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Non-binary codes approach on the performance of short-packet full-duplex transmissions

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ABSTRACT

This paper illustrates the enhancement of the performance of short-packet full-duplex (FD) transmission by taking the approach of non-binary low density parity check (NB-LDPC) codes over higher Galois field. For the purpose of reducing the impacts of self-interference (SI), high order of modulation, complexity, and latency decoder, a blind feedback process composed of channels estimation and decoding algorithm is implemented. In particular, this method uses an iterative process to simultaneously suppress SI component of FD transmission, estimate intended channel, and decode messages. The results indicate that the proposed technique provides a better solution than both the NB-LDPC without feedback and the binary LDPC feedback algorithms. Indeed, it can significantly improve the performance of overall system in two important factors, which are bit-error-rate (BER) and mean square error (MSE), especially in high order of modulation. The suggested algorithm also shows a robustness in reliability and power consumption for both short-packet FD transmissions and high order modulation communications.

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1. INTRODUCTION

During the age of advanced wireless communications such as 5G and beyond, in conjunction with internet of things (IoT) applications, one of the main goals is to facilitate communication among massive connections of new devices and empower them to make decisions autonomously. This is achieved through the utilization of a range of technologies and interconnection of a vast number of devices [1]–[3]. The primary focus encompasses two key services: ultra-reliable low latency communication (uRLLC) and massive machine-type communication (mMTC) [4]. Moreover, it is certain that the fast development of wireless and mobile communication leads to the requirement of spectrum efficiency and high data rates [5], [6]. Consequently, an efficient spectrum sharing technique called full-duplex (FD) transmission has been proposed [5], [7] by using the time-frequency resource at the same time for transmission and reception. Due to the efficient usage of resource and outstanding performance compared with traditional methods, FD transmission has many applications to the modern transmission networks, not only for data transmission but also for security maintenance [8]–[11]. However, the influence of self-interference (SI) should be carefully and fully suppressed as much as possible to achieve the best performance of FD transmission, especially in short-packet FD transmission and IoT applications.

Since 2018, the third generation partnership project (3GPP) has introduced the quasi-cyclic low density parity check (QC-LDPC) as the standard codes of 5G new radio (NR) [12]–[14] because of their higher error correction performance and powerful decoding. However, the traditional binary LDPC codes have a drawback in high order of modulation such as 16-QAM or 64-QAM [15]. Therefore, an extended version of LDPC codes, which works over higher Galois field $GF(M)$ where $M > 2$, has been proposed and called as non-binary low density parity check (NB-LDPC) codes [16]. It has been proved by many researches that NB-LDPC outperforms their binary counterpart in the case of short code length and higher order of modulation [17], [18]. In the present era, NB-LDPC codes are increasingly seen as a promising coding method for mMTC devices within 5G networks or sensors used in IoT applications that handle limited data transmission [19]. However, it is important to address and mitigate the issue of excessive complexity and latency during the decoding process. Therefore, in this article, to reduce the impacts of SI component, high order of modulation as well as complexity and latency of decoding process, a NB-LDPC blind feedback process combining channel estimations and decoding algorithm is proposed and implemented. In particular, this algorithm uses an iterative process to simultaneously suppress SI component of FD transmission, estimate intended channel and decode intended messages.

This paper's contributions can be summarized as follows. First, we demonstrate that the proposed technique provides a better solution than the traditional NB-LDPC without using a feedback algorithm. Second, we show that the proposed technique is less sensitive to the increase of high order of modulation compared to binary LDPC blind and semi-blind feedback methods. Last but not least, we emphasize that the suggested algorithm also shows robustness in reliability and power consumption for both short-packet FD transmissions and high order modulation communications. The remaining of this article is organized as follows. Section 2 briefly describes the system models of traditional NB-LDPC codes FD transmission without feedback and the proposed NB-LDPC blind feedback. Section 3 shows numerical results and discussions. Finally, the conclusions will be highlighted in Section 4.

