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High performance binary LDPC-coded OFDM systems over indoor PLC channels

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ABSTRACT

Power line communication (PLC) technology is actually among the most renowned technologies for home environments due to their low-cost installation opportunities. In this study, the bit error rate (BER) performances of binary low-density parity check (LDPC) coded orthogonal frequency-division multiplexing (OFDM) systems have been considered over indoor PLC channels. Performances comparison of diverse soft and hard decision LDPC decoder schemes such as Min-Sum (MS), weighted bit flipping (WBF), gradient descent bit-flip (GDBF), noisy gradient descent bit-flip (NGDBF) and its few variants including the single-bit NGDBF (S-NGDBF), multi-bit NGDBF (M-NGDBF) and smoothed-multi-bit NGDBF (SM-NGDBF) decoders were examined in the modeled network. To evaluate the BER performance analyses three different PLC channel scenarios were generated by using new and more realistic PLC channel model proposal were also employed. All of the simulations performed in Canete's PLC channel model showed that remarkable performance improvement can be achieved by using short-length LDPC codes. Especially, the improvements are striking when the MS or SM-NGDBF decoding algorithms are employed on the receiver side.

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1. INTRODUCTION

Nowadays, power line communication (PLC) methods have greatly gained much interest in the field of communication and smart grid systems [1]. This kind of technology have being widely developed and assumed an exceptionally promising solution not only for home networking but also for high-speed Internet access and home network applications [2]. Up to now, the characteristics of PLC channel are intensively being examined and various PLC channel models have been presented by researchers in the literature. First channel model was presented by Hensen and Schulz [3] where they showed that channel attenuation can simply increased with frequency. After Hensen's model, a new model that also considers the effect of multipath was presented by Phillips [4]. Afterwards, an extended version of PLC channel model was also described by Zimmerman and Dostert. Later, a novel and more realistic PLC channel model was proposed by Canete. the results reported in [5], [6] showed that the PLC channel can be defined more accurately by using Canete's model [7].

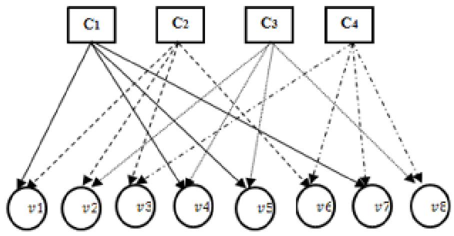
Low density parity check (LDPC) codes, also known as Gallager codes are considered among the types of linear block codes, first proposed by Gallager [8], [9]. The LDPC codes are regarded as a candidate scheme for the narrowband PLC when the short data blocks are transmitted in various communication channels, such as wireless indoor channels, acoustic channels, and power line channels [10], [11]. In this context we have regarded to use a novel and more realistic model as indoor PLC channels to evaluate the performance results of LDPC coded orthogonal frequency-division multiplexing (OFDM) system in terms of bit error rate (BER). The effect of impulsive and background noises is taken account in the modeled system. In this paper the BER performances of different variants of bit flipping algorithms used for decoding of LDPC code are compared.

The paper is organized as follows: section 'LDPC codes and decoding algorithms' describes the encoding and decoding of binary LDPC codes, while the PLC channel model and noise models used are analyzed in section 'channel and noise presentation'. The simulation results are examined in section 'simulation results', and finally, conclusions are shown in section 'conclusion'.

2. LDPC ENCODING

LDPC codes are considered as an important family of error-correction codes that has received much attention in wireless communication systems because of its excellent performance in error correction [12], [13]. LDPC codes are defined using by a parity-check matrix H. The parity-check matrix H contains mostly zeros (0s) and a few numbers of one (1s) element. A typical parity-check H matrix for a (8,4) regular LDPC code with w_c=2 and w_r=4 is given in the (1).

