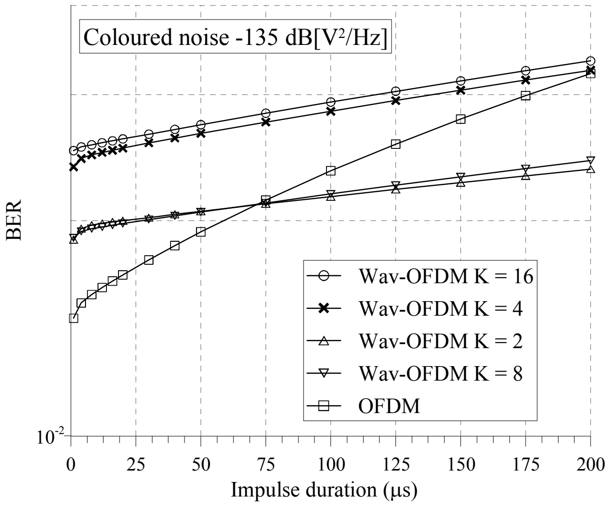

Fig.14. Wavelet-OFDM BER performance for impulsive disturbances with background colored noise at -135 dB [V^2/Hz] level.

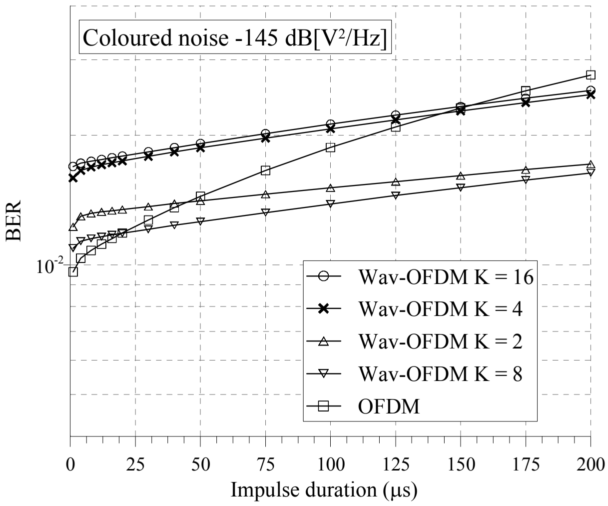

Fig.15. Wavelet-OFDM BER performance for impulsive disturbances with background colored noise at -145 dB [V^2/Hz] level.

4.7 Impulsive disturbances

Impulsive disturbances are the main reason of frames retransmission in PL communication. We investigated performance of OFDM, Wavelet-OFDM and Circular Wavelet-OFDM in the presence of impulsive disturbances and simultaneous colored background noise. Impulses were modeled as dumped sinusoids with randomly changed parameters. One impulse was composed of three sines generated in bandwidth from 1 MHz to 15 MHz with amplitudes in the range of -250 and 250 mV. Additionally, there were appearing in random moments according to Gaussian statistics. Figures 14 and 15 present results of Wav-OFDM for two levels of colored noise. In figures 16 and 17 the same is done for Circ Wav-OFDM.

However, surprisingly, Circ Wav-OFDM modulator performs worse than its non-circular version. For small amplitudes of narrowband interference the definitive winner is OFDM. Only Wav-OFDM with two times slots has better performance in small range depending on colored noise level. Additionally, we observe again that for four time slots the prototype filter is slightly worse for Wavelet-OFDM what is not the case for Circ Wav-OFDM.

In comparison to previous studies we observe significant differences between the two tested filter bank-based modulators. Wavelet-OFDM is less affected by colored noise: higher noise level only causes that the curves crossing is shifted towards longer impulses. Wav-OFDM modulators with 8 and 2 time slots have the lowest BERs for -145 dB [V^2/Hz] and -135 dB [V^2/Hz], respectively. Two other modulators (with 16 and 4 time slots) are much worse.

In case of Circ Wav-OFDM modulators we observe high sensitivity to colored background noise. OFDM presents the lowest BER for the colored noise level of -135 dB [V^2/Hz]. However, utterly different situation is observed

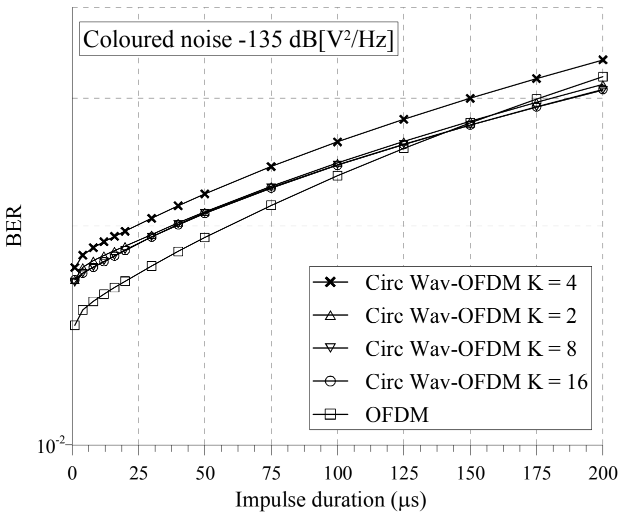

Fig.16. Circular Wavelet-OFDM BER performance for impulsive disturbances with background colored noise at -135 dB [V^2/Hz] level.