2. SYSTEM MODEL AND PROPOSED METHOD

2.1. Traditional NB-LDPC codes FD transmission without feedback model

Let us consider a short-packet FD transmission between Alice and Bob as shown in Figure 1, we shortly call them as A and B, respectively. Two antennas are equipped at the transceiver of B for simultaneously transmitting and receiving messages in FD operation. Assuming that NB-LDPC codes [12] are used at transceivers of A and B. We further make an assumption that the intended channel gains between A and B is h_{AB} and the SI channel gains at B is h_{BB}. Both channels are independent and identically distributed complex random variables with $\mathcal{CN}(0, 1)$. Normally, two components such as line-of-sight (LoS) and non-line of sight (NLoS) are available on the SI channel of FD transmissions. By the implementation of passive and analog suppression techniques, it becomes possible to substantially reduce the impact of LoS component, while also keep the influence of reflections, as demonstrated in [20], [21]. Consequently, this results in a reason to model SI channel as Rayleigh fading in the digital domain.

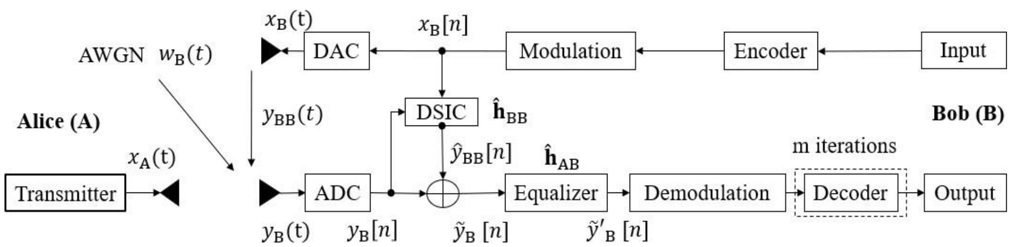

Figure 1. Traditional NB-LDPC codes FD transmission without feedback model

Moreover, we also assume that the NB-LDPC encoding processes are the same at transmitter of A and B as symmetric properties. Indeed, the binary input message with length K in $GF(2)$ will be converted into $GF(M)$ as [17], where M is the order of M-PSK modulator, and then encoded by NB-LDPC codes over $GF(M)$. After that, the codeword will be modulated by M-PSK modulation process to form the transmitted signal $x_B[n]$ before passing to the digital-to-analog conversion (DAC) process to obtain the continuous time signal $x_B(t)$. Without loss of generality by by-passing the distances between A and B and also the pair of antennas at B, the received signal at B can be given by:

$$y_B(t) = y_{BB}(t) + y_{AB}(t) + w_B(t) = (h_{BB} * x_B)(t) + (h_{AB} * x_A)(t) + w_B(t), \quad (1)$$

where $w_B(t)$ is the complex Gaussian background noise at B with $\mathcal{CN}(0, \sigma_B^2)$. Furthermore, let us denote $\rho_{BB} = p_B/\sigma_B^2$ as self-interference to noise ratio given by the SI channel at B and $SNR = p_A/\sigma_B^2$ as the signal to noise ratio (SNR) at B, where p_A, p_B are the transmitted power of A and B, respectively.

At the receiver of B, the signal $y_B(t)$ will go to the ADC process to convert back to a discrete time domain signal, $y_B[n]$. Here, the residual quantization noise error can be suppressed by assuming that the and digital-to-analog conversion/analog-to-digital conversion (DAC/ADC) processes at transceiver have enough bit resolution and voltage dynamic range, which has been studied in [22]. The other hardware impairments and synchronization problems are also not indicated in this paper. An adaptive filter using the recursive least square (RLS) algorithm with the forgetting factor $\lambda = 0.999$ is then applied to estimate SI channel $\hat{h}_{BB}$, we call digital self-interference cancellation (DSIC) process. Since B knows its transmitted signal $x_B[n]$, this value can be used to eliminate the SI component to obtain:

$$\tilde{y}_B[n] = y_B[n] - \hat{y}_{BB}[n] = y_B[n] - (\hat{h}_{BB} * x_B)[n]. \tag{2}$$

Then, at the equalizer process, the recursive least square-constant modulus algorithm (RLS-CMA) blind method [23] is used to estimate intended channel $\hat{h}_{AB}$ and obtain equalized signal $\tilde{y}'_B[n]$. After that, this signal will go to demodulation and decoding processes and convert back from $GF(M)$ to $GF(2)$ to achieve the binary output. In the decoding process, the sum of product algorithm (SPA) in log domain is performed based on the LLR belief sequence received from the M-PSK demodulation process, as studied in [24], [25]. For this model, we shortly call it as *"NB-LDPC without feedback"*.

