

# **An Efficient C Language Based Message Passing Codec for LDPC**

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This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge, it contains no material previously published or written by another person, except where due reference is made in the text.

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# ABSTRACT

The term Low-Density Parity Check code was firstly introduced by Dr. Gallager in the year 1963 and reinvented by Mackay and Neal in 1996 (Mackay and Neal's decoding algorithm). This particular code has contributed extraordinarily to many peoples' research works and has been utilized in a diverse range of applications in the signal processing domain. One of the applications is the Digital Video Broadcasting – Satellite generation 2 (DVB-S2).

In this thesis, the basic knowledge of the encoding process and decoding process are firstly introduced. Additionally, the currently used DVB-S2 standard encoding algorithm is explained in detail. Furthermore, four types of message - passing decoding algorithms (Erasure decoding, Bit-flipping decoding, Sum-product decoding and Mackay and Neal's decoding algorithms) are detailed illustrated.

Next, the first attempt on implementing a low-complex encoding algorithm is demonstrated with detailed coding procedures provided. What's more, the realized MN decoder of the Mackay and Neal's decoding algorithm is also fully interpreted.

Apart from these, the comparison of the practical decoding performance of the Sum-product decoder and the new constructed MN decoder will be shown with detailed analysis provided.

In addition to the conclusion, the future development of the decoder is also suggested so that those who might use this thesis as a reference for their academic research could obtain some valuable ideas.

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# Glossary of Terms

Symbol /Abbreviation	Description
AWGN	Additive white Gaussian Noise
$B_i$	Set of bits in the i-th parity check equation
BER	Bit Error Rate
$c$	Encoded codeword
$E$	Extrinsic information matrix
$E_b/N_0$	Signal to noise ratio
$G$	Generator matrix
$H$	Parity check matrix
$K$	Original message length in codeword
$L$	Updated Log likelihood ratio
LDPC	Low-density parity check
$LLR$	Log likelihood ratio
$p_i$	Parity check bits
$M_{j,i}$	Message sent from bit nRode j to check node i
$n$	Transmitted code length
$k$	Original code length
$Q0$	Hard decision determinant for $p(x=0)$
$Q1$	Hard decision determinant for $p(x=1)$
$r$	Received codeword
$s$	Syndrome
$\delta q$	$Q0-Q1$
$f0$	Initial likelihood value of $p(x=0)$
$f1$	Initial likelihood value of $p(x=0)$
$Q0$	Initial / updated likelihood value of $p(x=0)$
$Q1$	Initial / updated likelihood value of $p(x=1)$
$u$	Original message bits
$y$	Decoded codeword

# 1. Introduction

## 1.1 An Efficient C Language Based Message Passing Codec for LDPC

Along with the growth of the living standard and disposable income of the public, the demand for accurate and fast signal transmission technology is increasing. In the field of audio-visual experience, a systematic standard named Second Generation of Digital Video Broadcasting – Satellite (DVBS2, 2012) is widely applied to digital television system in many countries, such as the USA, Canada, Greenland, Saint Pierre and Miquelon and etc. (SRG SSR, 2016) due to its wide coverage and the large capacity of the programs. Furthermore, its theoretical transmitting data rate can reach up to 10Mb/s (Satellite end DVB, 2016), which realizes the simultaneously using of multi-programs while keeping the high quality of audio-visual experience.

When it comes to the domain of signal transmission, messages are firstly transmitted in the form of strings which consist of binary values ‘0’s and ‘1’s (Sarah Johnson, 2006). Then, based on the ASCII standard code, messages will be converted to corresponding characters and symbols, and finally represented to receivers. However, in the real world, there are a host of noise signals which can negatively affect the original message sent from the transmitter (such as randomly add a series of decimals to the bit values) and consequently cause the inaccurate data received at the receiver. Therefore, the method of automatic error detection and correction should be of great concern to the signal processing stage at the receiver.

In 1962, the term Low-density parity-check (LDPC) code was first introduced by doctor Gallager at MIT (Robert G. Gallager, 1963). It is a block code with a parity-check matrix which has only a small quantity of ‘1’s inside. Hence, the complexity of encoding and decoding process can be reduced by the sparseness of the matrix.

Up to now, a diverse range of the methods for constructing LDPC code have been introduced by many researchers. Such as Gallager’s parity-check matrices, constructing method



proposed by MacKay and Neal (MacKay and Neal, 1996), decoding algorithm introduced by Gottfried Lechner and Jossy Sayiretc (Gottfried Lechner and Jossy Sayir, 2004), etc. Although these methods were recognized as effective and efficient, the performance of the methods might be lower than expectations after constructing the methods in practice.

This project – An Efficient C Language Based Message Passing Codec for LDPC - aims to address the most efficient and feasible codec and seek for further improvement by comparing the actual performances after C programming. Previous research works on LDPC were used as references throughout the compiling and debugging stages.

Procedure of this project:

- Chose the most feasible method for implementing the codec from the existing theses.
- Construct the codec in C platform and test the processing speed.
- Compare the performance with the currently used code.
- Seek for further acceleration on the processing time of error detection and correction.

## **1.2 Outline**

### **Theory**

Briefly introduce the encoding and decoding process with correlated symbols and their relationships described.

DVB-S2 standard encoding algorithm is demonstrated in detail.

The comparison of different message-passing decoding algorithms is introduced.

The theories of existing decoder and new decoder are introduced in detail.

### **Methodology**

The methodology of implementing theoretical algorithms in C is fully described.

The methods of improving the performance and feasibility are described in detail.

### **Result and Discussion**

Practical performance of the decoder is analyzed.

Results from the sum-product decoder and the new decoder are fully compared and analyzed.

### **Conclusion and Future Development**

The project is briefly summarized. The review of the outcomes and the suggestions of future development are provided.

## 2. Theory Background

In the domain of signal processing, signals are firstly converted to binary sequences before being transmitted. In other words, each transmitted message is actually a sequence of binary number ‘1’s and ‘0’s. To begin with, it is necessary to introduce the relationships of original message  $\mathbf{u}$ , encoded codeword  $\mathbf{c}$ , received codeword  $\mathbf{r}$  and decoded codeword  $\mathbf{y}$ .

### 2.1 Brief introduction of encoding process

In the transmitter terminal, the original message  $\mathbf{u}$  - which contains  $\mathbf{k}$  message bits - is firstly encoded to codeword  $\mathbf{c}$  based on the module-2 additive equation  $\mathbf{c} = \mathbf{uG}$  (where  $\mathbf{G}$  is the generator matrix of the code in the size of  $\mathbf{k} * \mathbf{n}$  and  $\mathbf{n}$  is the code length of the encoded codeword  $\mathbf{c}$ ). The form of the matrix  $\mathbf{G}$  can be separated into two parts: a  $\mathbf{k} * \mathbf{k}$  identity matrix  $\mathbf{I}_k$  and the following matrix  $\mathbf{A}$  in the size of  $\mathbf{k} * (\mathbf{n}-\mathbf{k})$ . That is the form of matrix  $\mathbf{G}$  is  $[\mathbf{I}_k, \mathbf{A}_{k*(n-k)}]$ . Therefore, the first  $\mathbf{k}$  bits of the encoded codeword  $\mathbf{c}$  are exactly the same as the bits of the original codeword  $\mathbf{u}$  after encoding process. Additionally, the remaining  $\mathbf{n}-\mathbf{k}$  bits of  $\mathbf{c}$  will be the parity check bits.

$$\begin{bmatrix} c_1 & c_2 & c_3 & c_4 & c_5 & c_6 \end{bmatrix} = \begin{bmatrix} u_1 & u_2 & u_3 \end{bmatrix} \underbrace{\begin{bmatrix} \overbrace{1 \ 0 \ 0}^{\mathbf{I}_3} & \overbrace{1 \ 0 \ 1}^{\mathbf{A}_{3*3}} \\ 0 \ 1 \ 0 & 1 \ 1 \ 1 \\ 0 \ 0 \ 1 & 0 \ 1 \ 1 \end{bmatrix}}_{\mathbf{G}}$$

Figure 2.1: Encoding Algorithm with  $\mathbf{k} = 3$  and  $\mathbf{n} = 6$

## 2.2 Brief introduction of LDPC decoding process

In the ideal case, the received message codeword  $\mathbf{r}$  in the receiver should always be the same as the encoded codeword  $\mathbf{c}$  sent from the transmitter. However, in the real world, errors could occur during the transmission and so the parity-checks become useful to detect whether the error happens during the transmission.

For a received codeword  $\mathbf{r} = [r_1 \ r_2 \ r_3 \ r_4 \ r_5 \ r_6 \ r_7 \ r_8]$ , the bits should always satisfy the following parity-check equation:

$$r_1 \oplus r_2 \oplus r_3 \oplus r_4 \oplus r_5 \oplus r_6 \oplus r_7 \oplus r_8 = 0;$$

Where each bit  $r_i$  is either '1' or '0' and  $\oplus$  means modulo-2 addition.

If the result is '1', then at least one error has occurred during the transmission.

However, parity-check equations can only check the occurring of errors without indicating which bits are wrong. Furthermore, errors can only be detected but not able to be corrected by only applying a single parity-check equation. Therefore, parity-check matrix  $\mathbf{H}$  comes in handy.

The matrix  $\mathbf{H}$  is actually the orthogonal matrix of  $\mathbf{G}$ , that is the matrices  $\mathbf{H}$  and  $\mathbf{G}$  should satisfy that  $\mathbf{GH}^T = 0$ . As it was mentioned in the previous section, for a length  $\mathbf{k}$  codeword  $\mathbf{u}$  and its encoded codeword with a length of  $\mathbf{n}$ , the size of generator matrix  $\mathbf{G}$  should be  $\mathbf{k} * \mathbf{n}$  and in the form  $\mathbf{G} = [\mathbf{I}_k, \mathbf{A}_{k*(n-k)}]$ . Therefore, the size of  $\mathbf{H}$  should be  $(\mathbf{n}-\mathbf{k}) * \mathbf{n}$  ( $\mathbf{n}-\mathbf{k}$  check nodes and  $\mathbf{n}$  bit nodes), and the form of  $\mathbf{H}$  is supposed to be  $\mathbf{H} = [\mathbf{A}^T, \mathbf{I}_{n-k}]$

*Example 2.2:*

---


$$\mathbf{r} = [r_1 \ r_2 \ r_3 \ r_4 \ r_5 \ r_6], \quad \mathbf{H} = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{s} = \mathbf{H}\mathbf{r}^T = \underbrace{\begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 1 \end{bmatrix}}_{\mathbf{H}} \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \\ r_5 \\ r_6 \end{bmatrix} = \begin{bmatrix} r_1 \oplus r_2 \oplus r_4 \\ r_2 \oplus r_3 \oplus r_5 \\ r_1 \oplus r_2 \oplus r_3 \oplus r_6 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$


---

As shown in example 2.2, in the parity-check matrix  $\mathbf{H}$ , each row represents a parity-check equation and each column of  $\mathbf{H}$  indicates one bit in the codeword. So, if a received codeword  $\mathbf{r}$  and its parity-check matrix  $\mathbf{H}$  are known in advance, the codeword is valid only if:  $\mathbf{s} = \mathbf{H}\mathbf{r}^T = 0$ , where  $\mathbf{r}^T$  is the transpose matrix of the codeword  $\mathbf{r}$  and  $\mathbf{s}$  is the syndrome of the codeword  $\mathbf{r}$ . In the example, since all the three parity check equations equal to '0', the received codeword  $\mathbf{r}$  is valid. Hence, the first  $\mathbf{k}$  bits of  $\mathbf{r}$  will be extracted as the decoded codeword  $\mathbf{y}$ , which should be exactly the same as the original message  $\mathbf{u}$ . If any one of the equations equals to '1', then the error can be located in the correlated bits of the corresponding equation.

### 2.3 DVB-S2 standard encoding algorithm

Theoretically, the parity check bits should be the last  $\mathbf{n-k}$  bits of the codeword  $\mathbf{c}$ , which were calculated from the equation  $\mathbf{c} = \mathbf{u}\mathbf{G}$ . However, unlike the programming languages such as Matlab, which was generated for operating the matrix related calculation, C programming performs poorly in handling with the calculations of matrix. In other words, building a generator matrix with the size of 7200 x 16200 is extremely time-consuming and kind of wasting memory resource. Nevertheless, if 2D matrices can be converted to 1D vectors, the speed of operating algorithmic calculations will be sharply accelerated. Fortunately, the European Standard inner encoding algorithm (EBU-UER, 2009) has introduced the method to address the problem. In this thesis, the algorithm for 16200 coded block with half rate is demonstrated as the example.

As mentioned in previous sections, in the encoded codeword  $\mathbf{c}$  which has the length of  $\mathbf{n}=16200$ , the first  $\mathbf{k} = 7200$  bits are exactly the same as the original message  $\mathbf{u}$ , and the remaining  $\mathbf{n-k} = 9000$  bits are the parity check bits ( $\mathbf{p}_0, \mathbf{p}_1, \dots, \mathbf{p}_{8999}$ ) of the codeword. That is  $\mathbf{c} = (\mathbf{u}_0, \mathbf{u}_1, \dots, \mathbf{u}_{7198}, \mathbf{u}_{7199}, \mathbf{p}_0, \mathbf{p}_1, \dots, \mathbf{p}_{8999})$ . Since the bits of original message  $\mathbf{u}$  have been stored in the memory locations of the transmitter, the parity check bits can be acquired from the information bits  $\mathbf{u}_i$  (where  $i \in (0, 7199)$ ) at the designated addresses in the  $i^{\text{th}}$  line of the table shown in Appendix A. Detailed procedures are shown as follow:

- Initially, all parity check bits are reset to '0'.
- Then update the specified bits shown in the 1<sup>st</sup> row of the table in Appendix A:

$$\begin{aligned}
p_{20} &= p_{20} \oplus u_0, & p_{712} &= p_{712} \oplus u_0, \\
p_{2386} &= p_{2386} \oplus u_0, & p_{6354} &= p_{6354} \oplus u_0, \\
p_{4061} &= p_{4061} \oplus u_0, & p_{1062} &= p_{1062} \oplus u_0, \\
p_{5045} &= p_{5045} \oplus u_0, & p_{5158} &= p_{5158} \oplus u_0,
\end{aligned}$$

- Similarly, update the specified bits shown in the second row of the table in Appendix A:

$$\begin{aligned}
p_{45} &= p_{45} \oplus u_1, & p_{737} &= p_{737} \oplus u_1, \\
p_{2411} &= p_{2411} \oplus u_1, & p_{6379} &= p_{6379} \oplus u_1, \\
p_{4086} &= p_{4086} \oplus u_1, & p_{1087} &= p_{1087} \oplus u_1, \\
p_{5070} &= p_{5070} \oplus u_1, & p_{5183} &= p_{5183} \oplus u_1,
\end{aligned}$$

- Repeat the procedure for each following row until reaching the row 1800.
- For the row 1801, update the specified bits shown in Appendix A:

$$p_0 = p_0 \oplus u_{1800}, \quad p_{4046} = p_{4046} \oplus u_{1800}, \quad p_{6934} = p_{6934} \oplus u_{1800}$$

- Repeat above procedure for the remaining rows until the end of the table.

Once all the parity check bits are refreshed, the encoded codeword  $\mathbf{c}$  with the length of 16200(7200+9000) can be obtained from:

$$\mathbf{c} = (\mathbf{u}_0, \mathbf{u}_1, \dots, \mathbf{u}_{7198}, \mathbf{u}_{7199}, \mathbf{p}_0, \mathbf{p}_1, \dots, \mathbf{p}_{8998}, \mathbf{p}_{8999})$$

Practical results showed that the efficiency of the way for encoding the original message codeword is significantly higher than that of generating the encoded codeword directly from the pre-constructed generator matrix. Detailed discussion and analyzing will be shown in section 3.

## 2.4 Algorithms of Message- Passing Decoder

In this section, four message passing decoding algorithms (Erasure Decoding, Bit-Flipping Decoding, Sum-Product Decoding and Mackay and Neal's Decoding algorithms) are introduced on the theoretical level. In addition, reasonable justifications for the final choice of the implemented decoding algorithm are also provided.

### 2.4.1 Erasure Decoding

According to previous sections, in a parity check matrix  $\mathbf{H}$ , each row represents a single parity check equation and the value of each bit in the equation is either '1' or '0'. In order to simplify the decoding process and save the memory resources, only the column indexes of '1's in a parity check equation are necessary to be recorded in a new vector  $\mathbf{B}_i$ , where 'i' indicates the index of the parity check equation in the matrix  $\mathbf{H}$ . Therefore, if there is at least one parity check equation which contains only one unknown bit while other bit-values are known, the value of the unknown bit can be estimated by applying the module-2 addition on the known bits in the same parity check equation. Detailed procedures can be shown in the following example.

