A Modified Normalized Min - Sum Decoding Algorithm for Irregular LDPC Codes

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ABSTRACT

In this paper, a modified normalized Min-Sum algorithm (MNMSA) is proposed for decoding irregular Low Density Parity Check Codes (LDPC) with non-uniform degree distribution. The proposed algorithm provides an efficient decoding scheme to enhance the error performance of an irregular LDPC code without increasing the hardware complexity. An efficient 6 - bit quantization scheme is utilized in the proposed algorithm with optimally combined normalization and down scaling factors to resolve the magnitude overestimation issue which occurs during iterative message passing process between the nodes. The simulation results demonstrate that the proposed algorithm achieves good decoding performance in terms of Frame Error Rate (FER) and Bit Error Rate (BER) without the requirement of complex arithmetic calculations. Compared to other min - sum based decoding algorithms the decoding process of the proposed MNMSA requires only fewer decoding iterations over wide range of signal - to - noise ratio (SNR) to achieve comparable decoding performance to that of Belief Propagation (BP) algorithm without increasing the hardware complexity.

Keywords: Decoding algorithm, Irregular LDPC, Iterative message passing, Min-sum algorithm (MSA), Modified normalized min-sum algorithm (MNMSA), Quantization scheme.

1.0 Introduction

Low density parity check (LDPC) codes was first discovered by Gallager in 1960s [1] were proven to approach Shannon-limit since their rediscovery by Mackay and Neal in 1990s [2]. LDPC codes provide sufficient reliability while approaching performance close to Shannon limit with feasible complexity. Due to their simple decoding procedure and enhanced error- correcting capability the LDPC codes are preferred in emerging wireless communication standards such as WLAN IEEE (802.11n) standard [3] and WMAN IEEE (802.16e) standard [4].

LDPC codes can be represented by sparse parity check matrix (PCM) H which contains only fewer entries of non-zero elements. The sparseness of non-zero elements in rows and columns of H determines the degree distribution of the code. If there is uniform degree distribution in row (check node) weight and column (variable node) weight of PCM H then the LDPC code is called as *regular* LDPC code otherwise it is an *irregular* LDPC code.

In general *regular* LDPC code can be extended to *irregular* LDPC code by varying uniform degree distribution of rows and columns. However, well constructed irregular LDPC codes have demonstrated better decoding performance than regular LDPC codes [5]. Hence, *irregular* LDPC codes are strongly preferred and accepted in enhancing the limits and services of advanced wireless communication standards due to their amenability to rigorous analysis and design. Irregular LDPC codes can be decoded effectively with soft decision methods among which Belief Propagation (BP) algorithm [6] exhibits better decoding performance for irregular LDPC codes. Research works on LDPC decoding algorithms have focused on simplifying the decoding complexity with small signal - to - noise ratio (SNR). Min - sum algorithm (MSA) [7] the simplified version of BP algorithm reduces the computational complexity by utilizing less complex compare and simplified summation operations on check node process. Based on the trade - off variation between the hardware complexity and decoding performance the MSA can be classified into three categories: 1) MSA with correction factor [8] 2) MSA with normalization factor algorithm [9] and 3) offset – based MSA [10]. The first saves memory bits for look - up table (LUT) and latter two are more realizable because it can reduce total amount of memory bits for extrinsic messages and computational complexity.

In this paper, a modified version of normalized min sum algorithm (MNMSA) suitable for hardware implementation is proposed. The paper organization is as follows. In Section 2, background on irregular

LDPC codes and existing decoding algorithms is presented. The proposed MNMSA is presented in Section 3. Section 4 provides simulation results and the conclusions are drawn in Section 5.

2.0 Background on Low-Density Parity Check Codes

2.1 Irregular LDPC codes

Irregular LDPC codes are preferred in enhancing the limits and services of advanced wireless communication standards due to their amenability to rigorous analysis and design. In general a regular LDPC code can be extended to irregular LDPC code by varying the uniform degree distribution of rows and columns. An irregular LDPC code can be determined by degree distribution polynomials *v(x)* and *c(x)*, where *v(x)* and *c(x)* corresponds to variable node and check node degree distributions respectively. The degree distribution for check node and variable node is given by

$$c(x) = \sum_{m=1}^{d_c \max} c_m \cdot x^{m-1} \tag{1}$$

$$v(x) = \sum_{n=1}^{d_v \max} v_n \cdot x^{n-1} \tag{2}$$

where the variables d_c *max* and d_v *max* denotes maximum check node and maximum variable node degree respectively. Also the fraction of edges emanating from m^{th} check node edge to n^{th} variable node edge are represented by c_m and v_n respectively. Irregular LDPC codes when constructed for purposefully for a specific communication standard outperforms regular LDPC codes [11].

2.2 Belief Propagation (BP) Algorithm

Irregular LDPC codes can be decoded effectively with soft decision methods among which Belief Propagation (BP) algorithm [6] exhibits better decoding performance for irregular LDPC codes. Let S = (S_1, S_2, S_3, …. S_n), $S_i \in \{0 , 1\}$ denote the codeword which is mapped by binary phase shift-keying (BPSK) into transmitted sequence *t* = (t_1, t_2, t_3, … t_n). Then, *t* is our transmitted over symmetric channel corrupted by symmetric Additive White Gaussian Noise (AWGN) , i.e. $r = t + n$ where *r* is the received sequence and *n* is the Additive White Gaussian Noise with zero mean and variance $\frac{N_0}{2}$. The general BP algorithm consists of two phases of message passing between check node and variable node where they operate serially.

Let the set of variable nodes that participate in check node c is denoted as N(*c*), and set of check nodes in which *v* variable nodes participate is denoted as M(*v*). Also N(*c*) \ *v* and M(*v*) \ *c* denotes the set N(*c*) and M(*v*) excluding variable node *v* and check node *c*. The following are the notations associated with i^{th} iterations for the decoding process. The following are the notations associated with i^{th} iterations for the decoding process:

L_{ch} : the LLR information generated from channel output. $\alpha_{cv}^{(i)}$: the outgoing LLR information from check node *c* to variable node *v*.