2.2. Proposed NB-LDPC blind feedback model

NB-LDPC codes still remain a high complexity of decoder, although they give a robust performance compared to the conventional turbo-codes and binary LDPC codes, especially in high order modulation as indicated in [26]. Hence, it is not a possible option for transmitting short-packet FD transmission, as it fails to obtain the required level of accuracy in estimating SI channel. As a result, a NB-LDPC iterative process to simultaneously suppress SI component, estimate intended channel and decode messages is proposed, called as *"NB-LDPC blind feedback"* method. The flowchart of this method at the receiver of B is shown in Figure 2, and it contains three basic stages as follows:

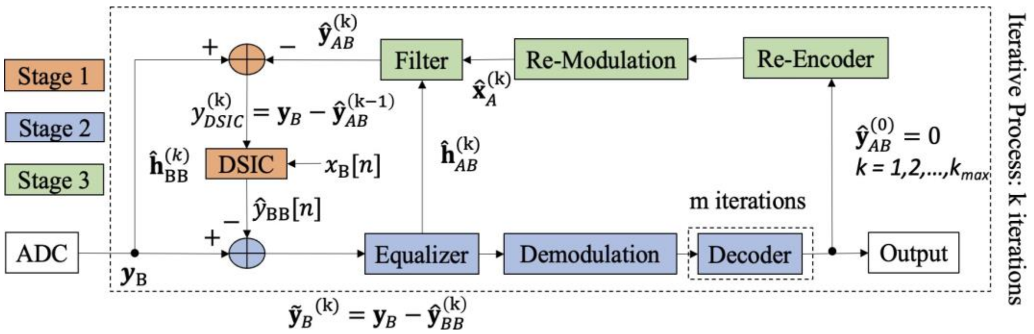

Figure 2. Proposed NB-LDPC blind feedback model

Stage 1: First of all, the received signal y_B is subtracted by an estimated intended signal $\hat{y}_{AB}$, where the initial value $\hat{y}_{AB}^{(0)} = 0$ due to an unknown message from A. Then, according to the reference signal x_B, the SI channel $\hat{h}_{BB}$ is first estimated, and then the SI component $\hat{y}_{BB}$ is suppressed. Hence, the residual signal $\tilde{y}_B$ is obtained as a result of this operation;

Stage 2: A RLS-CMA equalizer is used to approximate the intended channel $\hat{h}_{AB}$ and produce the equalized signal. The belief sequence is then obtained by the demodulation process and the SPA algorithm with only one iteration ($m_{max} = 1$) is used to temporarily decode the intended message from A.

Stage 3: When the iterative process does not complete the maximum number of iterative process (k_{max}), a temporary feedback loop is formed to obtain the intended feedback signal $\hat{y}_{AB}$. Indeed, the temporary obtained message in stage 2 is continually re-encoded, re-modulated and filtered with the estimated intended channel $\hat{h}_{AB}$ that obtained in stage 2. The SI channel estimate process can then be optimized in the following joint iteration by subtracting the feedback signal from the received signal.

3. RESULTS AND DISCUSSION

In this section, the mean square error (MSE) and bit-error-rate (BER) performances on different orders of M-PSK modulator are implemented using Monte Carlo simulations on MATLAB. A comparison with the LDPC blind feedback [27] and the LDPC semi-blind feedback [28] is also indicated. Based on the Rayleigh distribution, the SI and intended channels are generated independently in each transmission packet and are fixed with three taps and four taps, respectively, and the fading coefficients follow the ITU Radiocommunication Sector (ITU-R) channel model [29]. NB-LDPC codes are used with the code rate R =1/2 as a particular example to illustrate the performance of our proposed algorithm and 10^6 is the total transmission frames. Moreover, in this section, it is necessary to determine a lower bound as a benchmark for assessing the robustness of the NB-LDPC feedback method in relation to the MSE and BER performances. In particular, for the MSE performance, we assume that all of the transmission message symbols from A are known at B, the system then performs the SI channel estimation at stage 1 and only perform the equalization process at stage 2 to get the estimated intended channel $\hat{h}_{AB}$l. At stage 3, the known symbols from A will be used for re-encode and re-modulation processes then they will be performed a filter process with the estimated intended channel to obtain the intended signal $\hat{y}_{AB}$ and finally carry out subtraction in the incoming iterations. For the BER performance, the previously ideal estimation of SI channel and intended channel is used to perform SI cancellation and SPA decoding processes with one iteration ($m_{max} = 1$). We shortly call this assumption as *"Ideal Case"*.