#### Example 2.4.1

---

After transmitting through an erasure channel, the encoded codeword  $\mathbf{c} = [0\ 0\ 1\ 0\ 1\ 1]$  was received as  $\mathbf{r} = [0\ 0\ 1\ x\ x\ x]$ .

Given that the parity check matrix  $\mathbf{H}$  for the code is known as:  $H = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 \end{bmatrix}$

Then the vectors which include the positions of '1's in each row can be obtained as:

$$\mathbf{B}_1 = \{1, 2, 4\} \quad \mathbf{B}_2 = \{2, 3, 5\} \quad \mathbf{B}_3 = \{1, 5, 6\} \quad \mathbf{B}_4 = \{3, 4, 6\}$$

So from  $\mathbf{B}_1$ :  $\mathbf{r}_4 = \mathbf{r}_1 \oplus \mathbf{r}_2 = 0 \oplus 0 = 0$ ;

Similarly, from  $\mathbf{B}_2$ :  $\mathbf{r}_5 = \mathbf{r}_2 \oplus \mathbf{r}_3 = 0 \oplus 1 = 1$ ;

Since  $\mathbf{y}_4$  is known now, the value of  $\mathbf{y}_6$  can be obtained from  $\mathbf{B}_4$ :

$$\mathbf{r}_6 = \mathbf{r}_3 \oplus \mathbf{r}_4 = 1 \oplus 0 = 1.$$

Therefore, the recovered codeword is:

$$\mathbf{r} = [0\ 0\ 1\ 0\ 1\ 1]$$

which is the same as the transmitted codeword

$$\mathbf{c} = [0\ 0\ 1\ 0\ 1\ 1].$$

---

The erasure decoding provides a simplest but efficient way to recover the erased bits. However, if none of the parity check equations contains only one unknown bit-value, the transmitted codeword might not be fully recovered. Moreover, since the noise signals are randomly added to the transmitted signal, it is not able to ensure that there always exists a parity check equation which contains only one unknown bit. Therefore, this algorithm can not be used for the message passing decoder of DVB-S2.

#### 2.4.2 Bit-Flipping Decoding

The algorithm Bit-Flipping Decoding is similar to Erasure Decoding process. The only difference is that in addition to using the sets of bits  $\mathbf{B}_i$  only, each received bit-value also contributes to determining the final value of the codeword. To be brief, majority rule is the second step of bit correction. Detailed decoding procedures are shown in the following example.

##### *Example 2.4.2*

---

Recall example 2.4.1: The encoded codeword is  $\mathbf{c} = [0\ 0\ 1\ 0\ 1\ 1]$  and now the received codeword becomes to  $\mathbf{r} = [1\ 0\ 1\ 0\ 1\ 1]$  (after traveling through a BSC channel with crossover probability:  $p = 0.2$ ).

From the parity check matrix  $\mathbf{H}$ :

$$\mathbf{B}_1 = \{1, 2, 4\} \quad \mathbf{B}_2 = \{2, 3, 5\} \quad \mathbf{B}_3 = \{1, 5, 6\} \quad \mathbf{B}_4 = \{3, 4, 6\}$$

Firstly, similar calculation procedures shown in example 2.4.1 are applied to calculate values of the bits in each parity check equation ' $\mathbf{B}_i$ '. Calculating results can be shown in the following table:



Table 2.4.2: Bit values calculated from each parity check equation

Bit Value Resource	$r_1$	$r_2$	$r_3$	$r_4$	$r_5$	$r_6$
$B_1$ suggested	0	1		1		
$B_2$ suggested		0	1		1	
$B_3$ suggested	0				0	0
$B_4$ suggested			1	0		1
Received	1	0	1	0	1	1

Secondly, count the number of ‘1’s and ‘0’s in each column and then take the dominant value as the final value of the corresponding bit.

So, for bit  $r_1$ , 2/3 of the results suggested that the value should be ‘0’ rather than ‘1’.

Therefore,  $r_1$  is refreshed to ‘0’;

For bit  $r_2$ , 2/3 of the results suggested that bit value of  $r_2$  should remain ‘0’ and so  $r_2$  remains unchanged ( $r_2 = '0'$ ).

Consequently, the corrected codeword is:  $\mathbf{r} = [0\ 0\ 1\ 0\ 1\ 1]$ , which is the same as the transmitted value  $\mathbf{c} = [0\ 0\ 1\ 0\ 1\ 1]$ .

In order to verify whether the corrected bit-values are valid, parity check vectors ranging from  $\mathbf{B}_1$  to  $\mathbf{B}_4$  are applied on the refreshed codeword  $\mathbf{r}$ :

$$\text{From } \mathbf{B}_1: r_1 \oplus r_2 \oplus r_4 = 0 \oplus 0 \oplus 0 = 0 \text{ (Valid);}$$

$$\text{From } \mathbf{B}_2: r_2 \oplus r_3 \oplus r_5 = 0 \oplus 1 \oplus 1 = 0 \text{ (Valid);}$$

$$\text{From } \mathbf{B}_3: r_1 \oplus r_5 \oplus r_6 = 0 \oplus 1 \oplus 1 = 0 \text{ (Valid);}$$

$$\text{From } \mathbf{B}_4: r_3 \oplus r_4 \oplus r_6 = 1 \oplus 0 \oplus 1 = 0 \text{ (Valid);}$$

Since all the parity check equations are satisfied, the decoding algorithm completes. Otherwise, algorithm should repeat until the final codeword is valid.

Obviously, the bit-flipping algorithm further improved the decoding performance of the erasure decoding algorithm. Error bit-values can be detected and corrected even if more than 1 errors existing in the codeword. However, if there are two or more bits involved in the same parity-check equations, the system would not be able to locate the error bit accurately. Similarly, considering that the noise signals are randomly added to the transmitted codeword in the real case, this algorithm is not taken into account for the message passing decoder of DVB-S2.

### 2.4.3 Sum-Product Decoding

Unlike the previous decoding algorithms, Sum-Product algorithm is a soft decision message passing algorithm (Sarah Johnson, 2006). Which means that rather than received bits themselves, the probabilities of bit-values are utilized as the inputs of the algorithm.

As is was mentioned in previous sections, in the signal transmission domain, message bits are transmitted as binary values '0's or '1's. Therefore, for the value of a single codeword bit, there always exists a relationship between the likelihood that the value of bit  $\mathbf{x}$  is '1' and the likelihood that the value of the same bit is '0':  $p(\mathbf{x}=1) = 1 - p(\mathbf{x}=0)$ . So, the log likelihood ratio (LLR) for bit  $\mathbf{x}$  can be represented as:  $LLR(\mathbf{x}) = \log (p(\mathbf{x}=0) / p(\mathbf{x}=1))$ . Obviously, if the probability of  $\mathbf{x} = 0$  is larger than that of  $\mathbf{x} = 1$ , the value of the variable  $LLR(\mathbf{x})$  would be positive; In contrast, if the probability of  $\mathbf{x} = 0$  is smaller than that of  $\mathbf{x} = 1$ , the value of  $LLR(\mathbf{x})$  would be negative. Furthermore, the greater that the absolute value of  $LLR(\mathbf{x})$  is, the more reliable that the suggested bit-value will be.

In fact, the Sum-product decoding algorithm is similar to the Bit-flipping algorithm. As each column in the parity check matrix  $\mathbf{H}$  is actually the index of the corresponding codeword bit which participating in certain parity check equations, the Sum-product algorithm firstly calculates the log likelihood value of each codeword bit and assigns this probability to the positions of '1's in the corresponding column of a temporary matrix (which has the same size of  $\mathbf{H}$ ); then figures out the signed product of these elements to obtain the overall probability by iteratively applying the associated parity check equations. After combining the likelihood

product and the log likelihood value of the bit (calculate the sum of the two results), the final sum-product probability of the bit can be worked out. Therefore, if the probability value is positive, the bit value will be refreshed to '0'; Otherwise, it will be refreshed to '1'. This procedure will be repeated bit by bit and then the validity of the updated codeword  $\mathbf{r}$  will be checked by applying the equation:  $\mathbf{s} = \mathbf{H} * \mathbf{z}^T$  (where  $\mathbf{z}$  is the corrected codeword). If there is any element in the syndrome  $\mathbf{s} \neq '0'$ , the whole algorithm will be repeated from the second step.

Detailed procedures of the algorithm can be viewed in the following example.

#### Example 2.4.3

---

Same as example 2.4.2, the codeword  $\mathbf{c} = [0 \ 0 \ 1 \ 0 \ 1 \ 1]$  was received as  $\mathbf{r} = [1 \ 0 \ 1 \ 0 \ 1 \ 1]$  after traveling through the same BSC (crossover probability  $p = 0.2$ ).

For this codeword, the log likelihood of ' $\mathbf{r}_i = 1$ ' is  $\log(0.2/0.8) = -1.3863$  and the log likelihood of ' $\mathbf{r}_i = 0$ ' is  $\log(0.8/0.2) = 1.3863$ .

Therefore, the vector  $\mathbf{r}$  will be firstly refreshed as:

$$\mathbf{r} = [-1.3863, 1.3863, -1.3863, 1.3863, -1.3863, -1.3863].$$

And so, the matrix  $\mathbf{M}$  which has the same size of  $\mathbf{H}$  becomes to:

$$\mathbf{M} = \begin{bmatrix} -1.3863 & 1.3863 & 0 & 1.3863 & 0 & 0 \\ 0 & 1.3863 & -1.3863 & 0 & -1.3863 & 0 \\ -1.3863 & 0 & 0 & 0 & -1.3863 & -1.3863 \\ 0 & 0 & -1.3863 & 1.3863 & 0 & -1.3863 \end{bmatrix}$$

Therefore, the message sent from the bit node  $j$  to the check node  $i$  can be represented as  $M_{j,i}$ , which is also the log formed current estimated probability of the codeword's bit  $i = '1'$  according to check  $j$ .

Hence, the extrinsic message from check node  $j$  to bit node  $i$ , or the LLR of the probability that bit  $i$  causes parity-check  $j$  to be satisfied is:

$$E_{j,i} = \log \left( \frac{1 + \prod_{i' \in B_j, i' \neq i} \tanh(M_{j,i'}/2)}{1 - \prod_{i' \in B_j, i' \neq i} \tanh(M_{j,i'}/2)} \right)$$

Where:

$$\tanh \left( \frac{1}{2} \log \left( \frac{1 - \text{sq1}}{\text{sq1}} \right) \right) = 1 - 2 \text{sq1}$$

And:

$$M_{j,i} \neq 0;$$

Since in this example:

$$B_1 = \{1, 2, 4\}; \quad B_2 = \{2, 3, 5\}; \quad B_3 = \{1, 5, 6\}; \quad B_4 = \{3, 4, 6\};$$

So, from  $B_1$ :

$$\begin{aligned} E_{1,1} &= \log \left( \frac{1 + \tanh(M_{1,2}/2) \tanh(M_{1,4}/2)}{1 - \tanh(M_{1,2}/2) \tanh(M_{1,4}/2)} \right) \\ &= \log \left( \frac{1 + \tanh(1.3863/2) \tanh(1.3863/2)}{1 - \tanh(1.3863/2) \tanh(1.3863/2)} \right) \\ &= \log \left( \frac{1 + 0.6 * 0.6}{1 - 0.6 * 0.6} \right) = 0.7538. \end{aligned}$$

$$\begin{aligned} E_{1,2} &= \log \left( \frac{1 + \tanh(M_{1,1}/2) \tanh(M_{1,4}/2)}{1 - \tanh(M_{1,1}/2) \tanh(M_{1,4}/2)} \right) \\ &= \log \left( \frac{1 + \tanh(-1.3863/2) \tanh(1.3863/2)}{1 - \tanh(-1.3863/2) \tanh(1.3863/2)} \right) \\ &= \log \left( \frac{1 - 0.6 * 0.6}{1 - -0.6 * 0.6} \right) = -0.7538, \end{aligned}$$

$$\begin{aligned} E_{1,4} &= \log \left( \frac{1 + \tanh(M_{1,1}/2) \tanh(M_{1,2}/2)}{1 - \tanh(M_{1,1}/2) \tanh(M_{1,2}/2)} \right) \\ &= \log \left( \frac{1 + \tanh(-1.3863/2) \tanh(1.3863/2)}{1 - \tanh(-1.3863/2) \tanh(1.3863/2)} \right) \\ &= \log \left( \frac{1 - 0.6 * 0.6}{1 - -0.6 * 0.6} \right) = -0.7538. \end{aligned}$$

Repeat the calculations for each sets of parity check equations, the extrinsic LLRs will be:

$$E = \begin{bmatrix} 0.7538 & -0.7538 & 0 & -0.7538 & 0 & 0 \\ 0 & 0.7538 & -0.7538 & 0 & -0.7538 & 0 \\ 0.7538 & 0 & 0 & 0 & 0.7538 & 0.7538 \\ 0 & 0 & -0.7538 & 0.7538 & 0 & -0.7538 \end{bmatrix}$$

So the sums of non-zero elements in the matrix E will be:

$$Sum_E = [ 1.5076 \quad 0 \quad -1.5076 \quad 0 \quad 0 \quad 0 ]$$

Since the updated likelihood of each codeword bit:  $L_i = \mathbf{r}_i + Sum_E(i)$ , therefore:

$$\mathbf{r}_i \quad [ -1.3863 \quad 1.3863 \quad -1.3863 \quad 1.3863 \quad -1.3863 \quad -1.3863 ]$$

$$\begin{aligned}
&+ \\
Sum_E & \quad [ \quad 1.5076 \quad \quad 0 \quad \quad -1.5076 \quad \quad 0 \quad \quad 0 \quad \quad 0 \quad ] \\
&|| \\
L_i & \quad [ \quad 0.1213 \quad \quad 1.3863 \quad \quad -2.8938 \quad \quad 1.3863 \quad \quad -1.3863 \quad \quad -1.3863 ]
\end{aligned}$$

After applying the hard decision on received bits based on the sign of  $L_i$ , the corrected codeword will be:

$$\mathbf{z} = [ \quad 0 \quad 0 \quad 1 \quad 0 \quad 1 \quad 1 \quad ].$$

And the syndrome  $\mathbf{s}$  will be:

$$\mathbf{s} = \mathbf{H} * \mathbf{z}^T = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Therefore, the codeword  $\mathbf{z}$  is valid.

---

#### 2.4.4 Mackay and Neal's Decoding

In the year 1996, Doctor Mackay and Neal published a reinvented Gallager's Decoding algorithm (MacKay and Neal, 1996), which is called MN decoding algorithm. In this algorithm, the likelihoods of original bit-values were utilized to provide the hard decision for correcting the bit-values. However, rather than cumulative addition and cumulative multiplication used in the Sum-Product algorithm, only cumulative multiplication was involved in the algorithm. Furthermore, the signal to noise ratio (SNR) of AWGN channel was covered in the decoding process so that the error detecting and correcting processes could perform more accurate and faster. Brief introduction of the decoding process is shown in the following paragraphs.

For a received encoded codeword which has been interfered by an AWGN channel with the variance  $\sigma^2 = 1$ , the corresponding SNR can always be represented as:

$$SNR = \frac{E_b}{N_0} = \frac{a^2}{2R}$$

(Where ' $\pm a$ ' is the binary input of the noise signal, and  $R$  is the code rate of the transmitted codeword.). So, if the SNR for a 1/2 rate 16200-length (DVB-S2 standard) codeword is known,

the value of ‘ $\alpha$ ’ is exactly the root-value of SNR, that is  $\alpha = \text{SNR}^{1/2}$ . Therefore, the initial likelihood for the received bit  $\mathbf{r}_n = 1$  can be represented as:

$$f_n^1 = 1/(1+\exp(-2*\alpha*\mathbf{r}_n));$$

where  $n \in (1: 16200)$ .

Since each bit-value is either ‘1’ or ‘0’, the initial likelihood of  $\mathbf{r}_n = 0$  is:

$$f_n^0 = 1 - f_n^1.$$

So for a 16200-length codeword, the length of the two vectors  $f^0$  and  $f^1$  should both equal to 16200. Once these two vectors have been constructed, the values of each pair of initial likelihoods will be assigned to the associated nonzero positions in the two 2D likelihood arrays  $Q_{mn}^0$  and  $Q_{mn}^1$  respectively, where  $Q_{mn}^0$  and  $Q_{mn}^1$  are in the same size of the parity check matrix  $\mathbf{H}$  for the received codeword  $\mathbf{r}$ , and  $\mathbf{m}$  is the number of checks while  $\mathbf{n}$  is the number of bits. That is  $Q_{mn}^0$  actually means: the probability of parity-check  $\mathbf{m}$  being satisfied when bit  $\mathbf{r}_n = 0$ . Until now, the initialization step is finished and the horizontal step will begin.