$\beta_{vc}^{(i)}$: the outgoing LLR information from variable node *v* to check node *c*.

$\beta_{v}^{(i)}$: aposteriori LLR information computed at each iteration.

The conventional Belief-Propagation (BP) algorithm is based on following steps

Step 1: Initialization

Set *i* =1 and maximum number of iterations to I_{max}.

For each check node *c* and variable node *v*

$$\beta_{vc}^{(0)} = L_{ch} \tag{3}$$

Step 2: Check node processing (Horizontal Step)

$$\alpha_{cv} = \log \frac{1 + \prod_{n \in N(c)\backslash v} \tanh(\frac{\beta_{nc}^{(i-1)}}{2})}{1 - \prod_{n \in N(c)\backslash v} \tanh(\frac{\beta_{nc}^{(i-1)}}{2})} \tag{4}$$

Step 3: Variable node processing (Vertical Step)

$$\beta_{vc}^{(i)} = L_{ch} + \sum_{m \in M(v)\backslash c} \alpha_{mv}^{(i)} \tag{5}$$

The estimated information bit can be determined by taking hard decision on LLR information L_{ch}, for a variable node v it can be expressed mathematically as

$$\beta_{v}^{(i)} = L_{ch} + \sum_{m \in M(v)} \alpha_{mv}^{(i)} \tag{6}$$

Step 4: Decoding Stopping Criterion

The difficulty in decoding process of BP algorithm is to find the most likely vector $\tilde{S}$ such that

$$H \cdot \tilde{S}^{T} = 0 \,(\text{mod}2) \tag{7}$$

If the estimated codeword satisfy the above condition or if maximum decoding iterations are reached then the decoding algorithm stops. The decoding performance of BP algorithm is close to Shannon limit due to the utilization of iterative message passing schedule between the nodes. However, the main drawback of BP algorithm arises in the check node processing, in which hyperbolic tangent (tanh) function is too complex for hardware implementation.

2.3 Min - Sum Algorithm (MSA)

Min-Sum algorithm (MSA) [7] is the simplified version of BP algorithm where the product of hyperbolic tangent (tanh) function is approximated as min-sum operation. The approximated updating equations of check - to - variable (CTV) information and variable - to - check (VTC) information can be expressed mathematically as

$$\alpha_{cv}^{(i)} = \prod_{n \in N(c)\backslash v} \text{sgn}(\beta_{nc}^{(i-1)}) \times \min_{n \in N(c)\backslash v} \left|\beta_{nc}^{(i-1)}\right| \tag{8}$$

$$\beta_{vc}^{(i)} = L_{ch} + \sum_{m \in M(v)\backslash c} \alpha_{mv}^{(i)} \tag{9}$$

The estimated information bit can be determined by taking hard decision on LLR information L_{ch}, for a variable node v it can be expressed mathematically as

$$\beta_{v}^{(i)} = L_{ch} + \sum_{m \in M(v)} \alpha_{mv}^{(i)} \tag{10}$$

In MS algorithm the overall reliability of CTV is equal to minimum reliability of incoming VTC information bits along the other edges. The implementation of MS algorithm is much simpler than BP algorithm as it uses simple addition and comparison operations. However, the conventional MS algorithm suffers from severe performance degradation.

2.4 Normalized and Offset Min - Sum Algorithms

The conventional normalized min-sum algorithm (NMSA) [9] improves the decoding performance of MS algorithm by normalizing the messages generated by the check node processing unit. The normalized CTV updating step is given by

$$\alpha_{cv}^{(i)} = \theta \cdot \prod_{n \in N(c)\backslash v} \text{sgn}(\beta_{nc}^{(i-1)}) \times \min_{n \in N(c)\backslash v} \left|\beta_{nc}^{(i-1)}\right| \tag{11}$$

where θ is the normalization factor which is always less than 1. The normalized MS algorithm achieves better decoding performance and significant reduction in computational complexity with regular LDPC codes with short and moderate lengths. However, the performance gap between the normalized MS algorithm and BP algorithm is quite large. The two dimensional normalized Min-Sum algorithm (2D - NMSA) [12] improves the decoding performance of NMSA by utilizing individual normalization factors for check node and variable node. However, 2D - NMSA exhibits good improvement in the decoding performance compared to NMSA and MSA but it comes at the cost of minor increase in the computational complexity.

The offset Min-Sum algorithm (OMSA) [10] further improves the performance of conventional MS algorithm. The updated CTV and VTC equation can be expressed mathematically as

$$\alpha_{cv}^{(i)} = \prod_{n \in N(c)\backslash v} \operatorname{sgn}(\beta_{nc}^{(i-1)}) \times \max(\min_{n \in N(c)\backslash v} \left|\beta_{nc}^{(i-1)}\right| - \sigma, 0) \tag{12}$$

where $\sigma > 0$ is an offset constant optimized by quantization scheme to remove the bias of minimum input reliability value down to minimum value, here 0. The VTC updating process of NMSA and OMSA is similar to that of conventional MS algorithm. For implementation of irregular LDPC codes both NMSA and OMSA improves the decoding performance but it comes at the cost of increased hardware complexity.

3.0 A Modified Normalized Min - Sum Algorithm

A unique advantage of NMSA and 2D-NMSA is that it improves the decoding performance without increasing the implementation cost. However, the normalization factor used in NMSA and OMSA is much suitable for regular LDPC codes with uniform degree distribution. In this paper, a modified normalized Min-Sum algorithm (MNMSA) is proposed with varying normalization factor which is suitable for both regular LDPC codes with uniform degree distribution and irregular LDPC codes with non-uniform degree distribution. In the proposed algorithm 6 - bit uniform quantization scheme with 3 fractional bits, 2 magnitude bits and 1 sign bit is utilized to achieve comparable decoding performance to that of BP algorithm without increasing the hardware complexity. The utilization of quantization scheme introduces magnitude overestimation during iterative message passing schedule between the nodes. In the proposed algorithm, the magnitude overestimation issue is resolved by using scaling factors which are obtained using heuristic simulations [13].

