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Girth aware normalized min sum decoding algorithm for shorter length low density parity check codes

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ABSTRACT

Recently, short block codes are in great demand due to the emergent applications requiring the transmission of a short data unit and can guarantee speedy communication, with a minimum of latency and complexity which are among the technical challenges in today's wireless services and systems. In the context of channel coding using low density parity check (LDPC) codes, the shorter length LDPC block codes are more likely to have short cycles with lengths of 4 and 6. The effect of the cycle with the minimum size is that this one prevents the propagation of the information in the Tanner graph during the iterative process. Therefore, the message decoded by short block code is assumed to be of poor quality due to short cycles. In this work, we present a study of the evolution of the messages on check nodes during the iterative decoding process when using the LDPC decoding algorithm normalized min sum (NMS), to see the destructive effect of short cycles and justify the effectiveness of the girth aware normalized min sum (GA-NMS) decoding LDPC codes algorithm in terms of correction of the errors, particularly for the codes with short cycles 4 and 6. In addition to this, the GA-NMS algorithm is evaluated in terms of bit error rate performance and convergence behavior, using wireless regional area networks (WRAN) LDPC code, which is considered as a short block code.

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1. INTRODUCTION

We are living in an era of advanced technology, the need for wireless access for voice and multimedia has increased enormously. This need has created a wide range of technical challenges like cost, high speed, throughput, low complexity, low power and low latency as in [1]-[4]. Low density parity check (LDPC) codes [5] of shorter length (i.e., codes with dimension k in the range of 50 to 1000 bits) are considered as they offer advantages in terms of latency and complexity, at the cost of performance degradation due to the increased number of short cycles in the tanner graph (TG) [6], contrary to the LDPC code with the large block length as we can see in the study presented in [7] or [8]. The advantages of short codes nominate them to be used in new application classes such as enhanced mobile broadband (eMBB) communication, ultra-reliable and low latency communications (uRLLC), massive machine type communications (mMTC), and the internet of things (IoT), which have gained significant interest recently for 5G wireless networks as mentioned in [9]-[13].

During the decoding iterative process using LDPC code, the circulation of messages between different nodes is beneficial to error correction. The major problem when using a short block LDPC code is the existence of short cycles with lengths (4, 6, or 8) as shown in Figure 1. So when a node is connected to a cycle with a short length (4, 6, or 8), the message coming out of this node may enter into a short loop and cannot interact with the other nodes during the iterative process. This prevents the evolution of the message and the correction of errors. In order to get rid of this drawback, there are several research attempts that can be divided into two axes, the first one focusing on creating codes without cycles 4 and cycles 6, or at least without cycle 4. In this context, we can see the work presented in the papers [14]-[17].

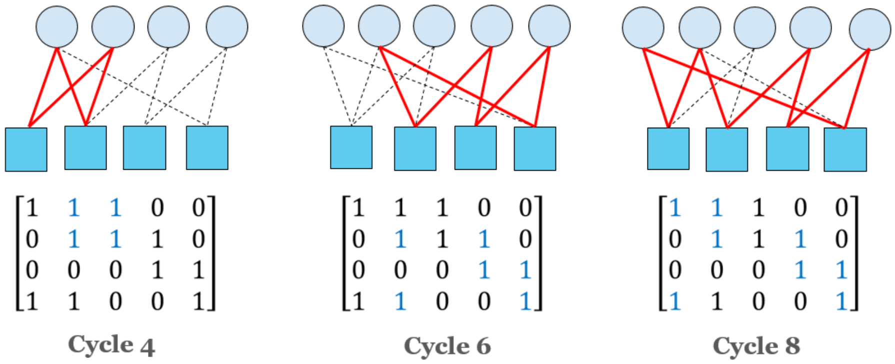

Figure 1. Graphic and matrix representation of cycles with size (4, 6 and 8)