In the horizontal step, the difference between each pair of  $Q_{mn}^0$  and  $Q_{mn}^1$  is calculated in advance and the results will be saved in the matrix  $\delta Q$  ( $\delta Q_{mn} = Q_{mn}^0 - Q_{mn}^1$ ). After that, for each bit  $\mathbf{r}_n$ , its likelihood difference  $\delta Q_{mn}$  will be updated according to the equation:

$$\delta Q_{mn} = \prod_{n' \in N(m), n' \neq n} \delta Q_{mn'} \quad \text{where } N(m) \equiv \{n : H_{mn} = 1\}$$

Which means that the value of  $\delta Q_{mn}$  is now the product of other values  $\delta Q_{mn'}$ , which also participate in the same parity check equation  $\mathbf{m}$  (Figure 2.4.4). Hence, the temporary probabilities  $R_{mn}^0$  and  $R_{mn}^1$  from horizontal step can be calculated as:

$$R_{mn}^0 = 0.5(1 + \delta Q_{mn}) \quad \text{and} \quad R_{mn}^1 = 0.5(1 - \delta Q_{mn}) = 1 - R_{mn}^0$$

These temporary probability arrays will be used in the following vertical step.

As to the vertical step, the product of each set of checks  $\mathbf{m}$  in which the same bit  $\mathbf{n}$  participates will be firstly calculated (Figure 2.4.4). Eventually, the pseudo-posterior probabilities  $q_n^0$  and  $q_n^1$  can be calculated as:

$$q_n^0 = f_n^0 \prod_{m \in M(n)} R_{mn}^0 \quad q_n^1 = f_n^1 \prod_{m \in M(n)} R_{mn}^1$$

where  $M(n) \equiv \{m : H_{mn} = 1\}$  and equivalent to the set of checks in which the bit  $\mathbf{n}$  participates.

Therefore, each bit-value of the received codeword  $\mathbf{r}$  is able to be updated according to the probabilities  $q_n^0$  and  $q_n^1$ . That is, if  $q_n^0$  is greater than  $q_n^1$ , the bit value of  $\mathbf{r}_n$  will be set to '0'; Otherwise,  $\mathbf{r}_n = '1'$ .

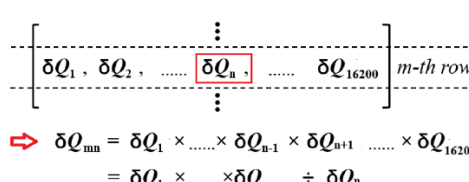
However, if the corrected message  $\mathbf{r}$  failed to pass the syndrome  $\mathbf{s} = \mathbf{H}\mathbf{r}^T = 0$ , the probabilities  $Q_{mn}^0$  and  $Q_{mn}^1$  for each bit will be refreshed as:

$$Q_{mn}^0 = f_n^0 \prod_{m' \in M(n), m' \neq m} R_{m'n}^0 \quad Q_{mn}^1 = f_n^1 \prod_{m' \in M(n), m' \neq m} R_{m'n}^1$$

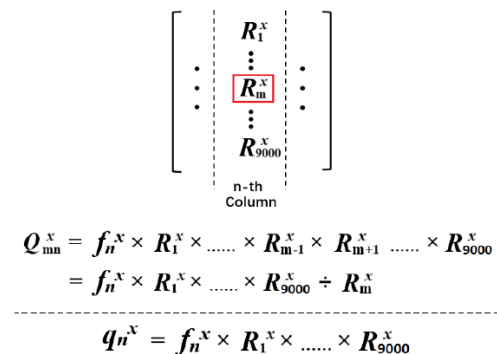
(Schematic of the operation can also be seen in figure 2.4.4).

And then the whole decoding process will repeat starting from horizontal step until the syndrome  $\mathbf{s} = 0$  is satisfied.

Obviously, the Mackay and Neal's Decoding algorithm includes more cumulative multiplication operations than the Sum-Product Decoding method. On the C programming basis, implementing the cumulative multiplication operation is undoubtedly time-consuming. However, since the operation can be simplified to module-2 addition in this project, and the Sum-Product decoder has already been implemented by the ANU graduated student Mr. Sang Ik Park, the Mackay and Neal's Decoding algorithm is finally chosen as the decoding algorithm for this project.



$\Rightarrow \delta Q_{mn} = \delta Q_1 \times \dots \times \delta Q_{n-1} \times \delta Q_{n+1} \times \dots \times \delta Q_{16200}$   
 $= \delta Q_1 \times \dots \times \delta Q_{16200} \div \delta Q_n$



$Q_{mn}^x = f_n^x \times R_1^x \times \dots \times R_{m-1}^x \times R_{m+1}^x \times \dots \times R_{9000}^x$   
 $= f_n^x \times R_1^x \times \dots \times R_{9000}^x \div R_m^x$ 


---

 $q_n^x = f_n^x \times R_1^x \times \dots \times R_{9000}^x$

Figure 2.4.4: Schematic of the cumulative operations

### 3. Methodology

#### 3.1 Attempt of Implementing New Encoder

As it has been mentioned in section 2.3, the DVB-S2 standard encoder is still in use for the associated models. The practical performance of the encoder has shown that the process for encoding a 7200-length message codeword takes no more than 20ms (Figure 3.0). This impressive speed ensures that the time interval between sending out two adjacent message codewords will not be aware of the users who are enjoying the audio-visual experience.

```
Clocks per sec = 1000000
BPSK_encoding - 15 (ms) elapsed.
Number of iterations, sim = 1    max_sim = 1
```

Figure 3.0: Practical Performance of the DVB-S2 Standard Encoder

However, this encoder is still dependent on the generator matrix  $\mathbf{G}$ . In order to seek for the feasibility of directly encoding a message from the parity check matrix  $\mathbf{H}$ , the algorithm – Low-Complexity Encoding of LDPC Codes (Hanghang Qi and Norbert Goertz, unknown) – was first-tentatively implemented in C programming.  $\mathbf{y} = \{\mathbf{y}_1, \mathbf{y}_2, \dots, \mathbf{y}_k\}$

According to Sarah Johnson's paper (Sarah Johnson, 2006), this particular encoding algorithm only using row and column permutations and back substitution to reform a randomly generated sparse parity check matrix  $\mathbf{H}$  so that it could be shifted into systematic approximate lower triangular (SALT) form (Figure 3.1.1), and be utilized to generate parity check bits directly.

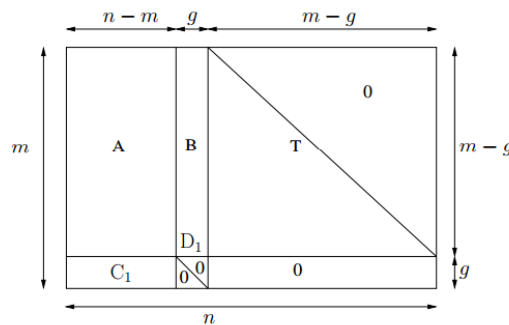


Figure 3.1.1: Parity Check Matrix  $\mathbf{H}$  in SALT Form



By reviewing the paper of MacKay and Neal (MacKay and Neal, 1996), it can be noticed that the parity check matrix for the MN Decoder is suggested to be constructed by applying the construction 2A. That is in the  $\mathbf{m} \times \mathbf{n}$  sized parity check matrix  $\mathbf{H}$  (9000 x 16200 in this project), the first  $\mathbf{m}/2$  columns should be designated as weight 2 columns with zero overlaps between any pair of columns. That is, for each column ranging from index 1 to 4500, the number of nonzero elements should be '2' and the inner product for any two columns should be '0' (Figure 3.1.2). As to the remaining columns, three nonzero elements will be assigned to random locations with the inner product of any two columns is not greater than '1' (Figure 3.1.3).

$$\begin{array}{cc} \text{Column1} & (\text{Column2})^T \\ \left[ \begin{array}{c} 1 \\ 0 \\ 1 \\ 0 \end{array} \right] & \times \left[ 0 \ 1 \ 0 \ 1 \right] = 0 \end{array}$$

*Figure 3.1.2: Example of the First 4500 Columns in H (Construct 2A)*

$$\begin{array}{cc} \text{Column4501} & (\text{Column4502})^T \\ \left[ \begin{array}{c} 1 \\ 0 \\ 1 \\ 0 \\ 1 \end{array} \right] & \times \left[ 0 \ 1 \ 0 \ 1 \ 1 \right] = 1 \end{array}$$

*Figure 3.1.3: Example of the Remaining Columns in H (Construct 2A)*

In order to achieve these special requirements, there are 2 nonzero values '1' which were allocated in the rows  $2i$  and  $2i-1$ , where  $i$  is the index of the current column being operated on. This could ensure that there is only 1 nonzero element in each row of the first 4500 columns (Figure 3.1.4). After that, the row indexes were randomly rearranged so that the randomness can be guaranteed as well. The simplified code is shown as follow.

*for j = 1: 4500 do*

$H[2j][j] = 1;$

$H[2j-1][j] = 1;$

*end for*

*for i = 1: 9000 do*

*generate a random row index 'ri' ranging from 1 to 9000;*

*for j = 1: 16200 do*

*swap  $H[i][j]$  and  $H[ri][j]$ ;*

*end for*

*end for*

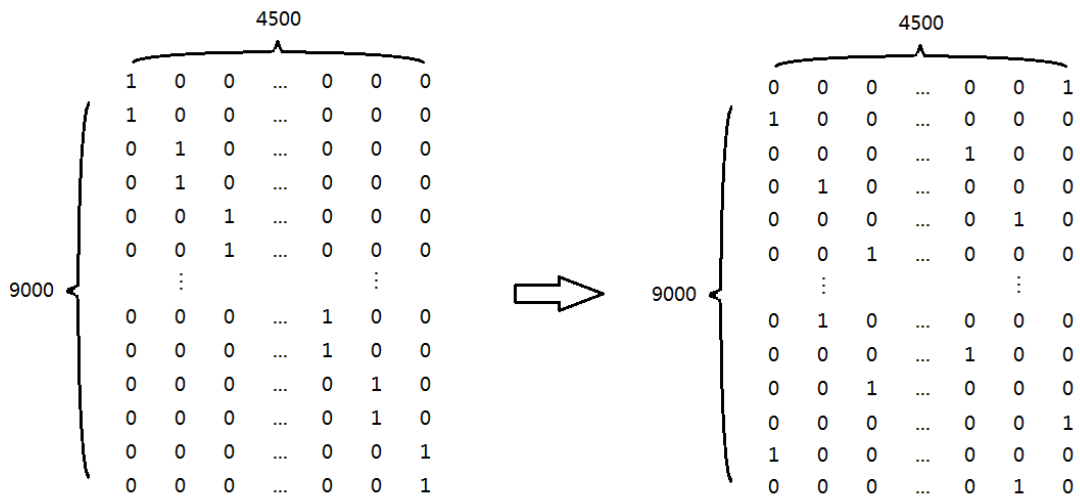


Figure 3.1.4: Partial Result of Construction 2A

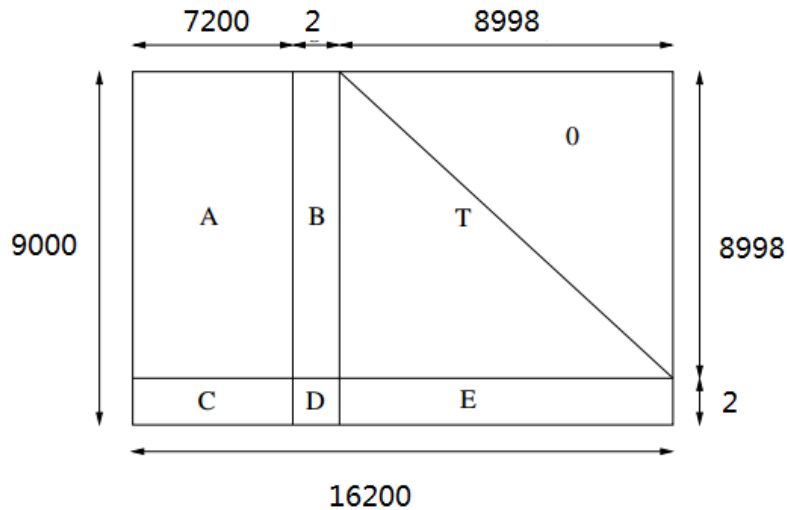
In addition, the swap function (Appendix C) was achieved by using the *pointer* and the operation '^' so that the temporary variable used to assist the values' interchange in the traditional method can be abandoned. As a result, the memory resource is able to be saved for other operations.

Ideally, the remaining columns could be constructed by applying the above methods. However, since there would be  $16200 - 4500 = 11700$  columns in the second part of the matrix

**H**, if the inner product between any 2 columns is not greater than 1, there should be at least  $11700 * (3-1) = 23400$  rows in the whole matrix. That is, the predicted result of this particular method conflicts with the initial size of parity check matrix **H** ( $9000 * 16200$ ). Therefore, the integrated algorithm was proven unachievable.

Nevertheless, the Low-Complexity encoding algorithm also includes the row and column permutations. So, as long as the sparseness of the matrix **H** is satisfied, the matrix is still able to be constructed by permutations. Hence, the total number of nonzero elements were firstly calculated based on the construction method 2A, which is  $4500 * 2 + 11700 * 3 = 44100$ . Secondly, these nonzero binary numbers ('1's) were randomly allocated in the whole parity matrix **H**, which had been reset to an all '0' matrix. Since the size of matrix **H** is 145,800,000 ( $9000 * 16200$ ), the sparse rate of the matrix is  $44100 / 145,800,000 = 0.03\%$ . This proved that the Low-Complexity encoding algorithm is suitable for this project.

In order to reform the parity check matrix **H** to the SALT form (figure 3.1.1), the first step should be applying rows and columns permutation so that the approximate lower triangular (ALT) form (Figure 3.1.5) can be obtained for the following back substitution.



*Figure 3.1.5: Parity Check Matrix **H** in ALT Form*

As it has been mentioned in the previous slide, the columns ranging from 4501 to 16200 are weight 3 columns. Therefore, once the ALT formed matrix **H** has been generated, there should be 2 rows at the bottom of the matrix. As it can be shown in figure 3.1.5, the whole

matrix  $\mathbf{H}$  was separated into 6 sub-matrices. Furthermore, the permutation operations are applied to reallocate the nonzero elements to the diagonal from the top-left corner to the bottom-right corner of the sub-matrix 'T', and then assign the rest nonzero elements to the locations except those which are above the diagonal. The method for this operation is: Firstly, finding out the row which has a '1' in the column 7203 and smaller number of '1's in the remaining columns; Then, reallocate the entire row to the first row while put the original first row to the bottom of the matrix; After that, the columns which contain '1' in the first row are interchanged with the columns which contain '0' and located in the areas 'AC' and 'BD'; Next, a row which contains a '1' in column 7204 is reallocated to the second row; Meanwhile, the original second row is moved to the bottom of the matrix; Similarly, columns which have a '1' in this row will be permuted to the areas 'AC' and 'BD'; Repeat the procedures for the rest elements in 'T' until the ALT formed matrix  $\mathbf{H}$  is obtained.

Undoubtedly, the operation of rows and columns permutation was the stumbling block of this algorithm and it will sharply slow down the simulation speed of the encoder. Hence, an alternative method was figured out and implemented to construct the ALT formed matrix  $\mathbf{H}$ .

In the initialization stage, all the elements in the matrix  $\mathbf{H}$  were firstly reset to '0'. Then 8998 binary values '1' were assigned to the diagonal elements in 'T'. Meanwhile, the remaining 35102 '1's were randomly assigned to the elements in the area 'A', 'B', 'C', 'D', 'E' and the elements below the diagonal of sub-matrix 'T'. Hence, the complicated and time-consuming operations of rows and columns permutation have finally been replaced. Procedures can be represented in the following figure.