3.1. MSE performances

The MSE of the SI channel and the intended channel are respectively given by (3) and (4) [30].

$$MSE_{BB} = \left|h_{BB} - \hat{h}_{BB}\right|^2, \tag{3}$$

$$MSE_{AB} = \left|h_{AB} - \hat{h}_{AB}\right|^2. \tag{4}$$

Figure 3 and Figure 4 show the MSE performances of SI channel and intended channel versus SNR (dB) for different orders of M-PSK modulator, respectively. It can be clearly observed that the SNR increases will lead to the MSE decreases on both SI channel (MSE_{BB}) and intended channel (MSE_{AB}). The results illustrate that the NB-LDPC blind feedback method approximately reaches to the lower bound (the Ideal Case) at all regions of SNR, regardless of the order of M-PSK modulation. It can also be seen that the proposed NB-LDPC blind feedback method has a better performance than the LDPC blind feedback scheme studied in [27], especially for high order of modulation. In particular, for 8-PSK and 16-PSK, the NB-LDPC feedback curves converge quickly to saturation error floor, i.e. 10^{-5} (for 8-PSK) or 10^{-3} (for 16-PSK) at $SNR = 30$ dB, while the LDPC blind feedback curves require more SNR to obtain those values.

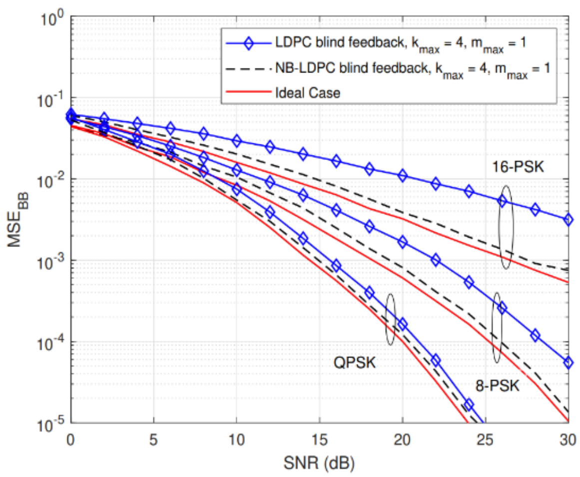

Figure 3. MSE performances of SI channel, $\rho_{BB} = 30\ dB, K = 132$ symbols

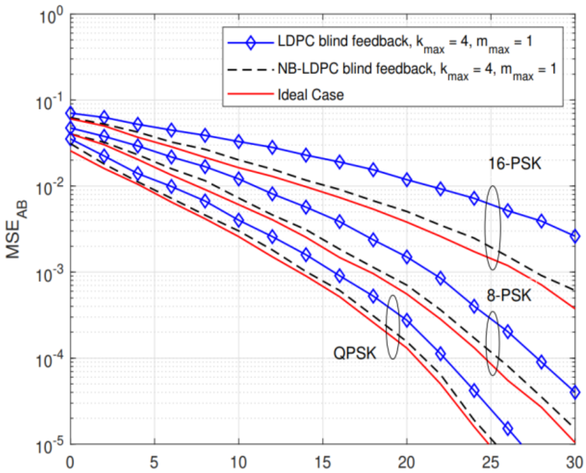

Figure 4. MSE performances of intended channel, $\rho_{BB} = 30\ dB, K = 132$ symbols

3.2. BER performances

First of all, Figure 5 illustrates the BER performance versus SNR (dB) for different values of k_{max} iterations. It can be clearly observed that the SNR increases will significantly lead to the BER decreases. It can also see that the BER of NB-LDPC blind feedback method when $k_{max} = 4$, $m_{max} = 1$ is quite closed to that when $k_{max} = 10$, $m_{max} = 1$ and also nearly achieve the BER of Ideal Case by using the ideal channel estimation of SI channel and intended channel in Figure 3. Furthermore, it is unnecessary to increase the number of iterations m_{max} in order to reduce the latency in SPA decoding process. Therefore, it indicates that the possible choice for convergence performance is when $k_{max} = 4$, $m_{max} = 1$ to save the computation and power consumption. Moreover, the suggested NB-LDPC blind feedback method also gives a better performance than the traditional NB-LDPC without feedback. For example, at $BER = 10^{-5}$, the gap is about 3 dB when $k_{max} = 2$, $m_{max} = 1$ and about 8 dB when $k_{max} = 4$, $m_{max} = 1$, although the traditional NB-LDPC without feedback uses $m_{max} = 20$ iterations to perform the decoding process. Therefore, this result shows the efficient usage of NB-LDPC blind feedback method to significantly improve the reliability and also reduce the complexity and latency (by reducing mostly the decoding iteration m_{max}, which takes a lot of time in whole transmission process) for practical uses in 5G transmissions and IoT applications.