An LDPC code can be also presented by a bipartite graph called Tanner graph [14] which contains *n∈{1….N}* called variable nodes and *m∈{1…..M}* called check nodes. We denote by *N(m)* the set of variable nodes n connected to a certain check node m. A variable node n is related to the check node m if *n∈N(m).* Furthermore, the set *N(m)\n* denotes the set of variable nodes linked to the check node m excluding n. Similarly, the set of check nodes related to a certain variable node n is denoted by *M(n).* A check node m is connected to the variable node n if *m∈M(n).* The set *M(n)\m* denotes the ensemble of check nodes linked to the variable node n excluding m. A Tanner graph for (1) is shown in Figure 1.



$$\longleftrightarrow \quad H = \begin{bmatrix} 1 & 0 & 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 \end{bmatrix}$$

Figure 1. Tanner graph representation for (8, 4) regular LDPC code

3. LDPC DECODING PROCESS

The decoding process of LDPC codes can be implemented using either soft or hard decision decoders [15]. The BF algorithm is a hard decision for decoding on the binary symmetric channel (BSC) introduced by Gallager. The BF algorithm has exceptionally low complexity since it only requires a summation over binary parity-check values for each symbol at each iteration; nevertheless, the BFA provides weak decoding performance. Up to now, various studies have been evaluated to improve the performance of the BF decoder and its modified variants, such as the weighted bit flipping (WBF), gradient descent bit-flip (GDBF), noisy gradient descent bit-flip (NGDBF) and (single/multi) NGDBF algorithms.

In the following, it is assumed that binary codeword $\mathrm{C} = [\mathrm{c}_1, \mathrm{c}_2, \ldots.., \mathrm{c}_\mathrm{n}]$ which is associated with matrix H is defined by C={$\boldsymbol{c}.F_2^n$: $H\boldsymbol{c}$ = 0} where F_2denotes the binary Galois field. Before the transmission, the codeword C is modulated using Binary phase shift key (BPSK) modulation. After modulation the codeword $\hat{\mathrm{C}}$ is given by $\hat{\mathrm{C}} = \{(1-2\mathrm{c}_1), (1-2\mathrm{c}_2), \ldots..(1-2\mathrm{c}_\mathrm{n})\}$. Later the codeword $\hat{\mathrm{C}}$ is transmitted over an Additive White Gaussian noise (AWGN) channel. The received value corresponding to $\hat{\mathrm{C}}$ after the demodulator is defined by $\mathrm{r}_\mathrm{n} = \mathrm{c}_\mathrm{n} + \mathrm{n}_\mathrm{n}$; where n_n is a random variable with a zero mean and variance of $\mathrm{N}_0/2$ [16]. Let N(i) be the parity check neighborhood presented as N(i)={j€[1,n]:hij=1}for i=1,2,…m and M(n) be the symbol neighborhood defined as M(n)={i€[1,m]:hij=1}for j=1,2,…,n where hij is the ij element of parity check matrix. Using these notation the parity check condition is expressed as $\mathrm{S_j}=\prod_{j\epsilon N(i)} x_j$, where the value of $\mathrm{S_j}$€ (+1,-1) is called as $\mathrm{j^{th}}$ bipolar syndrome component of x.

3.1. Weighted bit flipping (WBF) algorithm

The WBF algorithm is a single bit flipping algorithm introduced by Kou *et al* [17]. It improves performance over the BFA by incorporating soft channel information, making it better suitable for use on the Additive White Gaussian Noise (AWGN) channel and other soft-information channels [18]. In this algorithm only one bit is flipped at each iteration, the flipped bit depends on inversion function value of WBF [19] which is given by:

$$\Delta k^{WBF}(x) \triangleq \sum_{i\epsilon M(n)} \beta_i \prod_{j\epsilon N(i)} x_j \quad (2)$$

where $\beta_i \triangleq min_{j\epsilon N(i)} abs(\mathrm{r_j})$ represents the reliability of bipolar syndrome. In this case, the inversion function $\Delta_k{}^{WBF}(x)$ gives the measure of invalidness of symbol assignment of x_k, which is given by the sum of the weighted bipolar syndromes. The bit with lower inversion function value will be flipped.

3.2. Improved modified (IMWBF) algorithm

The inversion function of IMWBF is same as that of WBF except that in the first term in the equation tells about interior bit based message and the second term in the equation give information about only check based message, it comes from check constraints. A weighting factor α is considered for bit message because for different code with different column weight or for different values of SNR the weight of bit message should not be same. The optimal choice of the weighting factor α is positive real and can be determined through the Monte Carlo simulations. The inversion function of IMWBF is given by:

$$\Delta k^{IMWBF} \triangleq \alpha * abs(r_j) - \sum_{i\epsilon M(n)} \beta_i \prod_{j\epsilon N(i)} x_j \quad (3)$$