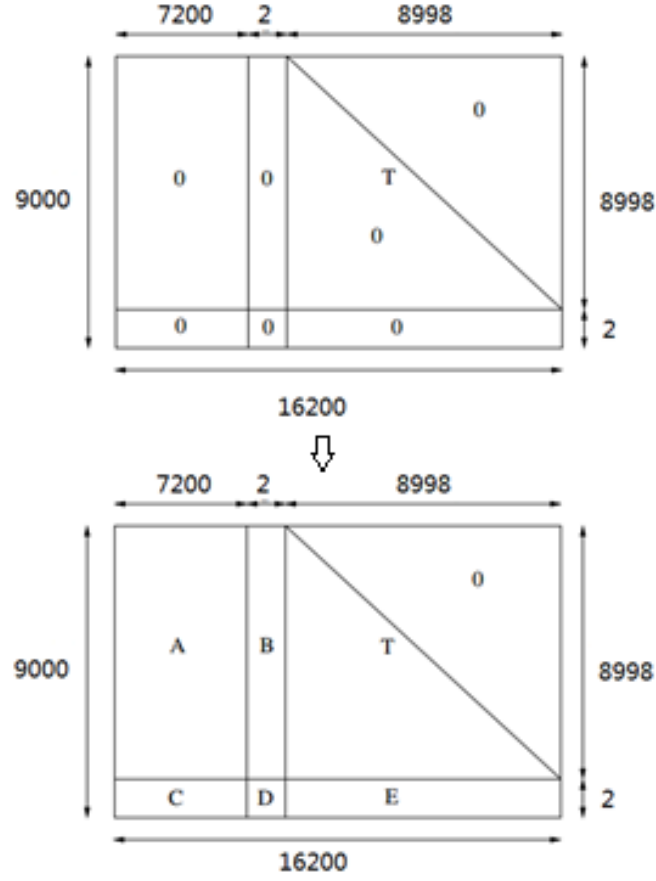


Figure 3.1.6: Alternative Algorithm to Construct ALT Formed Matrix  $H$

After that, the sub-matrices ‘C’ and ‘D’ should be updated based on the equations:

$$C = -ET^{-1}A + C, \quad D = -ET^{-1}B + D.$$

So, the following task for this algorithm is to figure out the way of obtaining the transpose matrix ‘ $T^{-1}$ ’. C code for obtaining the transpose matrix can be found in Appendix D. The procedures of this function can be summarized as:

- Find out the matrix of mirrors

The matrix ‘ $T$ ’ is in the size of 8998 x 8998. Therefore, for each element  $T[i][j]$  in the matrix, the whole matrix excludes the elements in the  $i$ -th row and  $j$ -th column (that is ‘ $T_m$ ’ is in the size of 8997 x 8997) was firstly transferred to the *determinant* function.

- Find out the determinant

Firstly, calculate the results from the equation  $determinant = ad-bc$  (where the paired elements ‘ $a$ ’ & ‘ $b$ ’ and ‘ $c$ ’ & ‘ $d$ ’ share the same row index accordingly and the paired

elements ' $a$ ' & ' $c$ ' and ' $b$ ' & ' $d$ ' share the same column index respectively) and save the sum of the results in the determinants matrix ' $T_d$ ' which has the same size of matrix ' $T$ '.

Secondly, assign positive signs '+' and negative signs '-' to the elements in ' $T_d$ ' so that in each pair of adjacent elements, the initial sign '+/-' of one element will remain unchanged while another's will be shifted inversely.

Finally, for each  $i$  and  $j$ , calculate  $T[i][j] * T_d[i][j]$  and sum these results up to obtain the *determinant* for the matrix ' $T$ '.

- *Transpose matrix*

For the elements in the matrix ' $T_d$ ' obtained from above procedure, swap their positions over the diagonal so that the *adjugate* matrix  $T_a$  can be obtained. Then multiply each element in ' $T_d$ ' by  $1/\text{determinant}$ . Thus, the transpose matrix ' $T^{-1}$ ' is worked out.

Obviously, this function is extremely complicated. Furthermore, hierarchical *for*-loops (inner *for*-loops within outer *for*-loops) were overused in the code, which directly caused the low speed of the encoder version 1. Surprisingly, it was found out that the resulted matrix ' $T^{-1}$ ' was exactly the same as the matrix ' $T$ ' if the negative sign '-' can be ignored. The reason why is that since the values of the elements in matrix ' $T$ ' is either '1' or '0', the results from the calculation shown in the previous slide will consequently be binary number '-1', '0' or '1'. Additionally, in the following calculation procedures, only the absolute values of the elements in ' $T^{-1}$ ' will be used to acquire the parity check bits. In other words, the matrix ' $T$ ' can be directly utilized for calculating the parity check bits. Therefore, the *inverse matrix* function was finally considered as unnecessary and has not been used in this project.

Once the transpose matrix  $T^{-1}$  (which was replaced by matrix ' $T$ ' in practice) is obtained, the functions *matrix multiplication* (Appendix E) and *matrix addition* (Appendix F) should be applied to find out the resulted matrix 'ET', 'ETA' & 'ETB' and updated 'C' & 'D' gradually.

In the following paragraphs, the equation:  $C = -ETA + C$  will be demonstrated to describe the these functions.

From figure 3.1.6, the size of 'E' should be 2 x 8998 and the size of 'T' is supposed to be 8998 x 8998. Therefore, the numbers of rows and columns in 'E' were initialized to  $r1 = 2$  and  $c1 = 8998$  correspondingly; And since the matrix multiplication is achievable only if the number of columns in the first matrix ('E') equals to the number of rows in the second matrix 'T', so the parameters of matrix 'T' were set to  $r2 = c1 = 8998$  and  $c2 = 8998$  accordingly. So, for each element in the matrix 'ET', its value should be the product of each pair of  $E[i][p]$  and  $T[p][j]$ , where  $i \in (1:2)$ ,  $p \in (1:8998)$ , and  $j \in (1:8998)$ . Since the elements in matrix 'ET' should always be '1' or '0' at the binary level, the systematic function '%' was utilized to convert the decimal results to binary values. Hence, by applying the *for-loops* hierarchically, the matrix 'ET' with the size of 2 x 8998 can be obtained by the following simplified code.

---

```

for  $i = 1:r1$  do
    for  $j = 1:c2$  do
        for  $p = 1:c1$  do
             $ET[i][j] += E[i][p] * T[p][j];$ 
             $ET[i][j] = ET[i][j] \% 2;$ 
        end for
    end for
end for

```

---

Similarly, the parameters were set to  $r1 = 2$ ,  $c1 = 7200$ ,  $r2 = c1 = 7200$ ,  $c2 = 8998$  to obtain the 2 x 8998 sized matrix 'ETA' and the inversely signed 'NETA' ( $-ET^T A$ ).

---

```

for  $i = 1:r1$  do

```

```

for  $j = 1:c2$  do

    for  $p = 1:c1$  do

         $ETA[i][j] += ET[i][p] * A[p][j];$ 

         $NETA[i][j] = -(ETA[i][j] \% 2);$ 

    end for

end for

end for

```

---

Once the matrix ‘NETA’ was obtained, the *matrix addition* function is called to calculate the sum of the matrix ‘NETA’ and original ‘C’. It is worth mention that since the matrix addition operation requires that the two matrices should be exactly in the same size, only one pair of parameters, which corresponds to the number of rows and number of columns respectively, are necessary to be set. Hence, the parameter  $r = 2$  and  $c = 8998$  were set as the input variables to the function.

---

```

for  $i = 1:r$  do

    for  $j = 1:c$  do

         $C[i][j] = NETA[i][j] + C[i][j];$ 

         $C[i][j] = C[i][j] \% 2;$ 

    end for

end for

```

---

Until now, the updated sub-matrices ‘C’ and ‘D’ were worked out. After resetting all the elements in the sub-matrix ‘E’ to ‘0’, the parity check bits are able to be figured out. Before proceeding to the following sections, some correlated concepts are necessary to be introduced in advance.



As it has been mentioned in section 2, the encoded codeword  $\mathbf{c}$  actually includes two sub-vectors. That is, for a 16200-length codeword  $\mathbf{c}$  in this project, the first 7200 bits are exactly the same as the bits in the original message  $\mathbf{u}$  and the remaining 9000 bits belong to the parity check vector  $\mathbf{p}$ . So, the form of  $\mathbf{c}$  can be represented as  $\mathbf{c} = \{\mathbf{u}, \mathbf{p}\}$ . However, by applying the algorithm in this section, the parity check vector  $\mathbf{p}$  is partially obtained from two equations:

$$\mathbf{p}_1 = D^{-1}C\mathbf{u}, \quad \mathbf{p}_2 = -T^{-1}(A\mathbf{u} + B\mathbf{p}_1)$$

Therefore, the encoded codeword  $\mathbf{c}$  should be represented as  $\mathbf{c} = \{\mathbf{u}, \mathbf{p}_1, \mathbf{p}_2\}$ . So, after applying the previously introduced functions and procedures, the original message  $\mathbf{u}$  is finally encoded to the codeword  $\mathbf{c}$ .

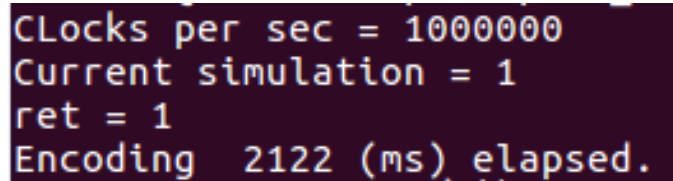
Ideally, this encoding algorithm should be able to encode a message which has either a systematic form of parity check matrix or a non-systematic form of parity check matrix. Although this requirement has been satisfied, the simulation result in C programming showed that the encoding time of this algorithm could take more than 5 minutes until complete. This is extremely terrible by comparison to the DVB-S2 standard encoder's performance (Figure 3.0). Therefore, improvements were made again to reduce the simulation time.

After doing some research works, it is noticed that the parity matrix for the DVB-S2 model should be in the systematic form already. That is the matrix  $\mathbf{H}$  consists of two sections, which are the matrix  $\mathbf{A}$  in the size of 9000 x 7200 followed by a 9000 x 9000 sized identity matrix  $\mathbf{I}$ . Hence the whole procedures in this section were further simplified as:

- Allocate 9000 binary values '1' into the elements which locate in the diagonal of the sub-matrix 'T'. Then randomly assign the remaining 35100 '1's to the elements in 'A'.
- Since there was no gap 'g' in the systematic-formed parity check matrix  $\mathbf{H}$ , the sub-matrices 'B', 'C' and 'D' are no longer existing in this algorithm. Hence, the parity check vector  $\mathbf{p}$  was directly calculated from the equation:  $\mathbf{p} = T(A\mathbf{u})$ .

- After combining with the initial message bits, the encoded codeword  $\mathbf{c}$  was obtained as  $\mathbf{c} = \{\mathbf{u}, \mathbf{p}\}$ .

This encoder was named as *Encoder Version 1* (Appendix G). Simulation result has shown that the performance of the encoder performs significantly faster than the encoder shown in previous slides. The encoding time for a 7200 length codeword  $\mathbf{u}$  takes around 2 seconds (Figure 3.1.7) to complete, which is much faster than 5 minutes of the previous version.



```
CLocks per sec = 1000000
Current simulation = 1
ret = 1
Encoding 2122 (ms) elapsed.
```

*Figure 3.1.7: Simulation Result of the Encoder Version 1*

However, this encoding speed is more than 100 times slower than the DVB-S2 standard encoder (Figure 3.0). After reviewing Sang's code (Appendix H), the reason was figured out. That is, unlike other types of software which were designed for matrix associated calculation, such as MATLAB, C programming requires more memory resources to operate the similar calculation. Therefore, generating a 2D matrix in C programming and apply calculations on it are not as convenient as it was assumed. However, convert the matrix into 1D vectors – just like the method applied in Sang's code – would be more feasible in C environment. Thus, the DVB-S2 standard encoder which was implemented by Mr. Sang Ik Park (Appendix H) was finally used for this project.

### **3.2 In-depth understanding on Sang's Code**

In order to test whether the decoder is working properly, the DVB-S2 encoder and the AWGN signal generator were used to create the initial message bits and the interfered encoded codeword bits. Although the DVB-S2 encoder and the AWGN signals generator were implemented in C by Mr. Sang Ik Park, it is still necessary to introduce the method of achieving

these implementations in advance so that the implementation of the decoder will not become sophisticated.

### 3.2.1 Gaussian Random Bit Generator

The function *Gaussian Random Bit Generator* was used to create the original message bits and the noise bits. Since the simulated noise signal in this project is the frequently used channel estimation method – the AWGN channel – which should have the additive noise of variance  $\sigma^2 = 1$ , so, the random bit generated from the function should range from ‘-1’ to ‘1’.

In this function (shown in Appendix I), two random values ranging from 0 to 32767 are firstly generated by using the systematic function *rand()*. After dividing these two values by 32767 (*RAND\_MAX*) and doubling the results, these two values will be narrowed to the range [0, 2]. After that, by subtracting ‘1’ from these two results accordingly, the variables *v1* and *v2* (range from -1 to 1), which participate in the variance check equation, will be generated.

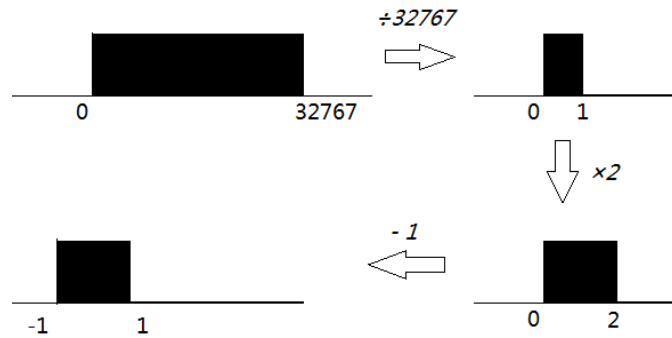


Figure 3.2.1: Procedures of Narrowing Random Generated Values

Therefore, the variance of the randomly generated values can be obtained as  $s = v1^2 + v2^2$ . Additionally, in order to ensure that the variance is ranging from ‘0’ to ‘1’, and to make sure the *double* typed values can be utilized properly, the *while* loop was applied to check whether the variance  $\sigma$  is greater than ‘0’ and less than ‘1’. Meanwhile, the generated bit value will be reformed by the equation:  $v1 = v1 * \sqrt{2\log(\sigma)/\sigma}$ .

Although the variances of the noise signals have been satisfied, the randomly generated bit values are still not able to be directly utilized as the original message bits. The reason why is that in the signal processing domain, the bit values should be either the binary number ‘1’ or

‘0’, while the generated bit values are actually decimals. Hence, the generated values are necessary to be converted to binary numbers accordingly by using the combination of *for-loop* and *if-loop*. That is if the result is greater than ‘0’, then the bit will be set to the binary number ‘1’; otherwise, it will be set to the binary number ‘0’. This method is exactly the same as the *hard decision* method which was used in the decoder. The detailed introduction will be demonstrated in the following sections.

As it has been mentioned in the previous paragraph, the additive noise of variance  $\sigma^2=1$  has already been satisfied as long as the noise signals were generated by the function. However, this noise signal is not able to be monitored for performance analysis. In other words, the signal to noise ratio (SNR) is supposed to be set before the simulation and utilized to control the noise level. Hence, extra procedures were applied on regulating the generated noise signal.

Firstly, the power of undisturbed signal bits was obtained by cumulatively summing up the values  $c[j]^2$ , where  $j$  is the index of the encoded message bit ranging from 1 to 16200 and  $c$  is the encoded message. Meanwhile, the noise’s power was also acquired by cumulatively calculating the sum of the generated noise bits. Therefore, the SNR of the raw AWGN signal was calculated by:

$$SNR_{raw} = Spower / Npower = Sum(Signal\_bit)^2 / Sum(Noise\_bit)^2$$

Secondly, the pre-set  $SNR_{dB}$  was converted to the ratio form by applying:

$$SNR_{input} = 10^{-SNR_{dB}/10}$$

Finally, the regulated noise signal bits and the final SNR for the encoded message were updated by:

$$Noise\_bit = Noise\_bit * \sqrt{SNR_{raw}} * \sqrt{SNR_{input}}$$

$$SNR = Sum(Signal\_bit)^2 / Sum(Noise\_bit)^2$$

And the bits of the encoded message  $c$  went through the AWGN channel can be represented as:

$$Message\_bit = Message\_bit + Noise\_bit$$

or equivalently:

$$z[j] = c[j] + \text{Noise}[j]$$

### 3.2.2 Method for Eliminating Zero Elements

Ideally, all the calculating operations should be applied on the 2D matrices. However, performing calculation procedures to all the elements in a large sized matrix, such as the 9000 x 16200 sized parity check matrix  $\mathbf{H}$  in this project, costs a host of memory resources and will consequently reduce the speed of decoding. Considering that the parity check matrix in this project is a sparse matrix, which means the quantity of nonzero elements is relatively small by comparison to the total number of elements in  $\mathbf{H}$ , and only nonzero elements are of interest in the decoding process, therefore, if there is a way to preserve the nonzero elements only while eliminating all the zero elements, the decoding process will be accelerated. Consequently, the creative approach introduced in Sang's code has been used in this project. The detailed introduction is shown in the follow paragraphs while the introduced index vectors of nonzero elements in the parity check matrix for this project can be found in Appendix B.