In study [27], the LDPC blind feedback method has a worst performance in low region of SNR (≤ 0 dB) due to the high error of decoding at the first iteration leading to consequence of higher error in next iterations. So, the authors continuously proposed a second method called LDPC semi-blind feedback method by using at least four pilot symbols added to the transmission message at transmitter [27]. These pilot symbols are then used for SI and intended channels estimation as well as feedback loops. Subsequently, we will illustrate a comparison of the proposed NB-LDPC blind feedback method to these two LDPC blind feedback [27] and semi-blind feedback (using four pilot symbols) [27] methods, as shown in Figure 6. It can be observed that the suggested NB-LDPC blind feedback method shows a wonderful performance not only in high region of SNR but also in low region of SNR, although the pilot symbols are not necessary to implement in this method, compared to LDPC blind feedback [27] and semi-blind feedback [27] methods.

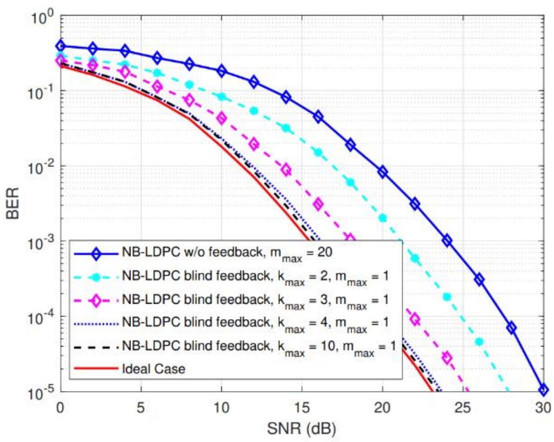

Figure 5. BER versus SNR when change k, 8-PSK, $\rho_{BB} = 30$ dB, $K = 132$ symbols

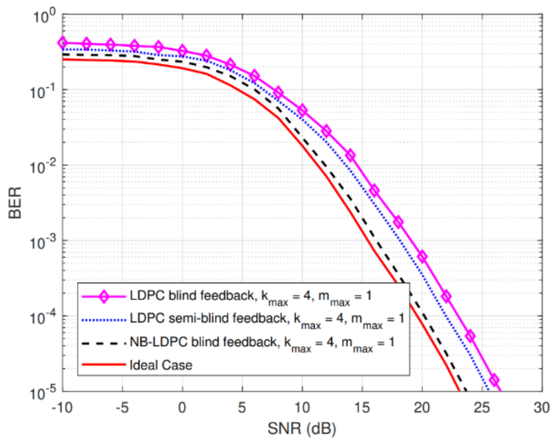

Figure 6. BER performance of NB-LDPC feedback, LDPC blind feedback and LDPC semi-blind feedback schemes, $\rho_{BB} = 30$ dB, $K = 132$ symbols

Last but not least, the BER performance of the proposed NB-LDPC blind feedback method, the LDPC blind and semi-blind feedback methods versus SNR (dB) for different order of modulation M-PSK, are compared in Figure 7. It indicates that with a small order of M-PSK modulation, i.e. QPSK, all methods are appropriated to each other and closed to the Ideal Case. However, when the order of modulation increases, i.e. 8-PSK and 16-PSK, the gaps between the proposed NB-LDPC blind feedback curve and the LDPC blind and semi-blind feedback curve are bigger when SNR is increased. Indeed, the proposed NB-LDPC blind feedback is still closed to the Ideal case, i.e. at $BER = 10^{-3}$ on 16-PSK, the proposed NB-LDPC feedback needs only 23 dB in SNR while the two LDPC methods require about 27 to 30 dB to obtain that result. Therefore, the result is possible in practical applications in high order communications since the proposed NB-LDPC blind feedback method is less sensitive to the increase of order of modulation.