3.1 Decoding steps of proposed modified normalized min - sum algorithm

Consider a set of VTC messages [$\beta_{1c}, \beta_{2c}, \beta_{3c} \ldots \beta_{vc}$] that satisfies the condition $|\beta_{1c}| \le |\beta_{2c}| \le \ldots . |\beta_{vc}|$. Then the updated CTV message can be denoted mathematically as

$$\left|\alpha_{c1}\right| = \theta \cdot \left|\beta_{2c}\right|, \left|\alpha_{c2}\right| = \theta \cdot \left|\beta_{1c}\right| \ldots\ldots \left|\alpha_{cv}\right| = \theta \cdot \left|\beta_{1c}\right| \tag{13}$$

The following steps briefly illustrate the decoding process of proposed algorithm.

Step1: Initialization

Set i =1 and maximum number of iterations to I_{max}.Therefore, for each check node c and variable node v

$$\beta_{vc}^{(0)} = L_{ch} \tag{14}$$

Step 2: Check node processing (Horizontal Step)

$$\alpha_{cv}^{(i)} = \theta \cdot \prod_{n \in N(c)\backslash v} \operatorname{sgn}(\beta_{nc}^{(i-1)}) \times \min_{n \in N(c)\backslash v} \left|\beta_{nc}^{(i-1)}\right| \tag{15}$$

where θ normalization factor $0 < \theta < 1$ which is used to reduce the incoming minimum reliability value. However, instead of using normalization factor like conventional NMSA the simplified version [14] is given by

$$\theta = \begin{cases} \theta_1 \text{ , if } \beta_{v,\min} = = 1^{st} \text{ minimum message} \\ \theta_2\text{, if } \beta_{v,\min} == 2^{nd} \text{minimummessage} \end{cases} \tag{16}$$

However, for decoding process of irregular LDPC the generated high precision intrinsic message from the nodes does not exhibit uniform degree distribution. Hence, varying normalization factors are used for varying code rates unlike conventional MS algorithms [7] and [9]. **Table 1** shows the normalization values used for different code rates for same code word length. The normalization values for code length 1944 and code rate 1/2, 2/3 and 3/4 are obtained from simulations [13]. Therefore, to reduce the hardware complexity the normalization value can be implemented as a combination of shifting and addition operations.

Table 1 Proposed Normalization values for different code rates

LDPC Type	**Code length**	**Code rate**	**Proposed Normalization Value θ**	
			θ_1	θ_2
Irregular	1944	1/2	0.825	0.875
Irregular	1944	2/3	0.80	0.866
Irregular	1944	3/4	0.77	0.825
Irregular	1944	5/6	0.75	0.8125

Step3: Variable node processing (Vertical Step)

In the proposed variable node process to avoid the loss of sign bit information due to overestimation of variable message magnitude in all iterations, the signs of all the current and previous messages are compared throughout the variable node process. For decoding Irregular LDPC codes the normalization factors are dependent on degree distribution of variable node. The optimized down scaling values Φ_1 and Φ_2 chosen here are decided by quantization scheme [15] and type of LDPC code. The following steps briefly illustrates variable node process of the proposed algorithm

$$\beta_{vc}^{(i)} = L_{ch} + \sum_{m \in M(v)\backslash c} \alpha_{mv}^{(i)} \tag{17}$$

$$\beta_{vc}^{(i)} = L_{ch} + \Big(\sum_{m \in M(v)\backslash c} \alpha_{mv}^{(i)} - \alpha_{mv}^{(i-1)}\Big) \tag{18}$$

$$\beta_{v}^{(i)} = L_{ch} + \sum_{m \in M(v)} \alpha_{mv}^{(i)} \tag{19}$$

$$\beta_{vc}^{(i)} = \beta_{v}^{(i)} - \alpha_{mv}^{(i-1)} \tag{20}$$

By updating $\beta_{vc}^{(i)}$ for each $m \in M(v)$

$$\beta_{vc}^{(i,t)} = L_{ch}^{(i)} - \alpha_{cv}^{(i)} \tag{21}$$

where t is the temporary soft information obtained from i^{th} iteration

If $\operatorname{sgn}(\beta_{vc}^{(i,t)}) == \operatorname{sgn}(\beta_{vc}^{(i-1)})$ then the updated message is

$$(\beta_{vc}^{(i)}) = \Phi_1(\beta_{vc}^{(i,t)}) \tag{22}$$

Else if $\operatorname{sgn}(\beta_{vc}^{(i,t)}) \neq \operatorname{sgn}(\beta_{vc}^{(i-1)})$ then the updated message is

$$(\beta_{vc}^{(i)}) = \Phi_2(\beta_{vc}^{(i,t)} + \beta_{vc}^{(i-1)}) \tag{23}$$

where Φ_1 and Φ_2 are optimized scaling values for variable node processing obtained through extensive simulation.

4.0 Simulation Results and Discussions

In this section, the Frame Error Rate and Bit Error Rate (FER & BER) performance of the proposed MNMSA is evaluated using an irregular LDPC code compliant to IEEE 802.11n WLAN standard. To validate the performance of the proposed MNMSA algorithm three IEEE 802.11n WLAN [3] irregular LDPC codes are considered namely (1944 , 972), (1944 , 1296) and (1944 , 1458) with 6-bit quantization scheme. For all the simulations the codewords are BPSK modulated and transmitted through binary AWGN channel. The maximum number of decoding iterations for simulation are set to 10.