The second approach that is used to reduce the destructive effect of a girth in the LDPC code consists of multiplying a node in Tanner graph by a factor depending on the number of short cycles passing through the nodes, in this context we find exponential factor appearance probability belief probability (EFAP-BP) [18], variable factor appearance probability belief propagation (VFAP-BP) [19] which are the improved version of belief propagation (BP) algorithm for decoding LDPC code. The decoding process using EFAP-BP and VFAP-BP is similar to the BP decoding algorithm except that the decoding process of these two algorithms consists in putting a weighting on the messages transiting between the nodes in TG to free themselves from the short cycle and to evolve through the iterations, the weighting parameter added is dependent on the cyclic structure of the code. In the context of the min sum algorithm for decoding LDPC code which is designed in order to reduce the complexity of the previous BP, we find in the literature the girth aware normalize min sum algorithm (GA-NMS) [20] which is inspired from the two algorithms discussed previously and which make the normalization factor dependent on the cyclic structure of the code, unlike the standard normalized min sum (NMS) algorithm which uses a constant normalization factor [21].

The GA-NMS is already evaluated using WIMAX IEEE P802.16e codes [22] and showed good performance in front of the NMS algorithm, in this paper we provide a statistical study that proves the destructive effect of cycles 4 and 6. From this study we could deduce that the nodes need to be multiplied by a factor dependent on the information of short cycles passing through it, in addition to this, the GA-NMS algorithm has been applied on WRAN IEEE 802.22 codes [23] which is considered short block code with the length (384, 192). The organization of this paper is as shown in section 2 introduces a state of the art which includes a detailed description of the GA-NMS algorithm. In section 3, a Statistic study of soft likelihood ratio (LLR) messages is presented. Section 4 shows the simulation results along with discussions. Finally, section 5 concludes the paper.

2. RESEARCH METHOD

2.1. Girth aware normalized min sum algorithm

LDPC is one of the most efficient error correcting codes, discovered for the first time by Robert Gallager in the year 1962 in the context of his thesis [5], among the most popular LDPC decoding algorithm we can find the normalized min sum. The NMS is an algorithm that can be placed between the belief propagation which provides very good performance in error correction at the price of computational complexity and min sum decoding algorithm which is a simplified version of the BP algorithm in terms of complexity with mediocre performance quality. However, the NMS algorithm presents a good compromise between performance and computational complexity, this makes it suitable for hardware implementation. The NMS decoding algorithm was developed in the year 2002 and from this year, there are many versions developed of this algorithm we can see in the literature [20], [24].

The GA-NMS is one of the improved versions of the NMS algorithm that consists in multiplying the messages transiting from check node to variable node in TG by a normalization factor $\alpha(G(k))$ that depend on the shortest cycle $G(k)$ passing through the check node k instead of multiplying all messages going from check nodes to variable nodes by a constant empirical factor $0 < \alpha < 1$. The determination of the values of $\alpha(G(k))$ of the GA-NMS algorithm is done using an off-line process. The knowledge of a cyclic structure of LDPC code is required when using the GA-NMS algorithm, More precisely, we need to know for each check node k in the TG the shortest cycle passing through it. There are many pieces of research that were done in this context and many efficient algorithms were proposed in the literature that can be used to determine the cyclic structure of LDPC code [25], [26]. We consider that the binary message that we have to transmit over an additive white Gaussian noise (AWGN) channel using a binary phase-shift keying (BPSK) modulation is $u = (u_1, ..., u_K)$ and the received symbol is $v = (v_1, ..., v_K)$. We note:

- $\mathcal{H}$, correspond to the tanner graph of an LDPC code.
- γ_k is defined as the information derived from the log-likelihood ratio of the received symbol v_k.
- $b_{l,k}$, is defined as the information coming from CN_l to VN_k as depicted in Figure 2.
- $a_{l,k}$, is defined as the information coming from VN_k to CN_l as depicted in Figure 2.
- $\mathcal{H}_V(l)$ is the set of variable nodes that are connected to the CN_l.
- $\mathcal{H}_C(k)$ is the set of check nodes that are connected to the VN_k.
- $k' \in \mathcal{H}_V(l) \backslash k$ represent $\mathcal{H}_V(l)$ except the variable node k.
- $l' \in \mathcal{H}_C(k) \backslash l$ represent $\mathcal{H}_V(l)$, except the check node l.
- $G(l)$ is the size of the shortest cycle in the tanner graph passing through node l.
- g is the shortest cycle in the tanner graph and can be written as $g = \min_{l=1 \cdots L} G(l)$.

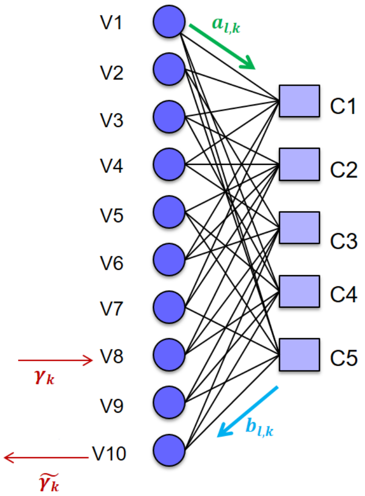

Figure 2. Tanner graph corresponds to the H matrix

The decoding using GA-NMS algorithm is done during an iterative process $i = 1, 2, 3, ..., I_{max}$, for each iteration i, we have to do the following four steps:
Firstly the priori information γ_k is calculated using (1) for each VN_k, and messages that should be transmitted from a variable node to check node $a_{l,k}$ are initialized $\forall k = 1, ..., K; \forall l \in \mathcal{H}_C(k)$.

$$\gamma_k = log \frac{p(u_k = 1|v_k)}{p(u_k = 0|v_k)} \tag{1}$$

$$a_{l,k} = \gamma_k \tag{2}$$

In the second step the messages that should be transmitted from check-to-variable messages $b_{l,k}$ are updated according to the $a_{l,k}$ messages computed previously, with $k' \in \mathcal{H}_V(l) \setminus \{k\}$; $\forall l = 1, ..., L; \forall k \in \mathcal{H}_V(l)$ and $\alpha(G(l))$ normalization factor depending on the short cycles passed through the node l, this parameter is determined empirically for each check node l:

$$b_{l,k} = \alpha(G(l)) \times \prod_{k' \in \mathcal{H}_V(l) \backslash k} sgn\left(a_{l,k'}\right) \times \min_{l' \in \mathcal{H}_V(l) \backslash k} |a_{l,k'}| \tag{3}$$

thirdly the messages $\alpha_{m,n}$ are updated again according to the input γ_k value and the messages $b_{l,k}$ computed in the last step, with $m' \in \mathcal{H}_C(n) \setminus \{m\}$ $\forall n = 1, ..., N; \forall m \in \mathcal{H}_C(n)$;

$$a_{l,k} = \gamma_k + \sum_{l' \in \mathcal{H}_C(k) \backslash l} \beta_{l',k} \tag{4}$$

finally the outgoing messages from variable node also called a posteriori LLRs (AP-LLR) are calculated by the following equation. These values are used to take a hard decision on each coded-bit $\forall k = 1, ..., K$:

$$\tilde{\gamma}_k^i = \gamma_k + \sum_{l \in \mathcal{H}_C(k)} b_{l,k} \tag{5}$$

then the estimated CodeWod vector $\hat{u} = [\hat{u}_1, \hat{u}_2, \ldots, \hat{u}_n]$ is calculated by:

$$\hat{u}_n = \begin{cases} 0 & \text{if and only if } \tilde{\gamma}_k \leq 0, \\ 1 & \text{if and only if } \tilde{\gamma}_k > 0. \end{cases} \tag{6}$$

when the estimated CodeWord satisfy $z = H \times \hat{u}^t = 0$, or if the maximum number of iterations has been reached, the iterative process stops.