3.3. Gradient descent bit flipping (GDBF) algorithm

The IMWBF algorithm give good performance but is not closer to min sum algorithm and requires a substantial increase in complexity compared to the original WBF. Therefore, in order to enhance the BER performance of MWBF and reduce the arithmetic complexity of bit-flipping algorithms, Wadayama *et al*. [20] conceived the GDBF algorithm as a gradient-descent optimization model for the ML decoding problem which can obtain an improved performance with a slight increase in complexity. In GDBF algorithm majority logic decoding is used to optimize the gradient descent model. Based on this method the derived objective function is given as follows:

$$f(x) \triangleq \sum_{i=1}^{n} x_j r_j + \sum_{i=1}^{m} \prod_{j\in N(i)} x_j \quad (4)$$

The first part in objective function gives the information about the correlation between bipolar codeword and received codeword, it should be maximized. The second term represents the summation of bipolar syndrome of x. If and only if $x \in C$, (x) reaches the maximum value with $\sum_{i=1}^{m} \prod_{j\in N(i)} x_j = M$. The Inversion function for GDBF is given by maximizing $f(x)$. Maximizing is obtained by taking partial derivative of $f(x)$ with respect to x_k and multiplying this derivative withx_k. Therefore, the inversion function for GDBF can be expressed by:

$$\Delta k^{GDBF} \triangleq x_k r_k + \sum_{i\epsilon M(k)} \beta_i \prod_{j\epsilon N(i)} x_j \quad (5)$$

3.4. Noisy gradient descent bit flipping (NGDBF) algorithm

The purpose of the GDBF algorithm is to reach the maximum value for the function to be optimized (x), if there are cycles in the parity matrix H, there is a local maximum phenomenon that appears. The performance of GDBF algorithm is increased by escaping from the local maxima, but it leads to increase in complexity. Therefore, the complexity can be decreased by adding a pseudo-random perturbation in the inversion function at each symbol node at each iteration. This produce a new algorithm called noisy GDBF [21]. At each iteration of the NGDBF algorithm, the inversion function of single-bit N-GDBF can be calculated according to:

$$\Delta k^{NGDBF} \triangleq x_k r_k + \omega \sum_{i\epsilon M(k)} S_i + q_i \quad (6)$$

where the parameter ω represents syndrome weighting parameter to scale the sum of the parity check operations, and q_i represents the random Gaussian distribution noise samples with zero mean and variance equal to $\sigma^2 = {}^{\eta^2 N_0}/_2$ where $0 < \eta < 1$; proportional to the variance of the channel noise. The optimal value of ω

and η are code independent and in other cases found to be faintly SNR dependent. It is single bit flipping algorithm then only one bit is flipped at each iteration. For the algorithm used is same as that of BF algorithm with only inversion function is replaced by (7).

In M-NGDBF algorithm instead of switching method threshold adaptation method is used. The convergence of multi bit flipping algorithm can be enhanced by using adaptation parameter θ. Due to this increased performance and decreased number of iterations the algorithm for M-NGDBF can be obtained by changing the following steps in BF algorithm.

Step 0: Initialization: For all $j \in \{1,2,\ldots,\mathrm{n}\}$, let $x_j = sign\left(r_j\right)$ let $x \triangleq (x_1, x_2, \ldots x_n)$,

and $\lambda_k = \lambda_0$ for all $k \in \{1,2,\ldots,\mathrm{n}\}$

Step 1: Compute syndrome components

$$S_i = \prod_{j\in N(i)} x_j \tag{7}$$

For all $i \in \{1,2,\ldots,\mathrm{m}\}$; If $S_i + 1$ for all i, output x and then exit.

Step 2: Compute inversion fonctions:

$$\Delta k^{NGDBF} \triangleq x_k r_k + \omega \sum_{i\epsilon M(k)} S_i + q_i \text{ for } k \in \{1,2,\ldots,\mathrm{n}\} \tag{8}$$

Step 3: Bit-flip operations:

If $\Delta k^{\ NGDBF} < \lambda_k \ (k \in [1,\mathrm{n}])$

Flip bit x_k

Otherwise $\lambda_k = \theta.\lambda_k$

In this algorithm two parameter is employed θ and λ, λ_k $(k \in [1,\mathrm{n}])$ be a negative threshold value associated with each received bit. In order to modify λ_k a constant scaling factor is used θ Є [0, 1].