4.1 Decoding Performance

Fig.1 depicts the decoding performances of (1944 , 972) irregular LDPC code. **Table 1** summarizes the optimal combination of normalization factors obtained through Monte-Carlo simulations. The proposed algorithm with normalization factors $\theta_1 = 0.825$ and $\theta_2 = 0.875$ achieves decoding performance close to

BP algorithm [6] and better than other Min-Sum algorithms (MSA) [7], [9] and [12]. In particular, the proposed MNMSA suffers from performance degradation of less than 0.1 dB in terms of FER and BER which is shown in **Fig. 2** and **Fig. 3**. It can be observed that the performance degradation suffered by proposed MNMSA is much less than other decoding algorithms.

Fig. 4 and Fig. 5 illustrates the decoding performance of (1944 , 1296) and (1944 , 1458) irregular LDPC codes. It can be seen that the proposed MNMSA achieves FER and BER performance close to BP algorithm [6] while out performing other Min-Sum algorithms [7], [9] and [12]. The proposed algorithm achieves significant SNR gain over other Min-Sum algorithms by utilizing the optimal combination of normalization factors and scaling factors in check node and variable node process. However, the proposed MNMSA suffers from little performance degradation compared to BP algorithm which is shown in Fig. 6 - 9. The scaling factors used in variable node process avoid the magnitude overestimation which affects the decoding performance at high SNR due to utilization of 6 - bit quantization scheme. The summary of decoding performance is shown in Table2.

4.2 Complexity Reduction

The average decoding iterations required to reduce the channel errors at relatively low SNR for various decoding algorithms are depicted in **Figure 10 - 12**. It can be observed that the proposed MNMSA for irregular LDPC with code length 1944 and code rates 1/2, 2/3 and 3/4 with 6-bit quantization scheme compliant to WLAN standard requires significantly fewer decoding iterations compared to BP algorithm and other Min-Sum algorithms. The utilization of 7 - bit quantization (including 1 sign bit) scheme requires 13608 memory bits per iteration where as by using 6 - bit quantization (including 1 sign bit) requires 11664 memory bits per iteration. Therefore, 6 - bit quantization scheme can reduces total number of memory accessing bits per iteration upto upto 14.28% which in turn reduces the hardware complexity.

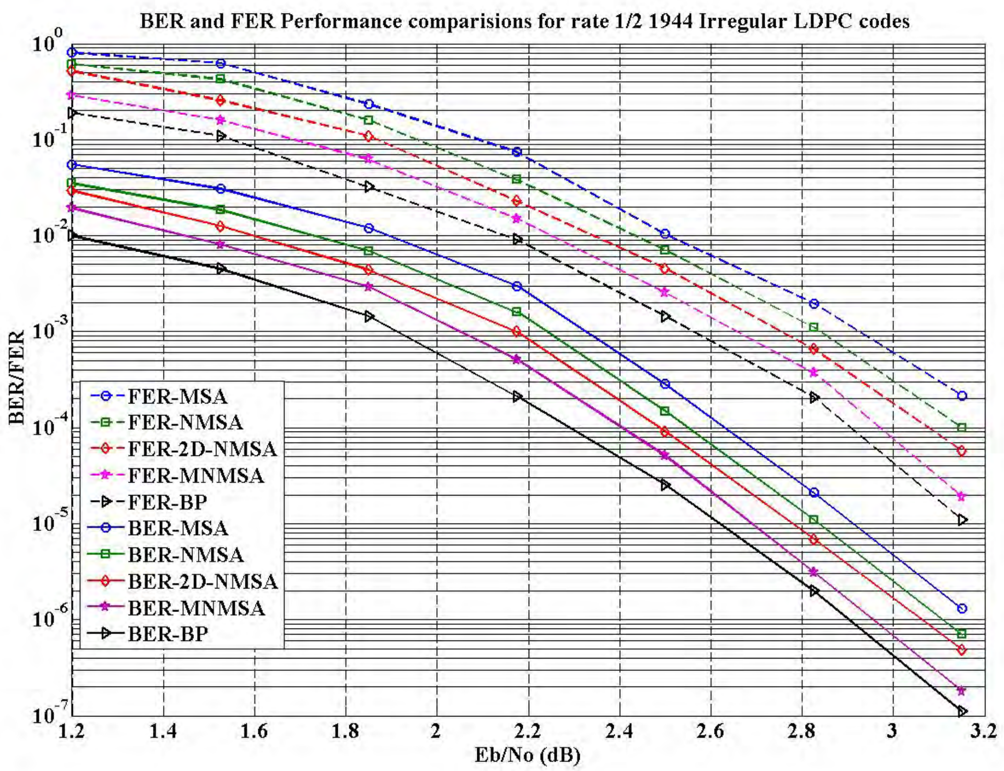

Fig.1 FER and BER decoding performance of proposed MNMSA with other decoding algorithms

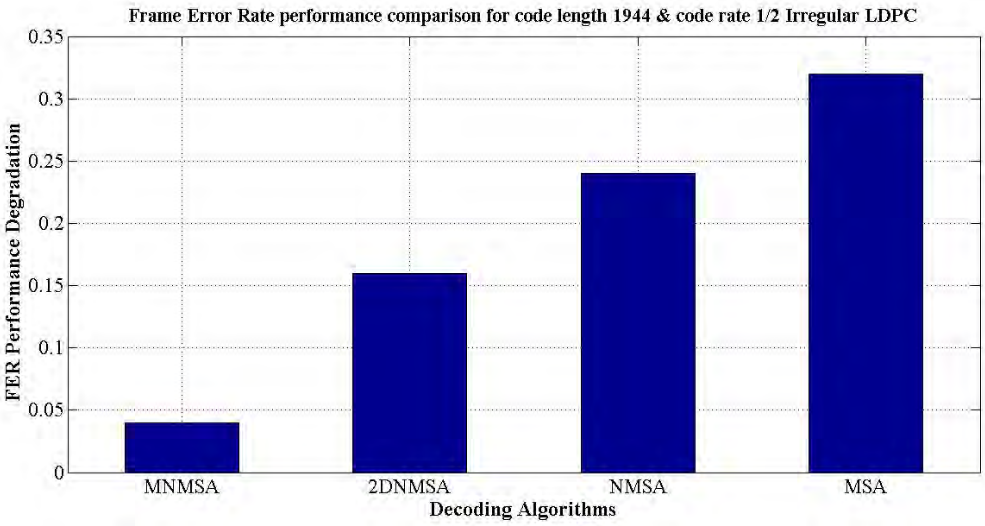

Fig.2 FER decoding performance degradation comparison between proposed MNMSA and other decoding algorithms with respect to BP algorithm at FER of 10^{-3}