3. STATISTIC STUDY OF SOFT LLR MESSAGES

As already shown in [20]. The WIMAX IEEE P802.16e code with size $N = 576$ and rate $r = 1/2$ has three types of variable nodes, 168 VNs crossed by girth 4, 144 VNs crossed by girth 6, and 264 crossed by girth 8 as mentioned in (Table I). The specific cyclic structure of this code is an advantage that will allow us to see the negative effect of short cycles and the evolution of the messages during the iterative process.

Table 1. Distribution of short cycles with sizes (4, 6 and 8) in the code chosen from IEEE P802.16e

Length of short cycle	$\mathcal{H}$	CN impacted	VN impacted
Cycle 4	96	144	168
Cycle 6	528	120	144
Cycle 8	7344	24	264

In this research, we propose to make a statistical analysis of the outgoing messages from variables nodes. In this a statistical analysis we consider just the received vectors y_n that fail to be decoded by Normalized MS after 50 iterations at $SNR = 3dB$, for each vector we calculate the SLLR messages by:

$$\forall k = 1, ..., K \qquad SLLR_n = \tilde{\gamma}_k \times sign(v_k) \tag{7}$$

then we calculate the mean of SLLR value for each class of variable nodes and we accumulate it, the obtained curve shows that there are appearances of an offset between the average of SLLR outgoing from variable nodes connected to girth 4, variable nodes connected to girth 6 and variable nodes connected to girth 8 and the majority of messages are between [-1.5 -2.5] after 50 iterations, as indicated in the following figure Figure 3. This result is considered due to the cyclic structure of the code which prevents the evolution of the messages during the iterative process.

Based on this result, we suppose that the check nodes connected to girth 4 need an optimization factor α_1 less than the nodes connected to girth 6, and girth 8. The check nodes passed by girth 6 should be multiplied by an optimization factor $\alpha_2 > \alpha_1$. Finally the check nodes with girth 8 should be re-weighted by an optimization factorα_3 between α_2 and 1.

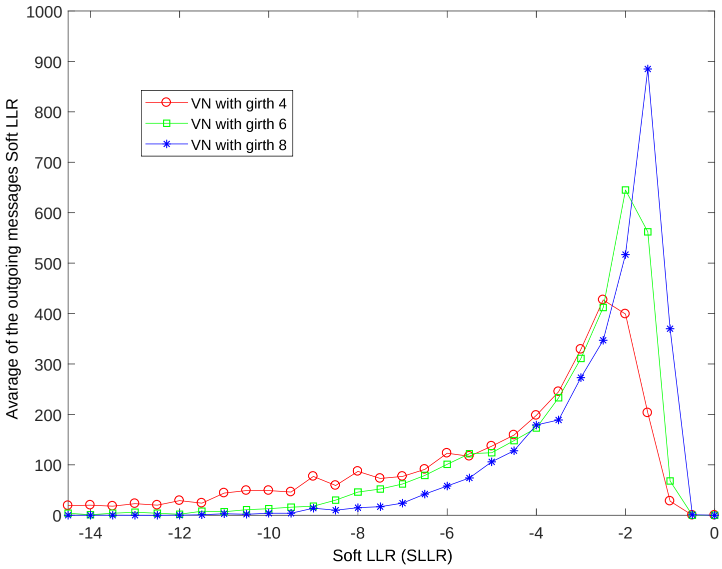

Figure 3. Average of the outgoing message soft LLR from variable nodes with girth [4, 6, 8]

4. METHOD FOR DETERMINATION OF VARIABLE OPTIMIZATION FACTOR FOR WRAN CODE

4.1. Wireless regional area network (WRAN)

In this study we have chosen to apply the GA-NMS method on short block code that consumes low power can be implemented in a small area and have good performance in terms of BER and throughput. For this reason, we chose WRAN code which is from IEEE 802.22 standard for wireless broadband access for the same reason why the authors in [27] chose it for hardware implementation. WRAN uses cognitive radio techniques for dynamically configuring to use the best wireless channels that are available in the area. This standard is highly suitable for providing broadband access to low population density areas worldwide. WRAN standard uses LDPC codes for error correction with $1/2$, $2/3$, $3/4$ and $5/6$ as code rates as depicted in the paper [28].