In a parity check matrix  $\mathbf{H}$ , each element always has a column index and a row index. So, the value of an particular element can be represented as:  $\mathbf{H}[\text{row\_index}][\text{column\_index}]$ . In order to eliminate the '0's in the matrix  $\mathbf{H}$  ( $\mathbf{m} \times \mathbf{n}$ ), the row indexes and the column indexes of the nonzero elements in the first row of  $\mathbf{H}$  are firstly stored in a row index vector and a column index vector respectively, and then the indexes of the nonzero elements in the second row of  $\mathbf{H}$  are recorded by using another pair of vectors accordingly. After repeating the procedure until the reaches the last element in  $\mathbf{H}$ , there will be  $\mathbf{m}$  sets of row index vectors and  $\mathbf{n}$  sets of column index vectors. After that, all the row index vectors and column index vectors are transferred orderly into a row-wise row index vector and a row-wise column index vector respectively. Hence, the length of the row-wise row index vector and row-wise column index vector will both equal to the number of nonzero elements in the parity check matrix  $\mathbf{H}$ . Thus, the nonzero elements are able to be preserved. The workflow diagram can be seen in the following example.

Example 3.2.1

---

Given that:

$$H = \begin{matrix} & \overbrace{\begin{matrix} 1 & 2 & 3 & 4 & 5 & 6 \end{matrix}}^{\text{column index}} \\ \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 \end{bmatrix} & \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} \end{matrix} \left. \vphantom{\begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 \end{bmatrix}} \right\} \text{row index}$$

So, the positions of nonzero elements ('1') can be represented as:

$$\text{Position of '1's} = \begin{bmatrix} (1,1) & (1,2) & - & (1,4) & - & - \\ - & (2,2) & (2,3) & - & (2,5) & - \\ (3,1) & - & - & - & (3,5) & (3,6) \\ - & - & (4,3) & - & (4,5) & (4,6) \end{bmatrix}$$

Therefore, the row index vector for the first row is: {1, 1, 1};

And the row index vectors for the remaining rows are: {2, 2, 2}, {3, 3, 3} and {4, 4, 4}

Similarly, the column index vectors for the corresponding rows will be:

$$\{1, 2, 4\}; \quad \{2, 3, 5\}; \quad \{1, 5, 6\}; \quad \{3, 5, 6\}$$

Combining these vectors so that:

$$\text{Row-wise row index vector} = \{1, 1, 1, 2, 2, 2, 3, 3, 3, 4, 4, 4\}$$

$$\text{Row-wise column index vector} = \{1, 2, 4, 2, 3, 5, 1, 5, 6, 3, 5, 6\}$$


---

However, in the decoding process, if two matrices are multiplied together, the elements in the  $i$ -th row of the first matrix and the elements in the  $i$ -th column of the second matrix should be multiplied with each other iteratively. Hence, the positions of nonzero elements in  $\mathbf{H}$  should also be represented in the column-wise form. And consequently, there will be a column-wise row index vector and a column-wise column index vector as well.

For the same parity check matrix **H** shown in example 3.1:

$$H = \begin{matrix} & \overbrace{1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6}^{\text{column index.}} \\ \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 \end{bmatrix} & \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} \end{matrix} \left. \vphantom{\begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 \end{bmatrix}} \right\} \text{row index}$$

The positions of nonzero elements ('1') are:

$$\text{Position of '1's} = \begin{bmatrix} (1,1) & (1,2) & - & (1,4) & - & - \\ - & (2,2) & (2,3) & - & (2,5) & - \\ (3,1) & - & - & - & (3,5) & (3,6) \\ - & - & (4,3) & - & (4,5) & (4,6) \end{bmatrix}$$

Now the row index vector for the nonzero elements in the first column is: {1, 3};

And the row index vectors for the nonzero elements in the remaining columns are:

$$\{1, 2\}; \quad \{2, 4\}; \quad \{1\}; \quad \{2, 3, 4\}; \quad \{3, 4\}.$$

Similarly, the column index vectors for the matrix will be:

$$\{1, 1\}; \quad \{2, 2\}; \quad \{3, 3\}; \quad \{4\}; \quad \{5, 5, 5\}; \quad \{6, 6\}.$$

Combining this vectors so that:

$$\text{Column-wise row index vector} = \{1, 3, 1, 2, 2, 4, 1, 2, 3, 4, 3, 4\}$$

$$\text{Column-wise column index vector} = \{1, 1, 2, 2, 3, 3, 4, 5, 5, 5, 6, 6\}$$

### 3.3 Implementation of the MN Decoder

The implementation of the MN Decoder was set as the main task for the second half project period. As it has been demonstrated in section 2.4.4, the MN Decoder covers six main steps, which are *Interfered signal delivery*, *Initialization*, *Horizontal step*, *Vertical Step*, *Hard*

*Decision and Validity Check.* During each simulation, the received signal, which has been interfered, will be iteratively corrected and checked. Practical results have shown that the maximum iteration for each simulation is supposed to be set as 150 so that the randomly generated original message could be fully recovered. The workflow block diagram of the decoder is shown as follow, while the detailed flowchart can be found in Appendix J.

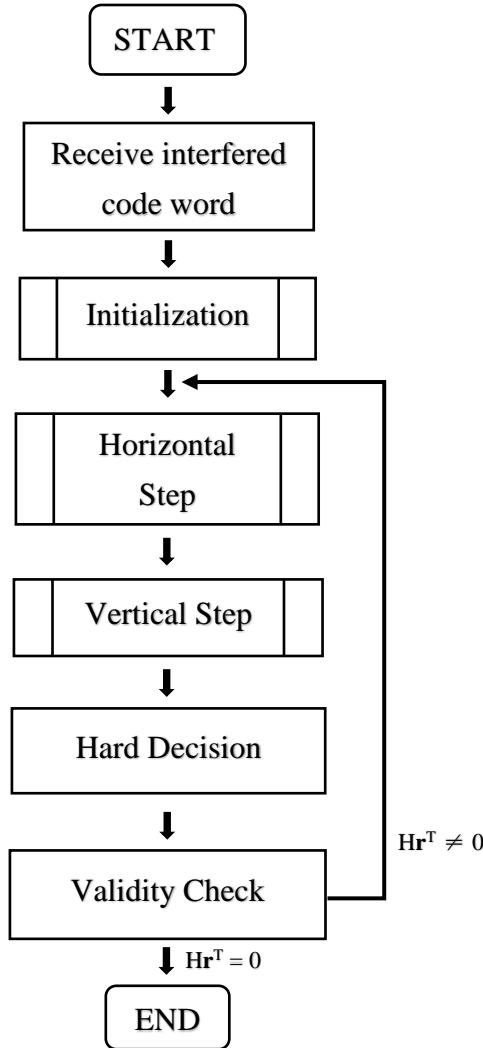


Figure 3.3: Workflow Block Diagram of the MN Decoder

Once the interfered message  $\mathbf{z}$  was received, the decoder will firstly compute the likelihood of each bit based on the equations in the initialization step:

$$f_n^I = 1/(1+\exp(-2*\alpha*\mathbf{z}_n)) \quad \text{and} \quad f_n^O = 1 - f_n^I.$$

Where  $\alpha = \sqrt{SNR}$  in this project.



Hence, the vector *Column-wise column index* is used to iteratively assign the likelihood for each message bit to the nonzero elements in the same column of the vector-formed matrices  $Q^l$  and  $Q^o$ . The simplified code can be shown as follow.

---

**for**  $i = 1$ : Number of nonzero elements **do**

$$Q^l[i] = f^l[\text{Column-wise column index}[i]];$$

$$Q^o[i] = f^o[\text{Column-wise column index}[i]];$$

**end for**

---

Since the elements in the same column of matrix  $\mathbf{H}$  share the same column index, so, in the column-wise column index, there always be sets of continuous elements sharing the same column index value. That is, with the increase of  $i$ , the values of variable *Column-wise column index* $[i]$  will periodically perform the same value. Hence, the variables  $f^l[\text{Column-wise column index}[i]]$  and  $f^o[\text{Column-wise column index}[i]]$  will assign sets of continuous same value to the vector-formed matrices  $Q^l[i]$  and  $Q^o[i]$  respectively. As a result, only the nonzero elements' likelihoods are saved in the vector-formed matrices  $Q^l$  and  $Q^o$ . Hence, these two vectors could be used to represent the likelihoods of nonzero elements in the entire matrix  $\mathbf{H}$ .

As to the horizontal step, the difference between each pair of  $Q^o[i]$  and  $Q^l[i]$  are calculated and stored in the vector-formed matrix  $dtQ$ , of which the length is the number of nonzero elements. According to section 2.4.4, the next step should be: for each element  $dtQ_{mn}[i][j]$ , computing the product of the other elements in the same row and assign the result back to  $dtQ_{mn}[i][j]$ . Alternatively, the product of the elements in the same row of  $dtQ_{mn}$  (including the element being operated on) was firstly computed and stored in an  $\mathbf{m}$ -length vector by using a *for-loop*. After that, another *for-loop* was used to calculate the quotient of the row-product value and the value of the element which is being operated on. An example of this particular step is shown as follow.

---

*Example 3.3.1*

Ideally, for a random row [1, 2, 3, 4] in a 4\*4 matrix, the elements of the three bits should be updated as:

$$Bit\ 1 = Bit\ 2 \times Bit\ 3 \times Bit\ 4 = 2 * 3 * 4 = 24; \quad Bit\ 2 = Bit\ 1 \times Bit\ 3 \times Bit\ 4 = 1 * 3 * 4 = 12;$$

$$Bit\ 3 = Bit\ 1 \times Bit\ 2 \times Bit\ 4 = 1 * 2 * 4 = 8; \quad Bit\ 4 = Bit\ 1 \times Bit\ 2 \times Bit\ 3 = 1 * 2 * 3 = 6;$$

By applying the alternative method, the product of bit values is firstly calculated as:

$$Row\ product = 1 * 2 * 3 * 4 = 24$$

Then the bit values can be updated as:

$$Bit\ 1 = Row\ product / Bit\ 1 = 24 / 1 = 24; \quad Bit\ 2 = Row\ product / Bit\ 2 = 24 / 2 = 12;$$

$$Bit\ 3 = Row\ product / Bit\ 3 = 24 / 3 = 8; \quad Bit\ 4 = Row\ product / Bit\ 4 = 24 / 4 = 6;$$

---

Similar to the initialization step, the vector *Column-wise row index* is utilized in the code to reduce the memory resource consumption. Meanwhile, the temporary probabilities  $R^0$  and  $R^1$  are also able to be computed. It is worth mention that the implementation of the alternative method shown in example 3.3.1 must be separated into two *for-loops* so that the product of the elements in each row can be fully computed and will not cause any error in the second procedure.

---

***for***  $i = 1$ : Number of nonzero elements ***do***

$$Product\ dtQ[Column\text{-}wise\ row\ index[i]] = Product\ dtQ[Column\text{-}wise\ row\ index[i]] / dtQ[i];$$

***end for***

***for***  $i = 1$ : Number of nonzero elements ***do***

$$Updated\ dtQ[i] = Product\ dtQ[Column\text{-}wise\ row\ index[i]] / dtQ[i];$$

$$R0[i] = 0.5 * (1 + Updated\ dtQ[i]);$$

$$R1[i] = 1 - R0[i];$$

***end for***

---

Until now, the program has finished the initialization and horizontal step. Recall the equations in the vertical step shown in section 2.4.4:

$$q_n^0 = f_n^0 \prod_{m \in M(n)} R_{mn}^0 \quad q_n^1 = f_n^1 \prod_{m \in M(n)} R_{mn}^1 \quad (1)$$

From equation (1) it can be found out that the pseudo-posterior probability  $q_n^0$  of the bit  $\mathbf{r}_n = 0$  equals to the product of the initial probability  $f_n^0$  and the term  $\prod_{m \in M(n)} R_{mn}^0$ . Therefore, the term  $\prod_{m \in M(n)} R_{mn}^0$  should be a vector which has the same size of the vector  $f_n^0$ . In other words, the vector  $\prod_{m \in M(n)} R_{mn}^0$  is an  $\mathbf{n}$ -length vector which consists of the products of the elements in the same columns of the matrix  $R^0$ . Thus, the vector *Column-wise column index* is used in the following simplified code.

---

**for**  $i = 1$ : Number of nonzero elements **do**

*Product*  $R1[\text{Column-wise column index}[i]] = \text{Product } R1[\text{Column-wise column index}[i]] * R1[i];$

*Product*  $R0[\text{Column-wise column index}[i]] = \text{Product } R0[\text{Column-wise column index}[i]] * R0[i];$

**end for**

**for**  $i = 1$ : 16200 **do**

$q1[i] = f1[i] * \text{Product } R1[i];$

$q0[i] = f0[i] * \text{Product } R0[i];$

**end for**

**//where:**  $\text{Product } R1[i] = \prod_{m \in M(n)} R_{mn}^1$  **and:**  $\text{Product } R0[i] = \prod_{m \in M(n)} R_{mn}^0$

---

Ideally, the sum of the two pseudo-posterior probabilities  $q_n^0$  and  $q_n^1$  for each bit  $\mathbf{r}_n$  should always equal to ‘1’ ( $p(\mathbf{r}_n=1) + p(\mathbf{r}_n=0)=1$ ). However, the practical results have shown that the generated result of  $q_n^0 + q_n^1$  may sometimes become a relatively small decimal which is less than ‘1’. Hence, a variable *sumq* is used to amplify the values  $q_n^0$  and  $q_n^1$  simultaneously so that their sum could be increased to ‘1’.

---

**for**  $i = 1: 16200$  **do**

$sumq = q1[i] + q0[i];$

$q1[i] = q1[i] / sumq;$

$q0[i] = q0[i] / sumq;$

$sumq = 0;$

**end for**

---

Once the pseudo-posterior probabilities have been worked out, the hard decision will be applied to the update the bit value  $\mathbf{r}_n$ . That is, if  $q_n^1$  is greater than  $q_n^0$ , the value of  $\mathbf{r}_n$  will become '1'; Otherwise,  $\mathbf{r}_n = '0'$ . Once all the message bits  $\mathbf{r}_n$  is updated, the program will check whether the syndrome  $\mathbf{s} = \mathbf{H} * \mathbf{r}$  is a sequence of '0's. This was easily achieved by calculating the sum of the elements in vector  $\mathbf{s}$  and check whether the result is a '0'.

As shown in section 2.4.4, the vector-formed pseudo-posterior probabilities  $Q^1[n]$  and  $Q^0[n]$  of bit  $\mathbf{r}_n$ , which were suggested by the check  $\mathbf{m}$ , should also be computed so that if the updated message failed to pass the validity check ( $\text{sum}(\mathbf{s}) \neq 0$ ), these two probabilities will be sent back to the horizontal step.

$$Q_{mn}^0 = f_n^0 \prod_{m' \in M(n), m' \neq m} R_{m'n}^0 \quad Q_{mn}^1 = f_n^1 \prod_{m' \in M(n), m' \neq m} R_{m'n}^1 \quad (2)$$

As it can be seen in equation (2), the calculating procedure looks similar to the procedure for computing  $q_n^0$  and  $q_n^1$ . However, in this procedure, the pseudo-posterior probability of the current bit, which is being operated on, is excluded in the cumulative multiplication operation. Since the terms  $\prod_{m \in M(n)} R_{mn}^1$  and  $\prod_{m \in M(n)} R_{mn}^0$  have already been worked out in the code shown in previous slide, the values  $\prod_{m' \in M(n), m' \neq m} R_{m'n}^0$  and  $\prod_{m' \in M(n), m' \neq m} R_{m'n}^1$  can be computed by applying the alternative method shown in example 3.3.1. Hence, the implementation of this equation can be achieved by the following simplified code.

---

**for**  $i = 1$ : Number of nonzero elements **do**

*product*  $R1[i] = \text{Product } R1[\text{Column-wise column index}[i]] / R1[i];$

*product*  $R0[i] = \text{Product } R0[\text{Column-wise column index}[i]] / R0[i];$

$Q1[i] = f1[\text{Column-wise column index}[i]] * \text{product } R1[i];$

$Q0[i] = f0[\text{Column-wise column index}[i]] * \text{product } R0[i];$

**end for**

**//where:**  $\text{product } R1[i] = \prod_{m' \in M(n), m' \neq m} R_{m'n}^1$       **and:**  $\text{product } R0[i] = \prod_{m' \in M(n), m' \neq m} R_{m'n}^0$

---

Similarly, for each pair of  $Q^1$  and  $Q^0$ , their values should also be amplified simultaneously so that the sum of these two likelihood values equals to ‘1’.