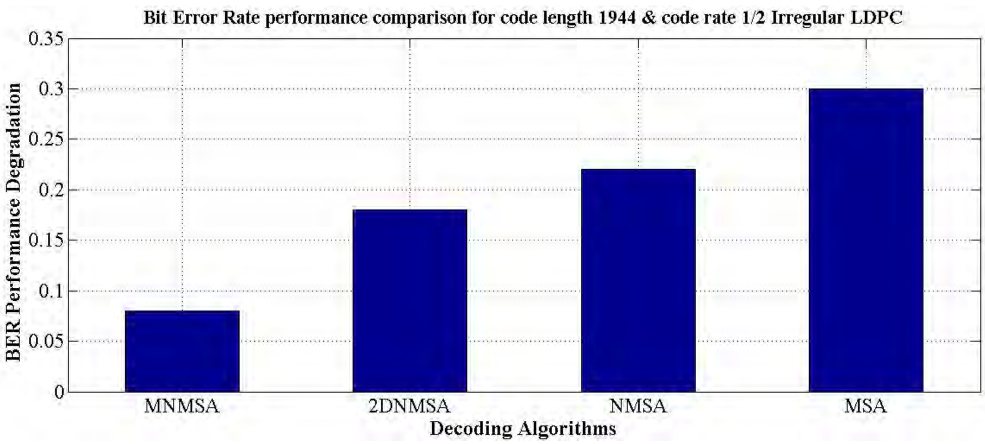

Fig.3 BER decoding performance degradation comparison between proposed MNMSA and other decoding algorithms with respect to BP algorithm at BER of 10^{-5}

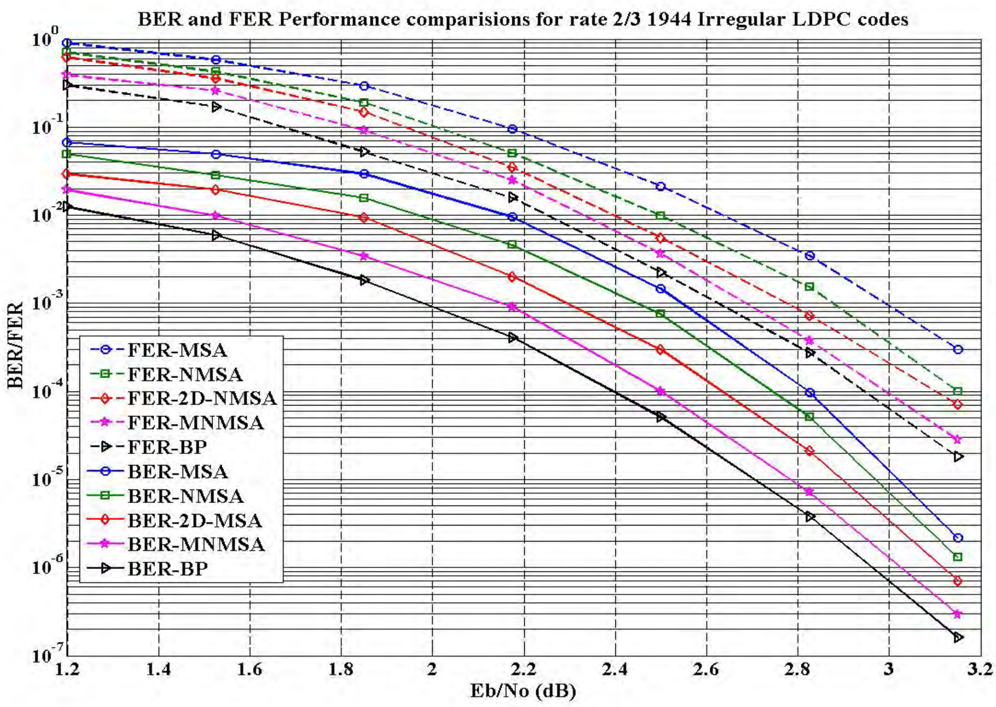

Fig.4 FER and BER decoding performance of proposed MNMSA with other decoding algorithms