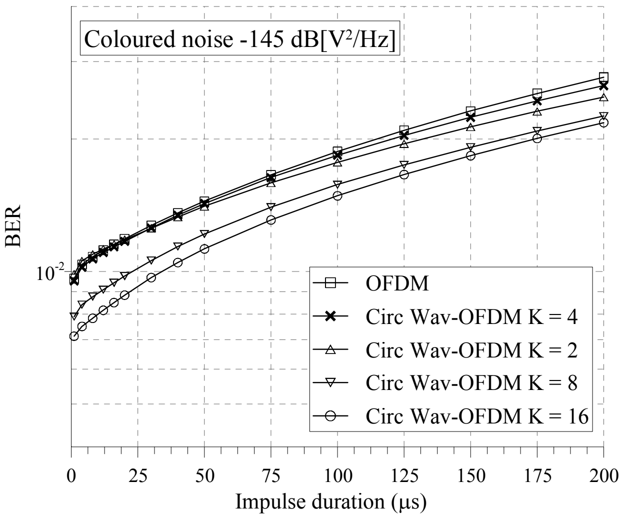

Fig.17. Circular Wavelet-OFDM BER performance for impulsive disturbances with background colored noise at -145 dB [V^2/Hz] level.

on fig. 17 where simulations were performed for colored noise at -145 dB [V^2/Hz] level. Now, Circular Wavelet-OFDM with 16 time slots presents the lowest BER and OFDM has the highest BER. We observe also the slightly worse performance of modulator with 4 time slots.

5 Concluding remarks

In this paper the influence of colored noise level on BER performance of OFDM, Wavelet-OFDM and Circular Wavelet-OFDM modulators working in power line environment has been investigated. It was shown that OFDM modulator has better performance in presence of colored noise and narrowband interferences. Wav-OFDM and Circ Wav-OFDM modulators in turn have some advantages in the power lines environment especially in case of relatively long impulsive disturbances. Unfortunately, in particular Circ Wav-OFDM has also a high level of sensitivity to a colored noise what results in low performance when the noise is below certain level. Non-prefixed Wavelet-OFDM, despite it simplified equalization, seems to provide promising results being resistant to both colored noise and impulsive disturbances.

Future research will be focused on testing different Wavelets-OFDM modulators together with advanced forward errors correction methods. Such tests will definitely approves or deny usefulness of these signaling methods to power line or any other harsh communication environments.

References

[1] E. Biglieri, S. Galli, Y.H. Lee, H.V. Poor and A.J. Han Vick, "Guest editorial power line communications", *IEEE Journal on Sel. Areas in Comm.*, vol. 24, pp. 1261–1264, July 2006 (special issue on PLC).

[2] S. Galli, H. Koga and N. Kodama, "Advanced signal processing for PLCs: Wavelet-OFDM", Proc. IEEE ISPLC2008, pp. 187-192, April 2008.

[3] N. Pavlidou, A.J. Han Vinck, J. Yazdani and B. Honary, "Power line communications: State of the art and future trends", *IEEE Comm. Mag.*, vol. 41, pp. 34–40, April 2003.

[4] J. Abad, L. M. Torres, and J. C. Riveiro, "OFDM and wavelets performance comparison in power line channels", Proc. IEEE ISPLC2005, pp. 341–345, April 2005.

[5] K. Izumi, D. Umehara and S. Denno, "Performance evaluation of Wavelet OFDM Using ASCET", Proc. IEEE ISPLC2007, pp. 246-251, March 2007.

[6] Zbydniewski L., Zielinski T.P. Turcza P., "Influence of Time-Frequency Tiling on BER Performance in Discrete Wavelet Multitone Power Line Transmission", Proc. IEEE ISPLC2009, Dresden, 29 Mar – 1 Apr 2009.

[7] P. Turcza, L. Zbydniewski and T. Zielinski, "Circular real sine/cosine Gabor transform modulator for Power Line Communication", 50th IEEE Global Telecomm. Conf. GLOBECOM-2007, Washington, 26-30 Nov. 2007.

[8] P. Turcza, "New TMUX for xDSL based on linear phase modulated filter banks", Proc. European Signal Processing Conference EUSIPCO'04, pp. 1935-1938, Vienna 2004.

[9] Galli, S. Logvinov, O., "Recent Developments in the Standardization of Power Line Communications within the IEEE", *IEEE Comm. Mag.*, vol. 46, pp. 64-71, July 2008.

[10] S.D. Sandberg, M. A Tzannes, "Overlapped discrete multitone modulation for high speed copper wire communications", *IEEE J. on Sel. Areas in Comm.*, vol. 13, no. 9. pp. 1571-1585, Dec. 1995.

[11] H. S. Malvar, *Signal Processing with Lapped Transforms*. Norwood, Artech House, 1992

[12] T. Ihalainen, T. H. Stitz, M. Rinne and M. Renfors, "Channel equalization in filter bank based multicarrier modulation for wireless communications", *EURASIP Journal of Applied Signal Processing*, Vol. 2007, ID 49389, 18 pages.

[13] M. Babic, M. Hagenau, K. Dostert, and J. Bausch, "Theoretical postulation of PLC channel model", IST Integrated Project Deliverable D4v2. 0, The OPERA Consortium, March 2005.