---

**for**  $i = 1$ : Number of nonzero elements **do**

$\text{sum}Q = Q1[i] + Q0[i];$

$Q1[i] = Q1[i] / \text{sum}q;$

$Q0[i] = Q0[i] / \text{sum}q;$

$\text{sum}Q = 0;$

**end for**

---

Consequently, the equations shown in the Mackay and Neal’s Decoding algorithm have been implemented in C programming. What’s more, debugging results suggested that in order to reset all the bits in a vector (such as  $R^1$  and  $R^0$ ,  $q^1$  and  $q^0$  and  $dtQ$ ) to ‘0’, the systematic function *memset* (*vector’s name*, *0x00*, *size of vector*) provides an instantaneous way to reset the entire vectors rather than set the elements to ‘0’ bit by bit gradually by using a *for-loop*. In addition, since all the elements in the vectors which are used to preserve the product (such as *product*  $R^1$ , *product*  $R^0$  and *product*  $dtQ$ ) should be initialized to ‘1’ in each iteration (*while-*

*loop*) in the decoder section, the same sized vectors (all elements = '1') were firstly generated in the main function; Secondly, elements in these vectors were copied into the corresponding vectors by using the systematic function *memcpy* (*targeted vector's name, all '1's vector, size of vector*). Hence, the duration of decoding each 16200-length encoded message was increased by up to 20ms.

## 4. Results and Discussion

In order to compare the decoding performance of the Sum-Product Decoder and the MN Decoder, both of the C code constructed by Sang Ik Park (Appendix H) and the new decoder constructed in this project period (Appendix I) were running on the same laptop. The system of the laptop is Linux Ubuntu 16.04. Additionally, the values of the parameters: maximum simulation of the code and the maximum iteration for the decoding process were both set as 150 in the two C codes.

### 4.1 Performance on Bit Error Correction

One of the key measurements for assessing the practical performance of a decoder is the ability of bit error correction. This parameter is usually represented as bit error rate (BER) which equals to the number of error bits divided by the total number of message bits. Since this parameter is highly correlated with the input variable Signal to Noise Ratio (SNR), during the simulations, the variable SNR was equally assigned as 0.1dB to 10dB in both of the codes. Detailed performance of these two decoders can be seen in the following table.

*Table 4.1: BER of the Decoded Message from the Decoders*

SNR(dB)	Raw BER	BER (Sum-Product Decoder)	BER (MN Decoder)
0	0.1560	0.0000	0.0000
1	0.1296	0.0000	0.0000
2	0.1018	0.0000	0.0000
3	0.0810	0.0000	0.0000
4	0.0565	0.0000	0.0000
5	0.0386	0.0000	0.0000
6	0.0213	0.0000	0.0000
7	0.0116	0.0000	0.0000
8	0.0064	0.0000	0.0000
9	0.0026	0.0000	0.0000
10	0.0011	0.0000	0.0000

As shown in table 4.1, after going through the decoding process, the bit error rates can be reduced to ‘0.0000’. That is both of the Sum-Product Decoder and the MN Decoder are able to fully correct the error bits. Therefore, there is no difference on the accuracy of bit error correction.

## 4.2 Performance on Decoding Speed

Another key measurement of a decoder’s practical performance is the decoding efficiency. That is how fast the decoding process could achieve. Similarly, the same set of SNR values were set as the input parameter for both of the decoders. Additionally, in order to enhance the accuracy of the data, the average decoding time calculated from totally 100 simulations was recorded as the result. Meanwhile, a *timer* was utilized to count the total time of the decoder to fully recovered a 16200-length received message. Hence, the average decoding time for each simulation was computed as *Average Decoding Time = Total Running Time / 100 Simulations*.

Table 4.2: Average Decoding Time of the Decoders

SNR(dB)	Average decoding time (Sum-Product Decoder)	Average decoding time (MN Decoder)
0.1	339.06ms	110.78ms
1	80.48ms	24.24ms
2	49.80ms	16.24ms
3	38.08ms	12.27ms
4	28.47ms	9.71ms
5	26.14ms	9.38ms
6	20.22ms	8.59ms
7	16.82ms	7.42ms
8	13.75ms	7.05ms
9	10.77ms	6.07ms
10	8.17ms	5.79ms

As shown in the above table, with the increase of SNR, the average decoding time for both of the two decoders gradually decrease. The reason is that the higher SNR value is, the smaller the total number of error bits will be. As a consequence, fewer iterations will be required



in the decoders. However, the result shows that when the parameters were set as the same, the decoding speed of the MN Decoder is always faster than that of the Sum-Product Decoder in each simulation. To be more specific, even if the bit error rate is 0.0011 (table 4.1), which means almost zero message bits were wrongly transmitted, the Sum-Product Decoder still need to spend almost 10ms to decoding the message. In contrast, the MN Decoder needs only 5.79 ms to correct the small quantity of error bits. Additionally, when the SNR was set to 0.1dB (all the received bits differ from the transmitted bits), the MN Decoder requires 110.78ms to fully recover the entire message, which is three times shorter than that of the Sum-Product Decoder (339.06ms)

To sum up, the MN Decoder performs the same error correction accuracy as the Sum-Product Decoder. However, the decoding speed of the MN Decoder is obviously faster than that of the Sum-Product Decoder.

## 5. Conclusion and Future Development

In the project period, the basic knowledge of signal encoding and decoding have been suggested and researched. Additionally, two types of encoding algorithms (DVB-S2 standard encoding algorithm and the Low-Complex encoding algorithm) and four types of decoding algorithms (Erasure Decoding, Bit-Flipping Decoding, Sum-Product Decoding and the Mackay and Neal's Decoding algorithms) also contributed extraordinarily to the construction of the correlated knowledge foundation.

From the encoder implementation stage, it is finally found out that the Low-Complex Encoding algorithm is not suitable for the DVB-S2 model since the parity check matrix for the model is already in the systematic form, in which the rows and columns permutation process is not required.

By comparison to the practical performance of Sang's Sum-Product decoder, the MN Decoder performs the same decoding accuracy but a faster decoding speed. Therefore, it can be concluded that the decoding efficiency of the MN Decoder is higher than that of the Sum-Product decoder. The reason can be concluded as that the trigonometric and log operations used in the Sum-product decoding algorithm are not utilized in the MN decoding algorithm, which saved the memory resource for the remaining procedures. Hence, it is suggested that the currently used Sum-Product decoder in the DVB-S2 model can be replaced by the MN Decoder.

As to the future development, it is worth mention that although the decoding efficiency of the MN Decoder is higher than the Sum-Product decoder, the data rate of the decoding process can reach up to 1.2Mbps only, which is still not as high as 10Mbps. However, the data rate of the decoding process is not able to be further accelerated in the C programming domain. Therefore, it is highly recommended to implement this algorithm in Verilog hardware description language to seek for the opportunity of boosting the decoding data rate.

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## Appendix A:

### Addresses of parity bit accumulators for $n_{ldpc} = 16200$ (Rate 1/2)

21	713	2387	6355	4062	1063	5046	5159
46	738	2412	6380	4087	1088	5071	5184
71	763	2437	6405	4112	1113	5096	5209
96	788	2462	6430	4137	1138	5121	5234
121	813	2487	6455	4162	1163	5146	5259
146	838	2512	6480	4187	1188	5171	5284
171	863	2537	6505	4212	1213	5196	5309
196	888	2562	6530	4237	1238	5221	5334
221	913	2587	6555	4262	1263	5246	5359
246	938	2612	6580	4287	1288	5271	5384
271	963	2637	6605	4312	1313	5296	5409
296	988	2662	6630	4337	1338	5321	5434
321	1013	2687	6655	4362	1363	5346	5459
346	1038	2712	6680	4387	1388	5371	5484
371	1063	2737	6705	4412	1413	5396	5509
396	1088	2762	6730	4437	1438	5421	5534
421	1113	2787	6755	4462	1463	5446	5559
446	1138	2812	6780	4487	1488	5471	5584
471	1163	2837	6805	4512	1513	5496	5609
496	1188	2862	6830	4537	1538	5521	5634
521	1213	2887	6855	4562	1563	5546	5659
546	1238	2912	6880	4587	1588	5571	5684
571	1263	2937	6905	4612	1613	5596	5709
596	1288	2962	6930	4637	1638	5621	5734
621	1313	2987	6955	4662	1663	5646	5759
646	1338	3012	6980	4687	1688	5671	5784
671	1363	3037	7005	4712	1713	5696	5809
696	1388	3062	7030	4737	1738	5721	5834
721	1413	3087	7055	4762	1763	5746	5859
746	1438	3112	7080	4787	1788	5771	5884
771	1463	3137	7105	4812	1813	5796	5909
796	1488	3162	7130	4837	1838	5821	5934
821	1513	3187	7155	4862	1863	5846	5959
846	1538	3212	7180	4887	1888	5871	5984
871	1563	3237	7205	4912	1913	5896	6009
896	1588	3262	7230	4937	1938	5921	6034
921	1613	3287	7255	4962	1963	5946	6059
946	1638	3312	7280	4987	1988	5971	6084
971	1663	3337	7305	5012	2013	5996	6109
996	1688	3362	7330	5037	2038	6021	6134
1021	1713	3387	7355	5062	2063	6046	6159
1046	1738	3412	7380	5087	2088	6071	6184
1071	1763	3437	7405	5112	2113	6096	6209
1096	1788	3462	7430	5137	2138	6121	6234
1121	1813	3487	7455	5162	2163	6146	6259
1146	1838	3512	7480	5187	2188	6171	6284
1171	1863	3537	7505	5212	2213	6196	6309
1196	1888	3562	7530	5237	2238	6221	6334
1221	1913	3587	7555	5262	2263	6246	6359
1246	1938	3612	7580	5287	2288	6271	6384
1271	1963	3637	7605	5312	2313	6296	6409
1296	1988	3662	7630	5337	2338	6321	6434
1321	2013	3687	7655	5362	2363	6346	6459
1346	2038	3712	7680	5387	2388	6371	6484
1371	2063	3737	7705	5412	2413	6396	6509
1396	2088	3762	7730	5437	2438	6421	6534
1421	2113	3787	7755	5462	2463	6446	6559
1446	2138	3812	7780	5487	2488	6471	6584
1471	2163	3837	7805	5512	2513	6496	6609
1496	2188	3862	7830	5537	2538	6521	6634
1521	2213	3887	7855	5562	2563	6546	6659
1546	2238	3912	7880	5587	2588	6571	6684

1571	2263	3937	7905	5612	2613	6596	6709
1596	2288	3962	7930	5637	2638	6621	6734
1621	2313	3987	7955	5662	2663	6646	6759
1646	2338	4012	7980	5687	2688	6671	6784
1671	2363	4037	8005	5712	2713	6696	6809
1696	2388	4062	8030	5737	2738	6721	6834
1721	2413	4087	8055	5762	2763	6746	6859
1746	2438	4112	8080	5787	2788	6771	6884
1771	2463	4137	8105	5812	2813	6796	6909
1796	2488	4162	8130	5837	2838	6821	6934
1821	2513	4187	8155	5862	2863	6846	6959
1846	2538	4212	8180	5887	2888	6871	6984
1871	2563	4237	8205	5912	2913	6896	7009
1896	2588	4262	8230	5937	2938	6921	7034
1921	2613	4287	8255	5962	2963	6946	7059
1946	2638	4312	8280	5987	2988	6971	7084
1971	2663	4337	8305	6012	3013	6996	7109
1996	2688	4362	8330	6037	3038	7021	7134
2021	2713	4387	8355	6062	3063	7046	7159
2046	2738	4412	8380	6087	3088	7071	7184
2071	2763	4437	8405	6112	3113	7096	7209
2096	2788	4462	8430	6137	3138	7121	7234
2121	2813	4487	8455	6162	3163	7146	7259
2146	2838	4512	8480	6187	3188	7171	7284
2171	2863	4537	8505	6212	3213	7196	7309
2196	2888	4562	8530	6237	3238	7221	7334
2221	2913	4587	8555	6262	3263	7246	7359
2246	2938	4612	8580	6287	3288	7271	7384
2271	2963	4637	8605	6312	3313	7296	7409
2296	2988	4662	8630	6337	3338	7321	7434
2321	3013	4687	8655	6362	3363	7346	7459
2346	3038	4712	8680	6387	3388	7371	7484
2371	3063	4737	8705	6412	3413	7396	7509
2396	3088	4762	8730	6437	3438	7421	7534
2421	3113	4787	8755	6462	3463	7446	7559
2446	3138	4812	8780	6487	3488	7471	7584
2471	3163	4837	8805	6512	3513	7496	7609
2496	3188	4862	8830	6537	3538	7521	7634
2521	3213	4887	8855	6562	3563	7546	7659
2546	3238	4912	8880	6587	3588	7571	7684
2571	3263	4937	8905	6612	3613	7596	7709
2596	3288	4962	8930	6637	3638	7621	7734
2621	3313	4987	8955	6662	3663	7646	7759
2646	3338	5012	8980	6687	3688	7671	7784
2671	3363	5037	5	6712	3713	7696	7809
2696	3388	5062	30	6737	3738	7721	7834
2721	3413	5087	55	6762	3763	7746	7859
2746	3438	5112	80	6787	3788	7771	7884
2771	3463	5137	105	6812	3813	7796	7909
2796	3488	5162	130	6837	3838	7821	7934
2821	3513	5187	155	6862	3863	7846	7959
2846	3538	5212	180	6887	3888	7871	7984
2871	3563	5237	205	6912	3913	7896	8009
2896	3588	5262	230	6937	3938	7921	8034
2921	3613	5287	255	6962	3963	7946	8059
2946	3638	5312	280	6987	3988	7971	8084
2971	3663	5337	305	7012	4013	7996	8109
2996	3688	5362	330	7037	4038	8021	8134
3021	3713	5387	355	7062	4063	8046	8159
3046	3738	5412	380	7087	4088	8071	8184
3071	3763	5437	405	7112	4113	8096	8209
3096	3788	5462	430	7137	4138	8121	8234
3121	3813	5487	455	7162	4163	8146	8259
3146	3838	5512	480	7187	4188	8171	8284
3171	3863	5537	505	7212	4213	8196	8309
3196	3888	5562	530	7237	4238	8221	8334
3221	3913	5587	555	7262	4263	8246	8359
3246	3938	5612	580	7287	4288	8271	8384
3271	3963	5637	605	7312	4313	8296	8409
3296	3988	5662	630	7337	4338	8321	8434