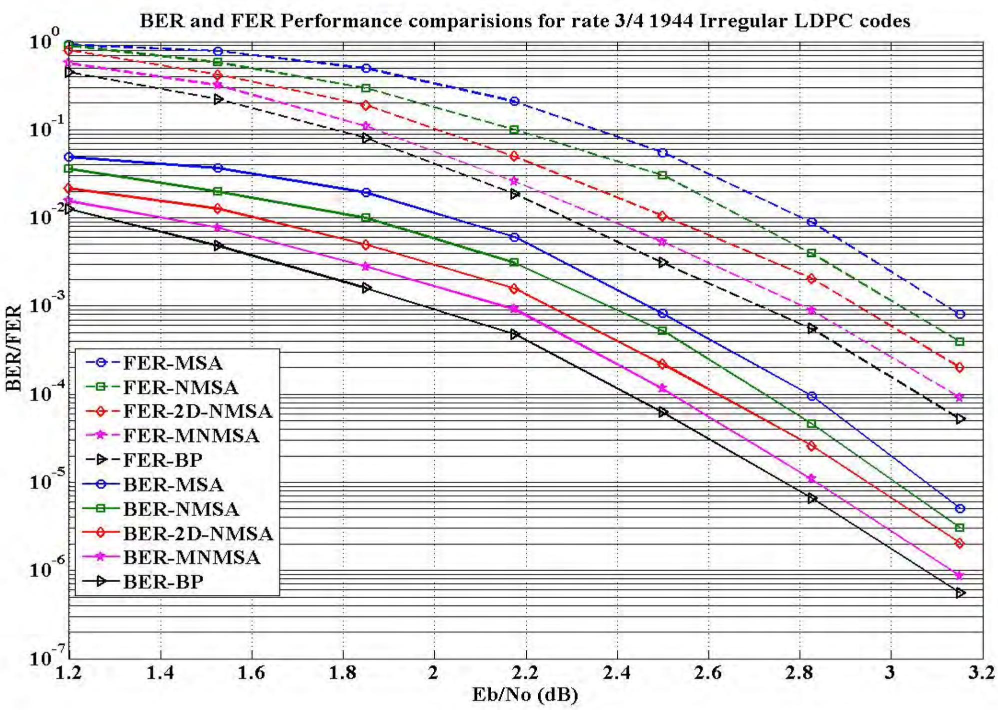

Fig.5 FER and BER decoding performance of proposed MNMSA with other decoding algorithms

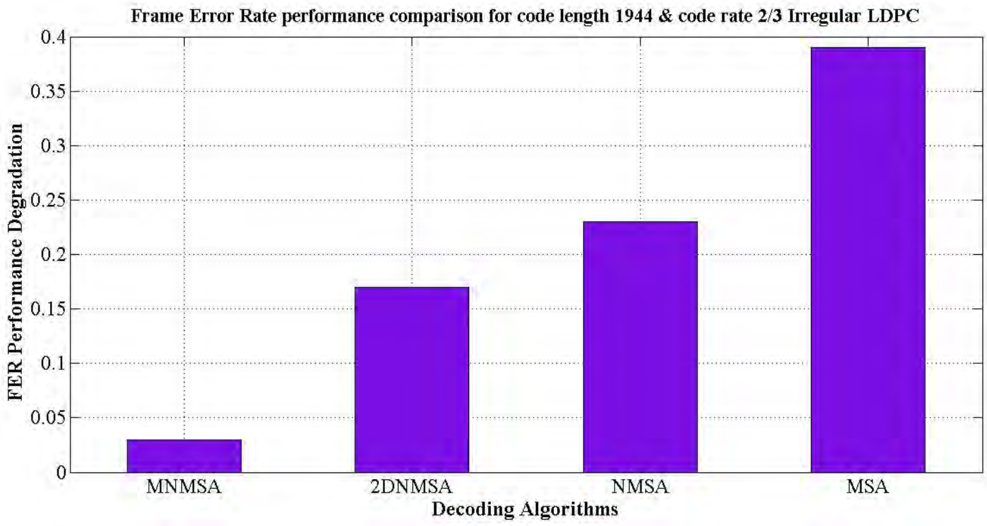

Fig.6 FER decoding performance degradation comparison between proposed MNMSA and other decoding algorithms with respect to BP algorithm at FER of 10^{-3}

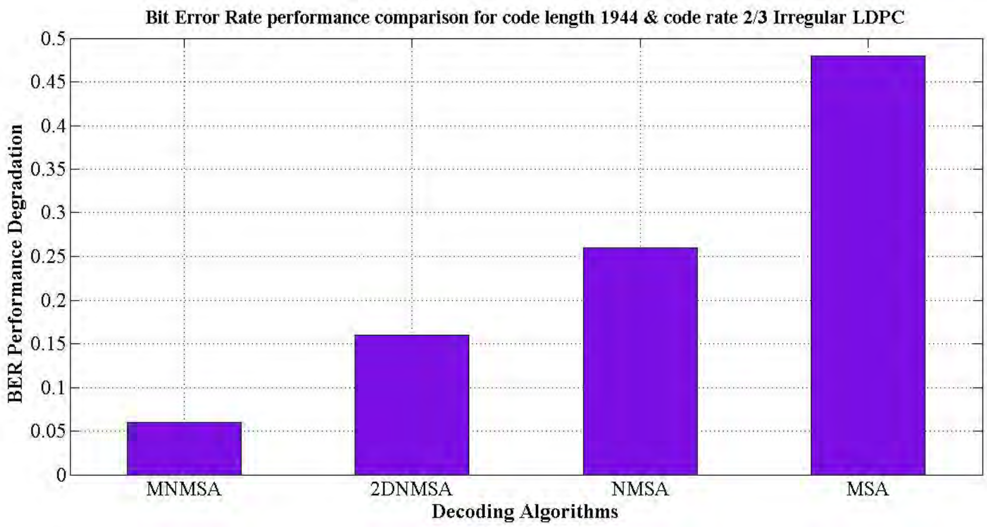

Fig.7 BER decoding performance degradation comparison between proposed MNMSA and other decoding algorithms with respect to BP algorithm BER of 10^{-5}