4.2. Optimization factor

In this section, the behavior and decoding performances of the GA-NMS algorithm obtained from computer simulations when decoding shorter length LDPC code are presented and compared with the standard MS and NMS. To illustrate the potential application of the GA-NMS algorithm, we have tested WRAN code from IEEE 802.22 standard with the rate $r = 1/2$ and size $N = 384$ from the database [23]. We performed simulations assuming binary phase-shift keying (BPSK) modulation and transmission over the additive white Gaussian noise (AWGN) channel. For each simulation, the decoder stops when a valid codeword is found or the decoder achieves the maximum number of iterations, which is limited to 50 iterations. The study of the cyclic structure of the WRAN codes has shown that this code has, on the one hand, 32 short cycles with size g=4 and 384 short cycles with size g=6, on the other hand, there are 64 check nodes connected to girth 4 and 128 check nodes connected to girth 6 as shown in (Table 2). Before proceeding to the decoding step, we need to determine the optimization factor γ for the NMS algorithm, and the variable optimization factors γ_1, γ_2 for the proposed GA-NMS algorithm as we did previously for the WIMAX code in [20]. The simulations show that γ for NMS takes the value 0.8 and γ_1, γ_2 takes the values 0.8 and 0.9 as depicted in figure Figure 4.

Table 2. Distribution of short cycles with sizes 4 and 6 in the code chosen from IEEE 802.22 standard

Length of girth	$\mathcal{H}$	CN impacted
Cycle 4	32	64
Cycle 6	352	128

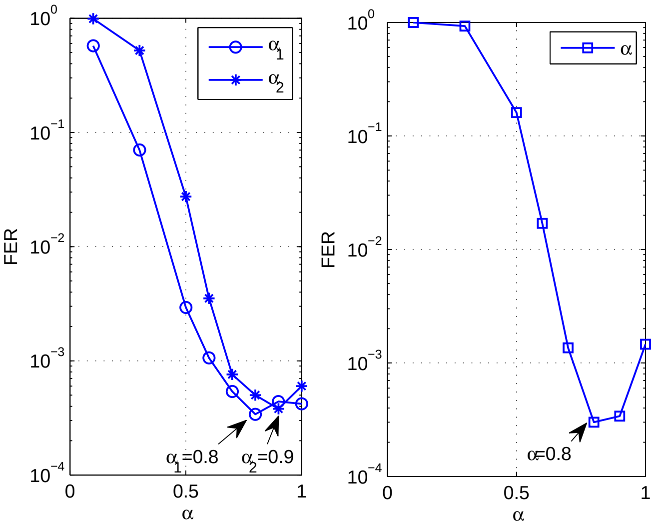

Figure 4. Determination of a normalization factor α for NMS, and α_1, α_2 parameters for GA-NMS at non-noisy region $SNR = 3dB$ and a maximum number of iterations $I_{max} = 50$ for WRAN code

5. SIMULATION AND RESULTS

5.1. BER and FER performances

The BER and FER performance of the algorithm GA-NMS are evaluated in comparison with NMS and standard MS algorithms using WRAN code. The result shows that the GA-NMS has almost similar performance as NMS algorithm in the noisy region. But we can see a small difference between GA-NMS and both algorithms (MS and NMS) particularly at error floor region at SNR=3dB as shown in the Figure 5.