3321	4013	5687	655	7362	4363	8346	8459
3346	4038	5712	680	7387	4388	8371	8484
3371	4063	5737	705	7412	4413	8396	8509
3396	4088	5762	730	7437	4438	8421	8534
3421	4113	5787	755	7462	4463	8446	8559
3446	4138	5812	780	7487	4488	8471	8584
3471	4163	5837	805	7512	4513	8496	8609
3496	4188	5862	830	7537	4538	8521	8634
3521	4213	5887	855	7562	4563	8546	8659
3546	4238	5912	880	7587	4588	8571	8684
3571	4263	5937	905	7612	4613	8596	8709
3596	4288	5962	930	7637	4638	8621	8734
3621	4313	5987	955	7662	4663	8646	8759
3646	4338	6012	980	7687	4688	8671	8784
3671	4363	6037	1005	7712	4713	8696	8809
3696	4388	6062	1030	7737	4738	8721	8834
3721	4413	6087	1055	7762	4763	8746	8859
3746	4438	6112	1080	7787	4788	8771	8884
3771	4463	6137	1105	7812	4813	8796	8909
3796	4488	6162	1130	7837	4838	8821	8934
3821	4513	6187	1155	7862	4863	8846	8959
3846	4538	6212	1180	7887	4888	8871	8984
3871	4563	6237	1205	7912	4913	8896	9
3896	4588	6262	1230	7937	4938	8921	34
3921	4613	6287	1255	7962	4963	8946	59
3946	4638	6312	1280	7987	4988	8971	84
3971	4663	6337	1305	8012	5013	8996	109
3996	4688	6362	1330	8037	5038	21	134
4021	4713	6387	1355	8062	5063	46	159
4046	4738	6412	1380	8087	5088	71	184
4071	4763	6437	1405	8112	5113	96	209
4096	4788	6462	1430	8137	5138	121	234
4121	4813	6487	1455	8162	5163	146	259
4146	4838	6512	1480	8187	5188	171	284
4171	4863	6537	1505	8212	5213	196	309
4196	4888	6562	1530	8237	5238	221	334
4221	4913	6587	1555	8262	5263	246	359
4246	4938	6612	1580	8287	5288	271	384
4271	4963	6637	1605	8312	5313	296	409
4296	4988	6662	1630	8337	5338	321	434
4321	5013	6687	1655	8362	5363	346	459
4346	5038	6712	1680	8387	5388	371	484
4371	5063	6737	1705	8412	5413	396	509
4396	5088	6762	1730	8437	5438	421	534
4421	5113	6787	1755	8462	5463	446	559
4446	5138	6812	1780	8487	5488	471	584
4471	5163	6837	1805	8512	5513	496	609
4496	5188	6862	1830	8537	5538	521	634
4521	5213	6887	1855	8562	5563	546	659
4546	5238	6912	1880	8587	5588	571	684
4571	5263	6937	1905	8612	5613	596	709
4596	5288	6962	1930	8637	5638	621	734
4621	5313	6987	1955	8662	5663	646	759
4646	5338	7012	1980	8687	5688	671	784
4671	5363	7037	2005	8712	5713	696	809
4696	5388	7062	2030	8737	5738	721	834
4721	5413	7087	2055	8762	5763	746	859
4746	5438	7112	2080	8787	5788	771	884
4771	5463	7137	2105	8812	5813	796	909
4796	5488	7162	2130	8837	5838	821	934
4821	5513	7187	2155	8862	5863	846	959
4846	5538	7212	2180	8887	5888	871	984
4871	5563	7237	2205	8912	5913	896	1009
4896	5588	7262	2230	8937	5938	921	1034
4921	5613	7287	2255	8962	5963	946	1059
4946	5638	7312	2280	8987	5988	971	1084
4971	5663	7337	2305	12	6013	996	1109
4996	5688	7362	2330	37	6038	1021	1134
5021	5713	7387	2355	62	6063	1046	1159
5046	5738	7412	2380	87	6088	1071	1184

5071	5763	7437	2405	112	6113	1096	1209
5096	5788	7462	2430	137	6138	1121	1234
5121	5813	7487	2455	162	6163	1146	1259
5146	5838	7512	2480	187	6188	1171	1284
5171	5863	7537	2505	212	6213	1196	1309
5196	5888	7562	2530	237	6238	1221	1334
5221	5913	7587	2555	262	6263	1246	1359
5246	5938	7612	2580	287	6288	1271	1384
5271	5963	7637	2605	312	6313	1296	1409
5296	5988	7662	2630	337	6338	1321	1434
5321	6013	7687	2655	362	6363	1346	1459
5346	6038	7712	2680	387	6388	1371	1484
5371	6063	7737	2705	412	6413	1396	1509
5396	6088	7762	2730	437	6438	1421	1534
5421	6113	7787	2755	462	6463	1446	1559
5446	6138	7812	2780	487	6488	1471	1584
5471	6163	7837	2805	512	6513	1496	1609
5496	6188	7862	2830	537	6538	1521	1634
5521	6213	7887	2855	562	6563	1546	1659
5546	6238	7912	2880	587	6588	1571	1684
5571	6263	7937	2905	612	6613	1596	1709
5596	6288	7962	2930	637	6638	1621	1734
5621	6313	7987	2955	662	6663	1646	1759
5646	6338	8012	2980	687	6688	1671	1784
5671	6363	8037	3005	712	6713	1696	1809
5696	6388	8062	3030	737	6738	1721	1834
5721	6413	8087	3055	762	6763	1746	1859
5746	6438	8112	3080	787	6788	1771	1884
5771	6463	8137	3105	812	6813	1796	1909
5796	6488	8162	3130	837	6838	1821	1934
5821	6513	8187	3155	862	6863	1846	1959
5846	6538	8212	3180	887	6888	1871	1984
5871	6563	8237	3205	912	6913	1896	2009
5896	6588	8262	3230	937	6938	1921	2034
5921	6613	8287	3255	962	6963	1946	2059
5946	6638	8312	3280	987	6988	1971	2084
5971	6663	8337	3305	1012	7013	1996	2109
5996	6688	8362	3330	1037	7038	2021	2134
6021	6713	8387	3355	1062	7063	2046	2159
6046	6738	8412	3380	1087	7088	2071	2184
6071	6763	8437	3405	1112	7113	2096	2209
6096	6788	8462	3430	1137	7138	2121	2234
6121	6813	8487	3455	1162	7163	2146	2259
6146	6838	8512	3480	1187	7188	2171	2284
6171	6863	8537	3505	1212	7213	2196	2309
6196	6888	8562	3530	1237	7238	2221	2334
6221	6913	8587	3555	1262	7263	2246	2359
6246	6938	8612	3580	1287	7288	2271	2384
6271	6963	8637	3605	1312	7313	2296	2409
6296	6988	8662	3630	1337	7338	2321	2434
6321	7013	8687	3655	1362	7363	2346	2459
6346	7038	8712	3680	1387	7388	2371	2484
6371	7063	8737	3705	1412	7413	2396	2509
6396	7088	8762	3730	1437	7438	2421	2534
6421	7113	8787	3755	1462	7463	2446	2559
6446	7138	8812	3780	1487	7488	2471	2584
6471	7163	8837	3805	1512	7513	2496	2609
6496	7188	8862	3830	1537	7538	2521	2634
6521	7213	8887	3855	1562	7563	2546	2659
6546	7238	8912	3880	1587	7588	2571	2684
6571	7263	8937	3905	1612	7613	2596	2709
6596	7288	8962	3930	1637	7638	2621	2734
6621	7313	8987	3955	1662	7663	2646	2759
6646	7338	12	3980	1687	7688	2671	2784
6671	7363	37	4005	1712	7713	2696	2809
6696	7388	62	4030	1737	7738	2721	2834
6721	7413	87	4055	1762	7763	2746	2859
6746	7438	112	4080	1787	7788	2771	2884
6771	7463	137	4105	1812	7813	2796	2909
6796	7488	162	4130	1837	7838	2821	2934

6821	7513	187	4155	1862	7863	2846	2959
6846	7538	212	4180	1887	7888	2871	2984
6871	7563	237	4205	1912	7913	2896	3009
6896	7588	262	4230	1937	7938	2921	3034
6921	7613	287	4255	1962	7963	2946	3059
6946	7638	312	4280	1987	7988	2971	3084
6971	7663	337	4305	2012	8013	2996	3109
6996	7688	362	4330	2037	8038	3021	3134
7021	7713	387	4355	2062	8063	3046	3159
7046	7738	412	4380	2087	8088	3071	3184
7071	7763	437	4405	2112	8113	3096	3209
7096	7788	462	4430	2137	8138	3121	3234
7121	7813	487	4455	2162	8163	3146	3259
7146	7838	512	4480	2187	8188	3171	3284
7171	7863	537	4505	2212	8213	3196	3309
7196	7888	562	4530	2237	8238	3221	3334
7221	7913	587	4555	2262	8263	3246	3359
7246	7938	612	4580	2287	8288	3271	3384
7271	7963	637	4605	2312	8313	3296	3409
7296	7988	662	4630	2337	8338	3321	3434
7321	8013	687	4655	2362	8363	3346	3459
7346	8038	712	4680	2387	8388	3371	3484
7371	8063	737	4705	2412	8413	3396	3509
7396	8088	762	4730	2437	8438	3421	3534
7421	8113	787	4755	2462	8463	3446	3559
7446	8138	812	4780	2487	8488	3471	3584
7471	8163	837	4805	2512	8513	3496	3609
7496	8188	862	4830	2537	8538	3521	3634
7521	8213	887	4855	2562	8563	3546	3659
7546	8238	912	4880	2587	8588	3571	3684
7571	8263	937	4905	2612	8613	3596	3709
7596	8288	962	4930	2637	8638	3621	3734
7621	8313	987	4955	2662	8663	3646	3759
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7671	8363	1037	5005	2712	8713	3696	3809
7696	8388	1062	5030	2737	8738	3721	3834
7721	8413	1087	5055	2762	8763	3746	3859
7746	8438	1112	5080	2787	8788	3771	3884
7771	8463	1137	5105	2812	8813	3796	3909
7796	8488	1162	5130	2837	8838	3821	3934
7821	8513	1187	5155	2862	8863	3846	3959
7846	8538	1212	5180	2887	8888	3871	3984
7871	8563	1237	5205	2912	8913	3896	4009
7896	8588	1262	5230	2937	8938	3921	4034
7921	8613	1287	5255	2962	8963	3946	4059
7946	8638	1312	5280	2987	8988	3971	4084
7971	8663	1337	5305	3012	13	3996	4109
7996	8688	1362	5330	3037	38	4021	4134
8021	8713	1387	5355	3062	63	4046	4159
8046	8738	1412	5380	3087	88	4071	4184
8071	8763	1437	5405	3112	113	4096	4209
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8121	8813	1487	5455	3162	163	4146	4259
8146	8838	1512	5480	3187	188	4171	4284
8171	8863	1537	5505	3212	213	4196	4309
8196	8888	1562	5530	3237	238	4221	4334
8221	8913	1587	5555	3262	263	4246	4359
8246	8938	1612	5580	3287	288	4271	4384
8271	8963	1637	5605	3312	313	4296	4409
8296	8988	1662	5630	3337	338	4321	4434
8321	13	1687	5655	3362	363	4346	4459
8346	38	1712	5680	3387	388	4371	4484
8371	63	1737	5705	3412	413	4396	4509
8396	88	1762	5730	3437	438	4421	4534
8421	113	1787	5755	3462	463	4446	4559
8446	138	1812	5780	3487	488	4471	4584
8471	163	1837	5805	3512	513	4496	4609
8496	188	1862	5830	3537	538	4521	4634
8521	213	1887	5855	3562	563	4546	4659
8546	238	1912	5880	3587	588	4571	4684



8571	263	1937	5905	3612	613	4596	4709
8596	288	1962	5930	3637	638	4621	4734
8621	313	1987	5955	3662	663	4646	4759
8646	338	2012	5980	3687	688	4671	4784
8671	363	2037	6005	3712	713	4696	4809
8696	388	2062	6030	3737	738	4721	4834
8721	413	2087	6055	3762	763	4746	4859
8746	438	2112	6080	3787	788	4771	4884
8771	463	2137	6105	3812	813	4796	4909
8796	488	2162	6130	3837	838	4821	4934
8821	513	2187	6155	3862	863	4846	4959
8846	538	2212	6180	3887	888	4871	4984
8871	563	2237	6205	3912	913	4896	5009
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8971	663	2337	6305	4012	1013	4996	5109
8996	688	2362	6330	4037	1038	5021	5134
22	2544	5749	4823	2349	3090	6329	5877
47	2569	5774	4848	2374	3115	6354	5902
72	2594	5799	4873	2399	3140	6379	5927
97	2619	5824	4898	2424	3165	6404	5952
122	2644	5849	4923	2449	3190	6429	5977
147	2669	5874	4948	2474	3215	6454	6002
172	2694	5899	4973	2499	3240	6479	6027
197	2719	5924	4998	2524	3265	6504	6052
222	2744	5949	5023	2549	3290	6529	6077
247	2769	5974	5048	2574	3315	6554	6102
272	2794	5999	5073	2599	3340	6579	6127
297	2819	6024	5098	2624	3365	6604	6152
322	2844	6049	5123	2649	3390	6629	6177
347	2869	6074	5148	2674	3415	6654	6202
372	2894	6099	5173	2699	3440	6679	6227
397	2919	6124	5198	2724	3465	6704	6252
422	2944	6149	5223	2749	3490	6729	6277
447	2969	6174	5248	2774	3515	6754	6302
472	2994	6199	5273	2799	3540	6779	6327
497	3019	6224	5298	2824	3565	6804	6352
522	3044	6249	5323	2849	3590	6829	6377
547	3069	6274	5348	2874	3615	6854	6402
572	3094	6299	5373	2899	3640	6879	6427
597	3119	6324	5398	2924	3665	6904	6452
622	3144	6349	5423	2949	3690	6929	6477
647	3169	6374	5448	2974	3715	6954	6502
672	3194	6399	5473	2999	3740	6979	6527
697	3219	6424	5498	3024	3765	7004	6552
722	3244	6449	5523	3049	3790	7029	6577
747	3269	6474	5548	3074	3815	7054	6602
772	3294	6499	5573	3099	3840	7079	6627
797	3319	6524	5598	3124	3865	7104	6652
822	3344	6549	5623	3149	3890	7129	6677
847	3369	6574	5648	3174	3915	7154	6702
872	3394	6599	5673	3199	3940	7179	6727
897	3419	6624	5698	3224	3965	7204	6752
922	3444	6649	5723	3249	3990	7229	6777
947	3469	6674	5748	3274	4015	7254	6802
972	3494	6699	5773	3299	4040	7279	6827
997	3519	6724	5798	3324	4065	7304	6852
1022	3544	6749	5823	3349	4090	7329	6877
1047	3569	6774	5848	3374	4115	7354	6902
1072	3594	6799	5873	3399	4140	7379	6927
1097	3619	6824	5898	3424	4165	7404	6952
1122	3644	6849	5923	3449	4190	7429	6977
1147	3669	6874	5948	3474	4215	7454	7002
1172	3694	6899	5973	3499	4240	7479	7027
1197	3719	6924	5998	3524	4265	7504	7052
1222	3744	6949	6023	3549	4290	7529	7077
1247	3769	6974	6048	3574	4315	7554	7102
1272	3794	6999	6073	3599	4340	7579	7127
1297	3819	7024	6098	3624	4365	7604	7152

1322	3844	7049	6123	3649	4390	7629	7177
1347	3869	7074	6148	3674	4415	7654	7202
1372	3894	7099	6173	3699	4440	7679	7227
1397	3919	7124	6198	3724	4465	7704	7252
1422	3944	7149	6223	3749	4490	7729	7277
1447	3969	7174	6248	3774	4515	7754	7302
1472	3994	7199	6273	3799	4540	7779	7327
1497	4019	7224	6298	3824	4565	7804	7352
1522	4044	7249	6323	3849	4590	7829	7377
1547	4069	7274	6348	3874	4615	7854	7402
1572	4094	7299	6373	3899	4640	7879	7427
1597	4119	7324	6398	3924	4665	7904	7452
1622	4144	7349	6423	3949	4690	7929	7477
1647	4169	7374	6448	3974	4715	7954	7502
1672	4194	7399	6473	3999	4740	7979	7527
1697	4219	7424	6498	4024	4765	8004	7552
1722	4244	7449	6523	4049	4790	8029	7577
1747	4269	7474	6548	4074	4815	8054	7602
1772	4294	7499	6573	4099	4840	8079	7627
1797	4319	7524	6598	4124	4865	8104	7652
1822	4344	7549	6623	4149	4890	8129	7677
1847	4369	7574	6648	4174	4915	8154	7702
1872	4394	7599	6673	4199	4940	8179	7727
1897	4419	7624	6698	4224	4965	8204	7752
1922	4444	7649	6723	4249	4990	8229	7777
1947	4469	7674	6748	4274	5015	8254	7802
1972	4494	7699	6773	4299	5040	8279	7827
1997	4519	7724	6798	4324	5065	8304	7852
2022	4544	7749	6823	4349	5090	8329	7877
2047	4569	7774	6848	4374	5115	8354	7902
2072	4594	7799	6873	4399	5140	8379	7927
2097	4619	7824	6898	4424	5165	8404	7952
2122	4644	7849	6923	4449	5190	8429	7977
2147	4669	7874	6948	4474	5215	8454	8002
2172	4694	7899	6973	4499	5240	8479	8027
2197	4719	7924	6998	4524	5265	8504	8052
2222	4744	7949	7023	4549	5290	8529	8077
2247	4769	7974	7048	4574	5315	8554	8102
2272	4794	7999	7073	4599	5340	8579	8127
2297	4819	8024	7098	4624	5365	8604	8152
2322	4844	8049	7123	4649	5390	8629	8177
2347	4869	8074	7148	4674	5415	8654	8202
2372	4894	8099	7173	4699	5440	8679	8227
2397	4919	8124	7198	4724	5465	8704	8252
2422	4944	8149	7223	4749	5490	8729	8277
2447	4969	8174	7248	4774	5515	8754	8302
2472	4994	8199	7273	4799	5540	8779	8327
2497	5019	8224	7298	4824	5565	8804	8352
2522	5044	8249	7323	4849	5590	8829	8377
2547	5069	8274	7348	4874	5615	8854	8402
2572	5094	8299	7373	4899	5640	8879	8427
2597	5119	8324	7398	4924	5665	8904	8452
2622	5144	8349	7423	4949	5690	8929	8477
2647	5169	8374	7448	4974	5715	8954	8502
2672	5194	8399	7473	4999	5740	8979	8527
2697	5219	8424	7498	5024	5765	4	8552
2722	5244	8449	7523	5049	5790	29	8577
2747	5269	8474	7548	5074	5815	54	8602
2772	5294	8499	7573	5099	5840	79	8627
2797	5319	8524	7598	5124	5865	104	8652
2822	5344	8549	7623	5149	5890	129	8677
2847	5369	8574	7648	5174	5915	154	8702
2872	5394	8599	7673	5199	5940	179	8727
2897	5419	8624	7698	5224	5965	204	8752
2922	5444	8649	7723	5249	5990	229	8777
2947	5469	8674	7748	5274	6015	254	8802
2972	5494	8699	7773	5299	6040	279	8827
2997	5519	8724	7798	5324	6065	304	8852
3022	5544	8749	7823	5349	6090	329	8877
3047	5569	8774	7848	5374	6115	354	8902