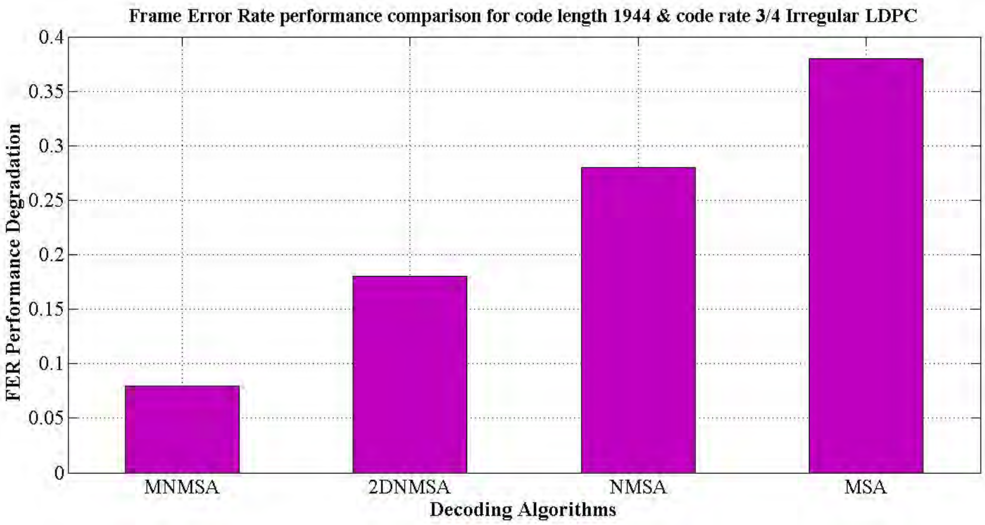

Fig.8 FER decoding performance degradation comparison between proposed MNMSA and other decoding algorithms with respect to BP algorithm at FER of 10^{-3}

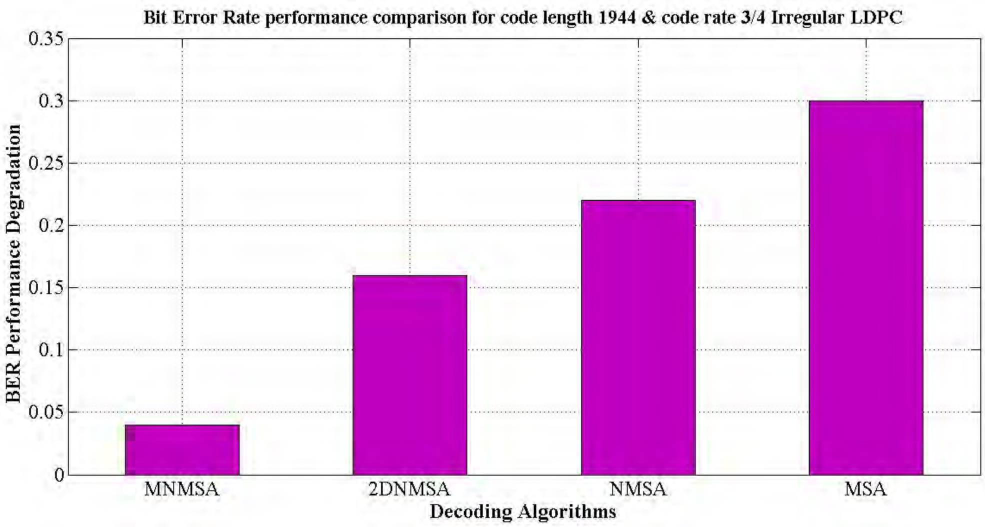

Fig.9 BER decoding performance degradation comparison between proposed MNMSA and other decoding algorithms with respect to BP algorithm BER of 10^{-5}

Table 2 Comparison of proposed MNMSA algorithm and other existing algorithms

Decoding Algorithm	**LDPC Code Standard**	**Block Size**	**Code Rate**	**Required SNR to achieve FER of 10^{-3} (dB)**	**Required SNR to achieve BER of 10^{-5} (dB)**
Belief Propagation Algorithm [6]	WLAN IEEE(802.11n) Standard [3]	1944	1/2	2.58	2.60
			2/3	2.61	2.72
			3/4	2.72	2.78
Proposed Modified Normalized Min-Sum Algorithm	WLAN IEEE(802.11n) Standard [3]	1944	1/2	2.62	2.68
			2/3	2.64	2.78
			3/4	2.80	2.82
2D-Normalized Min-Sum Algorithm [12]	WLAN IEEE(802.11n) Standard [3]	1944	1/2	2.74	2.78
			2/3	2.78	2.88
			3/4	2.90	2.94
Normalized Min-Sum Algorithm [9]	WLAN IEEE(802.11n) Standard [3]	1944	1/2	2.82	2.82
			2/3	2.84	2.98
			3/4	3.00	3.00
Min-Sum Algorithm [7]	WLAN IEEE(802.11n) Standard [3]	1944	1/2	2.90	2.90
			2/3	3.00	3.20
			3/4	3.10	3.08

The normalization factors used in proposed algorithm which are obtained by heuristic simulations can be implemented with simple shifting and less complex addition operations. This reduces the hardware complexity of the proposed MNMSA without compromising the decoding performance. Therefore, the proposed MNMSA algorithm with optimally combined normalization factor and down scaling factors influence the convergence speed of decoding process and achieves good decoding performance without requiring large number of decoding iterations to correct the channel errors at relatively low SNR.

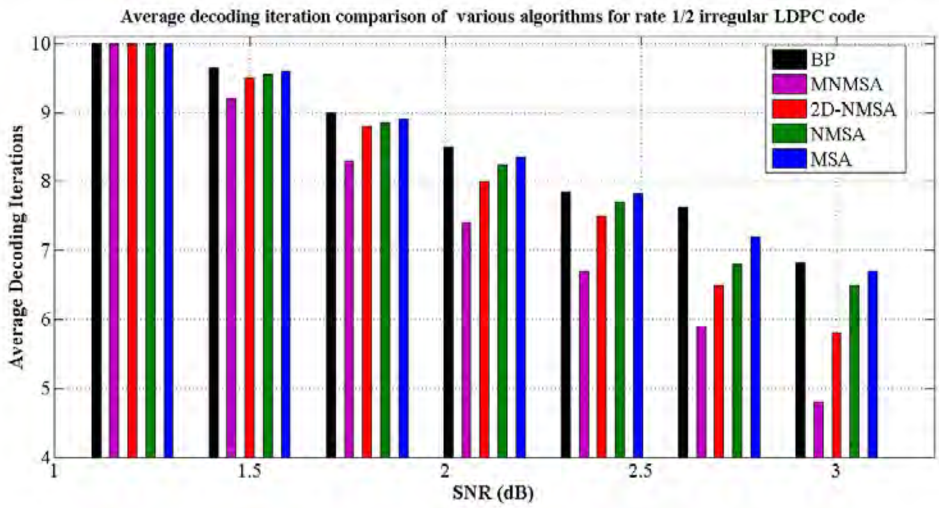

Fig.10 Average decoding iteration comparison between proposed MNMSA and other decoding algorithms