Due to its dependence on single bit messages and pseudo-random noise, the NGDBF algorithms resemble slightly to the family of stochastic iterative decoders that were first introduced by Gaudet and Rapley [22], [23] and developed after that with several researchers. Due to immoderate flipping of low confidence symbol convergence failure occur in M-NGDBF algorithm [24]. To avoid this up and down counter is used at output of everyx_k. The counter is initialized to zero at start of decoding. After each decoding iteration the counter is updated using the equation:

$$X_k(t+1) = X_k(t) + x_k(t) \tag{9}$$

This equation involves that the counter consist of running sum X_k for each output decision. If all parity check condition is satisfied before the completed maximum number of iterations, then output the x_k directly. If output is not decoded even after the maximum number of iterations, then smoothen the decision $x_k = sign\ X_k$.

4. CHANNEL AND NOISE REPRESENTATION

4.1. Channel model

In this we have adopted the PLC channel model proposed by Canete, this model can generate more realistic indoor channel scenarios since it considers the practical network structure of home and offices to create the channel scenarios. Figure 2 illustrate the simplified network layout used adopted to describe the PLC channel model. As can be seen, this model comprises seven line sections $L_i(i \in \{1,2,3,4\})$, $S_i(i \in \{1,2,3,\})$, and five terminal units (sockets) $Z_i(i \in \{1,2,3,\})$, transmitter and receiver structures in terms of the impedance loads are depicted as Z_G and Z_L respectively. From the principal path between transmitter and receiver, three stubs or "bridged taps" are diffused, each stub contain impedance. While the load impedances connected to the grid are illustrated with Z_1, Z_2 and Z_3. This configuration has been selected among others under the premise of being as simple as possible, but also offering a reasonable fit to the actual channel behavior.

From this structure, transmission line parameters such as resistance (R), inductance (L), conductance (G), capacitance (C), propagation constant (c), and characteristic impedance (Z_c) can be derived to define the transfer function of the PLC channel model. The mathematical relation between the transmitter and the receiver can be acquired by using a two-port network and ABCD matrix theory. In order to achieve this, characteristic impedance Z_c and propagation constant (γ) can be firstly calculated as follows:

$$\gamma = \sqrt{(R+j\omega L)(G+j\omega L)} \tag{10}$$

$$Z_c = \sqrt{\frac{R+j\omega L}{G+j\omega C}} \tag{11}$$

ABCD parameters of the simplified indoor PLC channel model can be analytically obtained by using (10) and (11) as follows:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh\ (\gamma l) & Z_c \sinh(\gamma l) \\ \frac{1}{Z_c}\sinh(\gamma l) & \cosh\ (\gamma l) \end{bmatrix} \tag{12}$$

where ω and l present the angular frequency and cable length, respectively. Finally, transfer function of the indoor network with respect to the ABCD parameters is given as

$$H = \frac{Z_C}{AZ_C+B+CZ_CZ_G+DZ_G} \tag{13}$$

The channel transfer functions of different channel scenarios generated between 0 Hz to 30 MHz according to the channel model already mentioned are illustrated in Figure 3. The created channel scenarios can be regarded as: Channel case #1 is the best-case, Channel case #2 is medium-case and Channel case #3 is the worst communication environment for the PLC applications according to attenuation values.

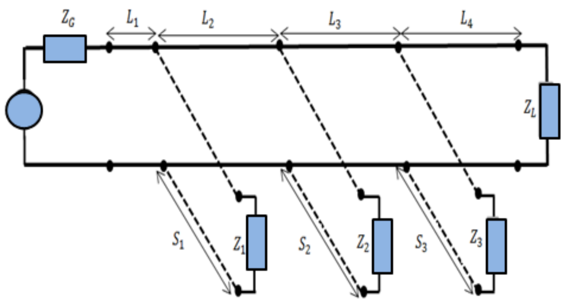


Figure 2. Simplified structure of PLC network used in bottom-up channel modeling

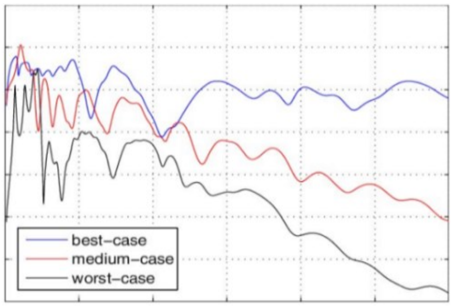


Figure 3. Amplitude responses of the indoor PLC channel scenarios

4.2. Noise model

In the literature, Middleton's Class A noise model [25] was introduced into a statistical model of impulsive noise environment, which is composed of sum of Gaussian noise and impulsive noise. The PDF of the noise amplitude z is as follows [26], [27]:

$$\mathrm{P(z)} = \sum_{m=0}^{\infty} \frac{e^{-A}A^m}{m} \cdot \frac{e^{-(z^2/2\sigma_m^2)}}{\sqrt{2\pi\sigma_m}} \tag{14}$$

where $\sigma_m{}^2 = \sigma^2 . \frac{(m/A)+\Gamma}{1+\Gamma}$ (15)

where A is the impulsive index; $\Gamma = \sigma_G{}^2/\sigma_i{}^2$ [28] is the GIR (Gaussian-to-impulsive noise power ratio) with Gaussian noise power $\sigma_G{}^2$ and impulsive noise power $\sigma_i{}^2$, and $\sigma^2 = \sigma_G{}^2 + \sigma_i{}^2$.

In this work we assume that the impulse burst amplitude is such that results in a power of impulsive noise NI= 10·N0, with N0 the power of the background noise. It follows that the received signal can be written as:

$$y(t) = x(t) * h(t) + n_i(t) + n_B(t) \tag{16}$$

where $n_i(t)$ is the impulsive noise and $n_B(t)$ is the background which is considered to be AWGN with zero mean and variance *N0*.

5. SIMULATION RESULTS

In this section we present simulation results to show the BER performances for a binary LDPC coded PLC-OFDM system. The simulations are carried out for different channel conditions to investigate the high potential of the LDPC coded communication over the indoor PLC channels with (1008, 504) code length. The soft and hard decision decoders are employed in all the simulations to compare their performances over the indoor PLC channels. Parameters of computer simulations performed in this work are given in Table 1.

Table 1. Simulation parameters used to obtain BER performances

Parameters	Values
Sizes of parity check matrix	(1008, 504)
LDPC code rate	0. 3
LDPC decoder schemes	MS, WBF, GDBF, NGDBF, SNGDBF, MNGDBF, SMNGDBF
Maximum iteration number	25
Modulation type	OFDM
Cyclic prefix length	0.53
Channel model	PLC channel model (Canete model)
Noise types	Background and Impulsive noise

Figure 4 shows the performance results of the LDPC coded OFDM system in terms of BER versus Eb/N0 value in the PLC channel. As we can see the figure illustrates the performance comparisons between BER curves for WBF, GDBF, NGDBF, SNGDBF, MNGDBF (θ=0.9, λ0=-0.9) and SM-NGDBF decoding algorithms for the maximum number of iterations L_{max}, and for the best-case channel condition mentioned before. It is clearly observed that the MS decoder outperforms other hard decision. The BER performance of SM-NGDBF is very close to MS algorithm and its improvement is nearly about 8.2 dB than that of the uncoded case at a BER level of 10^{-3}. The SNGDBF and the MNGDBF decoders offer also high performance as well as the MS decoder and the improvements achieved by using these hard decision decoders are nearly 7.51 dB and 7.52 dB for a BER of 10^{-3} respectively.

Figure 5 depicts the BER performance comparisons of the coded and uncoded systems over indoor PLC channel medium case. From the figure it is observed that the MS decoder provide almost 10.2 dB improvement in the level of 10^{-2}. For the performance of the hard decision decoders, it is clearly seen that the SM-NGDBF decoder outperforms nearly 0.45 dB and 0.9 dB than that of the M-NGDBF and S-NGDBF respectively in the level of 10^{-2}, and it offer 8.9 dB amelioration compared to uncoded case. The WBF decoder presents the worst BER performance when compared to the other LDPC decoders. Even so, the performance of the WBF decoder is 8 dB better than that of the uncoded case at a BER level of 10^{-2}.

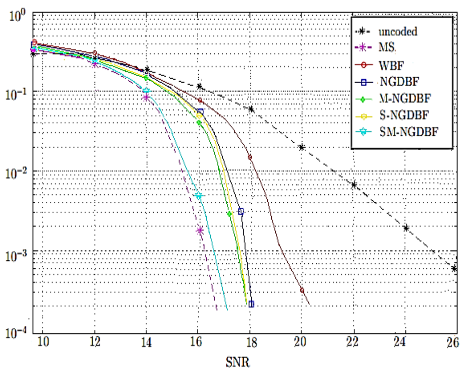


Figure 4. The performance of the $1/3$ LDPC codes with different decoders over PLC channel in best case