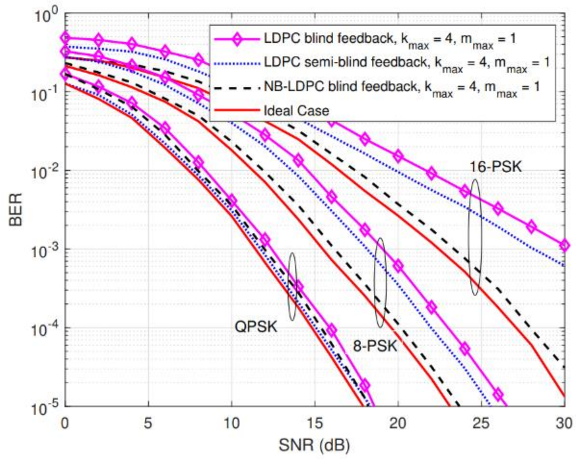

Figure 7. BER versus SNR when change M-PSK, $\rho_{BB} = 30\ dB$, $K = 132$ symbols

3.3. Processing time and computation complexity

In this section, we compare the processing time and computational complexity, which are two important factors to quantify the effectiveness of the proposed method. For processing time, the MATLAB Version 2023a was run on a computer with the hardware configuration of 12th Gen Intel(R) Core(TM) i7-12700 2.10 GHz and a memory of 16 GB of RAM. For the simulation specification, we use $\rho_{BB} = 30$ dB, 10^6 transmission frames, $K = 132$ symbols and 8-PSK modulation. We also fix $k_{max} = 4$, and $m_{max} = 1$ for the maximum number of joint iteration and decoding iteration of all methods at all levels of the SNR, the processing time is nearly the same. So, this set up is used to calculate the processing time to achieve BER performance at the specified SNR level, $SNR = 20$ dB. Furthermore, the computational complexity is also calculated as the summation of the number of computations of the processes such as encoder/decoder processes, modulation/demodulation processes, channel estimation processes, as illustrated in [27], [28].

Based on the results in Table 1, it was observed that the LDPC semi-blind method in [28] implements the fastest result and less number of operations because it only uses pilot symbols rather than using temporary decoding and encoding to form the feedback loop as our NB-LDPC blind feedback and LDPC blind feedback method in [27]. NB-LDPC blind feedback method is slightly larger than LDPC blind feedback because of higher complexity in the decoding processing over $GF(M)$. However, NB-LDPC blind feedback method does not need pilot symbols and it also shows a better performance in high order of modulation as well as low region of SNR. The advantages and disadvantages of all methods are summarized in Table 2. Therefore, based on various applications and purposes, the use of three methods should be considered carefully to achieve an optimal solution.

Table 1. Processing time and computation complexity

Method	Processing Time (in minute)	Number of operations
LDPC Blind Feedback	179.3	1.17×10^5
LDPC Semi-blind Feedback	59.2	1.05×10^4
NB-LDPC Feedback	180.8	1.22×10^5
NB-LDPC without Feedback	620.4	3.41×10^5

Table 2. Processing time and computation complexity

Method	Advantages	Disadvantages
LDPC blind feedback [27]	- Performance well in high SNR - No pilot symbols	- Worst performance in low SNR - Poor performance in high order of modulation - Need more time to process
LDPC semi-blind feedback [28]	- Performance well in both low and high SNR - Less processing time and computational complexity	- Need pilot symbols - Poor performance in high order of modulation
NB-LDPC feedback	- Performance well in high order of modulation - Performance well in both low and high SNR - No pilot symbols	- Need more time to process

4. CONCLUSION

This paper proposed a blind feedback process that combined channels estimation and decoding algorithm by taking the approach of NB-LDPC codes over higher Galois field. Although the processing time and computational complexity are slightly higher than two LDPC feedback methods, NB-LDPC codes show its robustness in many factors. Indeed, the results show that the proposed technique provides a better performance in MSE and BER than both conventional NB-LDPC without feedback and traditional LDPC codes, especially in high order of modulation and low region of SNR without using pilot symbols. Consequently, based on various applications and purposes, NB-LDPC codes are a promise technique and it should be carefully considered to achieve an optimal solution in short-packet FD transmissions and high order modulation communications.

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