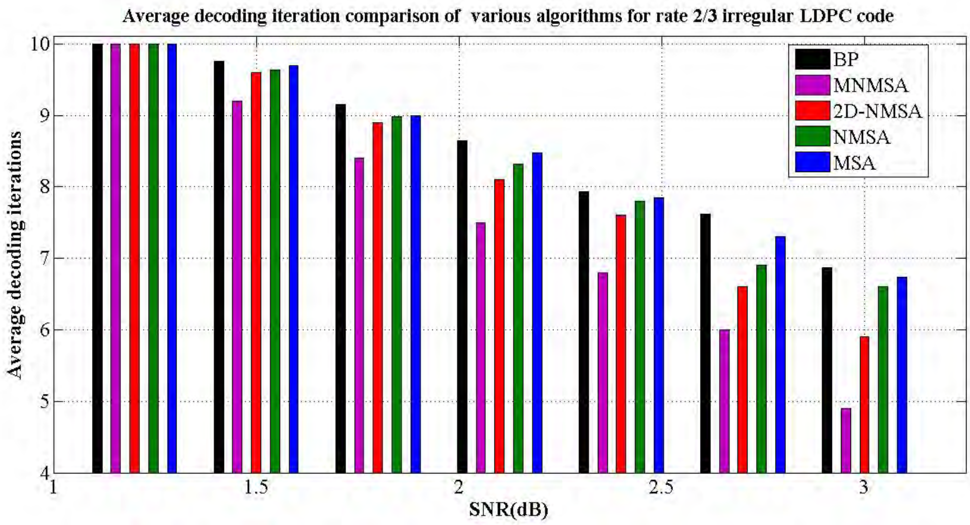

Fig.11 Average decoding iteration comparison between proposed MNMSA and other decoding algorithms

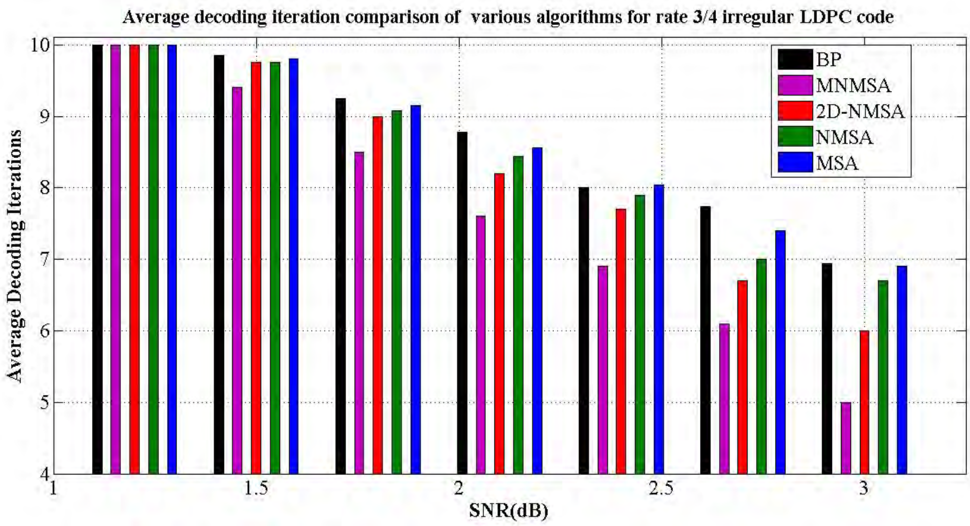

Fig.12 Average decoding iteration comparison between proposed MNMSA and other decoding algorithms

5.0 Conclusion

In this paper, a modified normalized Min-Sum algorithm (MNMSA) suitable for hardware implementation is proposed. Compared to other decoding algorithms the proposed MNMSA achieves good error correcting performance in terms of FER and BER with only small performance degradation of 0.1 dB. The proposed algorithm sorts out the magnitude overestimation issue and requirement for more decoding iterations by effectively utilizing 6 - bit quantization scheme and optimal combination of normalization and down scaling factors. The simulation results show that the proposed algorithm requires only fewer decoding iterations to achieve decoding performance close BP algorithm and better than other Min-Sum algorithms. Therefore, the proposed MNMSA is more suitable for hardware implementation since it reduces total number of memory bits per iteration and achieves reasonable error performance which is compatible for emerging wireless applications.

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BIOGRAPHY

Michaelraj Kingston Roberts received M.E degree in (Communication Systems) from Anna University of Technology Coimbatore in 2011and his B.E (ECE) degree from Hindustan College of Engineering and Technology Coimbatore in 2009, where he is currently working towards the Ph.D degree in faculty information and communication engineering under guidance of Dr. Ramesh JAYABALAN. His general research areas include Error Control Coding, Information - Theory Coding and Digital Communication.

Dr. Ramesh JAYABALAN received the BE degree in ECE from Bharathiar University, Coimbatore in the year 1995. He obtained his ME degree in communication systems in 1997 from NIT Trichy. He completed his Ph.D in the year 2009 from Anna University, Chennai. His area of interest includes Low Power VLSI design, Design and testing of Digital, Analog and Mixed Signal VLSI circuits and Communication Systems. He is currently working as a Assistant Professor (Sr.Gr) in the ECE department of PSG College of Technology, Coimbatore, Tamil Nadu, India. He is having around 17 years of teaching experience. He is a life member of ISTE. He is having 6 National and International Journal publications and more than 25 national and International conference publications.