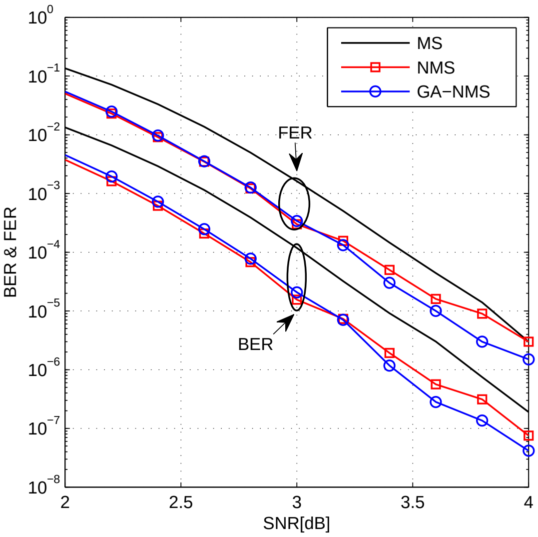

Figure 5. Performance evaluation of the decoding algorithms (GA-NMS, NMS and MS) in terms of (BER, FER)/SNR using a short block code chosen from IEEE 802.22 standard when the maximum number of iterations is 50

5.2. Convergence behaviors

In Figure 6, the decoding algorithms of LDPC codes GA-NMS, NMS, and the standard MS are studied and evaluated in terms of convergence behaviors throughout the iterations when decoding messages coded by WRAN code at non-noisy region SNR=[3, 4, 5, 6] dB. The GA-NMS converges faster than the NMS at higher SNR values SNR=[4, 5, 6] dB, by comparing the efficiency of the GA-NMS algorithm for the both WRAN and WIMAX codes already evaluated in [20]. It is seen that the results obtained by WIMAX code are better than those obtained by WRAN code, resulting from the difference of size a difference of cyclic structure for both codes and others parameters. However, generally the simulation results showed that GA-NMS is better than NMS and standard MS.

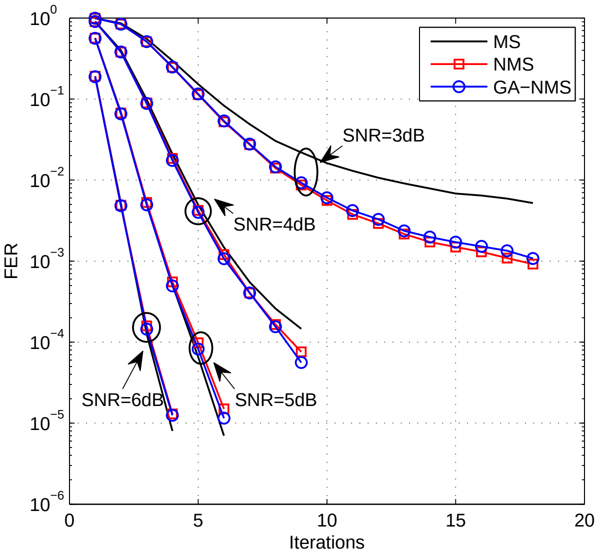

Figure 6. Convergence behaviors of the (GA-NMS, NMS and MS) decoding algorithms at non-noisy region SNR equal to 3 dB, 4 dB, 5 dB and 6 dB when decoding WRAN code with length (384, 192)

6. CONCLUSION

In this paper, an analysis of the behavior of the outgoing messages when decoding using normalized MS is presented, this analysis shows the destructive effect of short cycles and proves that we can classify the nodes according to the length of the short cycle connected to it and that each class of nodes needs to be multiplied by a factor different to the others classes, which explain the effectiveness of the GA-NMS when already tested on WIMAX code. On the other hand, in this paper, the GA-NMS decoding algorithm is tested on WRAN code with the length (384, 192) which is considered among the short LDPC codes, the result shows that the GA-NMS algorithm is better than NMS and MS algorithms in performances and can be efficient for short block LDPC codes. Summarizing this, the GA-NMS algorithm can be considered as a solution to the short block codes, which have the problem of short cycles of sizes 4 and 6.

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