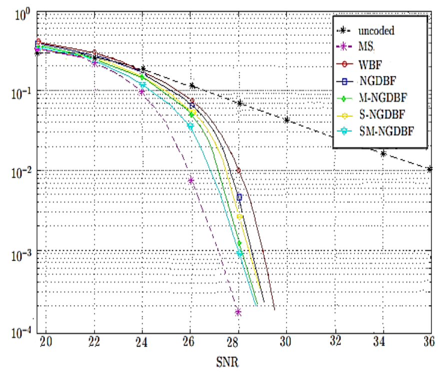


Figure 5. The performance of the $1/3$ LDPC codes with different decoders over PLC channel in medium case

The analysis for the NB PLC channel in worst case and the performance curves obtained for this case are depicted in Figure 6. As expected, all of the decoders are adversely affected by the channel condition and the low BER values of the LDPC coded systems. It is observed that the MS decoder provide almost 9.8 dB improvement in the level of 10^{-1}. For the performance of the hard decision decoders, it is clearly seen that the SM-NGDBF decoder outperforms nearly 9.2 dB than that of the uncoded case and offer 1.2 dB improvements when compared to WBF decoder in the level of 10^{-1}. When the simulation results obtained are compared, it is shown that MS decoder which is a soft decision decoder offered best performance for all channel scenarios; nevertheless, they require high decoding complexity and complicate their implementation in practical applications.

The Figure 7 was performed to describe the comparative performance curves of WBF, GDBF, NGDBF, M-NGDBF, S-NGDBF and SM-NGDBF with traditional MS when the maximum iteration numbers are set to 100 and 5, respectively. It is clearly seen that the BER fastly goes down with increasing SNR, which is known as the cascade region of the graph, followed by saturation in the improvement where the BER no longer goes down with increasing SNR. The most improved results were obtained with T=5. The SM-NGDBF is found to show a coding gain approaching 1 dB in the level of 10^{-2}.compared to NGDBF for the same value of T. The results show also a gain of 1 dB in the level of 10^{-3} for NGDBF compared to GDBF with a maximum of only five iterations.

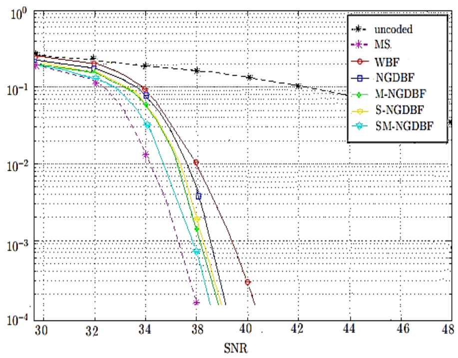


Figure 6. The performance of the $1/3$ LDPC codes with different decoders over PLC channel in worst case

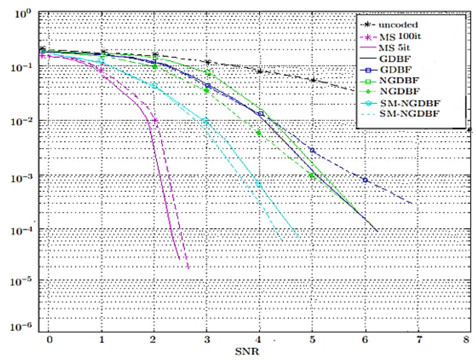


Figure 7. Comparative performance of GDBF, NGDBF, M-NGDBF, S-NGDBF and SM-NGDBF with traditional Min-Sum (MS) with 5 and 100 iterations, WBF algorithms

6. CONCLUSION

This study focused on the performances of the binary LDPC-coded OFDM systems employed over the indoor PLC channels in terms of BER by considering three different NB-PLC channel scenarios in home networks. The system model was analyzed for various decoding rules by means of comparative computer simulations. The simulations are carried out for different channel conditions to investigate the high potential of the LDPC coded communication system versus uncoded systems. It is clearly seen that the decoding operation of coded case performed with the MS algorithm owing to its efficient and robust features and it outperforms other hard decision decoders for all simulations. The performed simulations in the PLC channels showed that the LDPC codes can provide significant performance improvement with an acceptable encoding complexity when the S-NGDBF, M-NGDBF and SM-NGDBF decoders are utilized on the receiver unit. In order to confirm robust performance of the SM-NGDBF algorithm, it was compared by other LDPC decoders yielding the results shown in Figures 5-7. These results confirm that SM-NGDBF achieves significant performance benefit in comparison to the best-known versions of GDBF.

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