3072	5594	8799	7873	5399	6140	379	8927
3097	5619	8824	7898	5424	6165	404	8952
3122	5644	8849	7923	5449	6190	429	8977
3147	5669	8874	7948	5474	6215	454	2
3172	5694	8899	7973	5499	6240	479	27
3197	5719	8924	7998	5524	6265	504	52
3222	5744	8949	8023	5549	6290	529	77
3247	5769	8974	8048	5574	6315	554	102
3272	5794	8999	8073	5599	6340	579	127
3297	5819	24	8098	5624	6365	604	152
3322	5844	49	8123	5649	6390	629	177
3347	5869	74	8148	5674	6415	654	202
3372	5894	99	8173	5699	6440	679	227
3397	5919	124	8198	5724	6465	704	252
3422	5944	149	8223	5749	6490	729	277
3447	5969	174	8248	5774	6515	754	302
3472	5994	199	8273	5799	6540	779	327
3497	6019	224	8298	5824	6565	804	352
3522	6044	249	8323	5849	6590	829	377
3547	6069	274	8348	5874	6615	854	402
3572	6094	299	8373	5899	6640	879	427
3597	6119	324	8398	5924	6665	904	452
3622	6144	349	8423	5949	6690	929	477
3647	6169	374	8448	5974	6715	954	502
3672	6194	399	8473	5999	6740	979	527
3697	6219	424	8498	6024	6765	1004	552
3722	6244	449	8523	6049	6790	1029	577
3747	6269	474	8548	6074	6815	1054	602
3772	6294	499	8573	6099	6840	1079	627
3797	6319	524	8598	6124	6865	1104	652
3822	6344	549	8623	6149	6890	1129	677
3847	6369	574	8648	6174	6915	1154	702
3872	6394	599	8673	6199	6940	1179	727
3897	6419	624	8698	6224	6965	1204	752
3922	6444	649	8723	6249	6990	1229	777
3947	6469	674	8748	6274	7015	1254	802
3972	6494	699	8773	6299	7040	1279	827
3997	6519	724	8798	6324	7065	1304	852
4022	6544	749	8823	6349	7090	1329	877
4047	6569	774	8848	6374	7115	1354	902
4072	6594	799	8873	6399	7140	1379	927
4097	6619	824	8898	6424	7165	1404	952
4122	6644	849	8923	6449	7190	1429	977
4147	6669	874	8948	6474	7215	1454	1002
4172	6694	899	8973	6499	7240	1479	1027
4197	6719	924	8998	6524	7265	1504	1052
4222	6744	949	23	6549	7290	1529	1077
4247	6769	974	48	6574	7315	1554	1102
4272	6794	999	73	6599	7340	1579	1127
4297	6819	1024	98	6624	7365	1604	1152
4322	6844	1049	123	6649	7390	1629	1177
4347	6869	1074	148	6674	7415	1654	1202
4372	6894	1099	173	6699	7440	1679	1227
4397	6919	1124	198	6724	7465	1704	1252
4422	6944	1149	223	6749	7490	1729	1277
4447	6969	1174	248	6774	7515	1754	1302
4472	6994	1199	273	6799	7540	1779	1327
4497	7019	1224	298	6824	7565	1804	1352
4522	7044	1249	323	6849	7590	1829	1377
4547	7069	1274	348	6874	7615	1854	1402
4572	7094	1299	373	6899	7640	1879	1427
4597	7119	1324	398	6924	7665	1904	1452
4622	7144	1349	423	6949	7690	1929	1477
4647	7169	1374	448	6974	7715	1954	1502
4672	7194	1399	473	6999	7740	1979	1527
4697	7219	1424	498	7024	7765	2004	1552
4722	7244	1449	523	7049	7790	2029	1577
4747	7269	1474	548	7074	7815	2054	1602
4772	7294	1499	573	7099	7840	2079	1627
4797	7319	1524	598	7124	7865	2104	1652

4822	7344	1549	623	7149	7890	2129	1677
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4897	7419	1624	698	7224	7965	2204	1752
4922	7444	1649	723	7249	7990	2229	1777
4947	7469	1674	748	7274	8015	2254	1802
4972	7494	1699	773	7299	8040	2279	1827
4997	7519	1724	798	7324	8065	2304	1852
5022	7544	1749	823	7349	8090	2329	1877
5047	7569	1774	848	7374	8115	2354	1902
5072	7594	1799	873	7399	8140	2379	1927
5097	7619	1824	898	7424	8165	2404	1952
5122	7644	1849	923	7449	8190	2429	1977
5147	7669	1874	948	7474	8215	2454	2002
5172	7694	1899	973	7499	8240	2479	2027
5197	7719	1924	998	7524	8265	2504	2052
5222	7744	1949	1023	7549	8290	2529	2077
5247	7769	1974	1048	7574	8315	2554	2102
5272	7794	1999	1073	7599	8340	2579	2127
5297	7819	2024	1098	7624	8365	2604	2152
5322	7844	2049	1123	7649	8390	2629	2177
5347	7869	2074	1148	7674	8415	2654	2202
5372	7894	2099	1173	7699	8440	2679	2227
5397	7919	2124	1198	7724	8465	2704	2252
5422	7944	2149	1223	7749	8490	2729	2277
5447	7969	2174	1248	7774	8515	2754	2302
5472	7994	2199	1273	7799	8540	2779	2327
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5522	8044	2249	1323	7849	8590	2829	2377
5547	8069	2274	1348	7874	8615	2854	2402
5572	8094	2299	1373	7899	8640	2879	2427
5597	8119	2324	1398	7924	8665	2904	2452
5622	8144	2349	1423	7949	8690	2929	2477
5647	8169	2374	1448	7974	8715	2954	2502
5672	8194	2399	1473	7999	8740	2979	2527
5697	8219	2424	1498	8024	8765	3004	2552
5722	8244	2449	1523	8049	8790	3029	2577
5747	8269	2474	1548	8074	8815	3054	2602
5772	8294	2499	1573	8099	8840	3079	2627
5797	8319	2524	1598	8124	8865	3104	2652
5822	8344	2549	1623	8149	8890	3129	2677
5847	8369	2574	1648	8174	8915	3154	2702
5872	8394	2599	1673	8199	8940	3179	2727
5897	8419	2624	1698	8224	8965	3204	2752
5922	8444	2649	1723	8249	8990	3229	2777
5947	8469	2674	1748	8274	15	3254	2802
5972	8494	2699	1773	8299	40	3279	2827
5997	8519	2724	1798	8324	65	3304	2852
6022	8544	2749	1823	8349	90	3329	2877
6047	8569	2774	1848	8374	115	3354	2902
6072	8594	2799	1873	8399	140	3379	2927
6097	8619	2824	1898	8424	165	3404	2952
6122	8644	2849	1923	8449	190	3429	2977
6147	8669	2874	1948	8474	215	3454	3002
6172	8694	2899	1973	8499	240	3479	3027
6197	8719	2924	1998	8524	265	3504	3052
6222	8744	2949	2023	8549	290	3529	3077
6247	8769	2974	2048	8574	315	3554	3102
6272	8794	2999	2073	8599	340	3579	3127
6297	8819	3024	2098	8624	365	3604	3152
6322	8844	3049	2123	8649	390	3629	3177
6347	8869	3074	2148	8674	415	3654	3202
6372	8894	3099	2173	8699	440	3679	3227
6397	8919	3124	2198	8724	465	3704	3252
6422	8944	3149	2223	8749	490	3729	3277
6447	8969	3174	2248	8774	515	3754	3302
6472	8994	3199	2273	8799	540	3779	3327
6497	19	3224	2298	8824	565	3804	3352
6522	44	3249	2323	8849	590	3829	3377
6547	69	3274	2348	8874	615	3854	3402

6572	94	3299	2373	8899	640	3879	3427
6597	119	3324	2398	8924	665	3904	3452
6622	144	3349	2423	8949	690	3929	3477
6647	169	3374	2448	8974	715	3954	3502
6672	194	3399	2473	8999	740	3979	3527
6697	219	3424	2498	24	765	4004	3552
6722	244	3449	2523	49	790	4029	3577
6747	269	3474	2548	74	815	4054	3602
6772	294	3499	2573	99	840	4079	3627
6797	319	3524	2598	124	865	4104	3652
6822	344	3549	2623	149	890	4129	3677
6847	369	3574	2648	174	915	4154	3702
6872	394	3599	2673	199	940	4179	3727
6897	419	3624	2698	224	965	4204	3752
6922	444	3649	2723	249	990	4229	3777
6947	469	3674	2748	274	1015	4254	3802
6972	494	3699	2773	299	1040	4279	3827
6997	519	3724	2798	324	1065	4304	3852
7022	544	3749	2823	349	1090	4329	3877
7047	569	3774	2848	374	1115	4354	3902
7072	594	3799	2873	399	1140	4379	3927
7097	619	3824	2898	424	1165	4404	3952
7122	644	3849	2923	449	1190	4429	3977
7147	669	3874	2948	474	1215	4454	4002
7172	694	3899	2973	499	1240	4479	4027
7197	719	3924	2998	524	1265	4504	4052
7222	744	3949	3023	549	1290	4529	4077
7247	769	3974	3048	574	1315	4554	4102
7272	794	3999	3073	599	1340	4579	4127
7297	819	4024	3098	624	1365	4604	4152
7322	844	4049	3123	649	1390	4629	4177
7347	869	4074	3148	674	1415	4654	4202
7372	894	4099	3173	699	1440	4679	4227
7397	919	4124	3198	724	1465	4704	4252
7422	944	4149	3223	749	1490	4729	4277
7447	969	4174	3248	774	1515	4754	4302
7472	994	4199	3273	799	1540	4779	4327
7497	1019	4224	3298	824	1565	4804	4352
7522	1044	4249	3323	849	1590	4829	4377
7547	1069	4274	3348	874	1615	4854	4402
7572	1094	4299	3373	899	1640	4879	4427
7597	1119	4324	3398	924	1665	4904	4452
7622	1144	4349	3423	949	1690	4929	4477
7647	1169	4374	3448	974	1715	4954	4502
7672	1194	4399	3473	999	1740	4979	4527
7697	1219	4424	3498	1024	1765	5004	4552
7722	1244	4449	3523	1049	1790	5029	4577
7747	1269	4474	3548	1074	1815	5054	4602
7772	1294	4499	3573	1099	1840	5079	4627
7797	1319	4524	3598	1124	1865	5104	4652
7822	1344	4549	3623	1149	1890	5129	4677
7847	1369	4574	3648	1174	1915	5154	4702
7872	1394	4599	3673	1199	1940	5179	4727
7897	1419	4624	3698	1224	1965	5204	4752
7922	1444	4649	3723	1249	1990	5229	4777
7947	1469	4674	3748	1274	2015	5254	4802
7972	1494	4699	3773	1299	2040	5279	4827
7997	1519	4724	3798	1324	2065	5304	4852
8022	1544	4749	3823	1349	2090	5329	4877
8047	1569	4774	3848	1374	2115	5354	4902
8072	1594	4799	3873	1399	2140	5379	4927
8097	1619	4824	3898	1424	2165	5404	4952
8122	1644	4849	3923	1449	2190	5429	4977
8147	1669	4874	3948	1474	2215	5454	5002
8172	1694	4899	3973	1499	2240	5479	5027
8197	1719	4924	3998	1524	2265	5504	5052
8222	1744	4949	4023	1549	2290	5529	5077
8247	1769	4974	4048	1574	2315	5554	5102
8272	1794	4999	4073	1599	2340	5579	5127
8297	1819	5024	4098	1624	2365	5604	5152

8322	1844	5049	4123	1649	2390	5629	5177
8347	1869	5074	4148	1674	2415	5654	5202
8372	1894	5099	4173	1699	2440	5679	5227
8397	1919	5124	4198	1724	2465	5704	5252
8422	1944	5149	4223	1749	2490	5729	5277
8447	1969	5174	4248	1774	2515	5754	5302
8472	1994	5199	4273	1799	2540	5779	5327
8497	2019	5224	4298	1824	2565	5804	5352
8522	2044	5249	4323	1849	2590	5829	5377
8547	2069	5274	4348	1874	2615	5854	5402
8572	2094	5299	4373	1899	2640	5879	5427
8597	2119	5324	4398	1924	2665	5904	5452
8622	2144	5349	4423	1949	2690	5929	5477
8647	2169	5374	4448	1974	2715	5954	5502
8672	2194	5399	4473	1999	2740	5979	5527
8697	2219	5424	4498	2024	2765	6004	5552
8722	2244	5449	4523	2049	2790	6029	5577
8747	2269	5474	4548	2074	2815	6054	5602
8772	2294	5499	4573	2099	2840	6079	5627
8797	2319	5524	4598	2124	2865	6104	5652
8822	2344	5549	4623	2149	2890	6129	5677
8847	2369	5574	4648	2174	2915	6154	5702
8872	2394	5599	4673	2199	2940	6179	5727
8897	2419	5624	4698	2224	2965	6204	5752
8922	2444	5649	4723	2249	2990	6229	5777
8947	2469	5674	4748	2274	3015	6254	5802
8972	2494	5699	4773	2299	3040	6279	5827
8997	2519	5724	4798	2324	3065	6304	5852
23	927	5702	270	3694	2439	3191	3508
48	952	5727	295	3719	2464	3216	3533
73	977	5752	320	3744	2489	3241	3558
98	1002	5777	345	3769	2514	3266	3583
123	1027	5802	370	3794	2539	3291	3608
148	1052	5827	395	3819	2564	3316	3633
173	1077	5852	420	3844	2589	3341	3658
198	1102	5877	445	3869	2614	3366	3683
223	1127	5902	470	3894	2639	3391	3708
248	1152	5927	495	3919	2664	3416	3733
273	1177	5952	520	3944	2689	3441	3758
298	1202	5977	545	3969	2714	3466	3783
323	1227	6002	570	3994	2739	3491	3808
348	1252	6027	595	4019	2764	3516	3833
373	1277	6052	620	4044	2789	3541	3858
398	1302	6077	645	4069	2814	3566	3883
423	1327	6102	670	4094	2839	3591	3908
448	1352	6127	695	4119	2864	3616	3933
473	1377	6152	720	4144	2889	3641	3958
498	1402	6177	745	4169	2914	3666	3983
523	1427	6202	770	4194	2939	3691	4008
548	1452	6227	795	4219	2964	3716	4033
573	1477	6252	820	4244	2989	3741	4058
598	1502	6277	845	4269	3014	3766	4083
623	1527	6302	870	4294	3039	3791	4108
648	1552	6327	895	4319	3064	3816	4133
673	1577	6352	920	4344	3089	3841	4158
698	1602	6377	945	4369	3114	3866	4183
723	1627	6402	970	4394	3139	3891	4208
748	1652	6427	995	4419	3164	3916	4233
773	1677	6452	1020	4444	3189	3941	4258
798	1702	6477	1045	4469	3214	3966	4283
823	1727	6502	1070	4494	3239	3991	4308
848	1752	6527	1095	4519	3264	4016	4333
873	1777	6552	1120	4544	3289	4041	4358
898	1802	6577	1145	4569	3314	4066	4383
923	1827	6602	1170	4594	3339	4091	4408
948	1852	6627	1195	4619	3364	4116	4433
973	1877	6652	1220	4644	3389	4141	4458
998	1902	6677	1245	4669	3414	4166	4483
1023	1927	6702	1270	4694	3439	4191	4508
1048	1952	6727	1295	4719	3464	4216	4533

1073	1977	6752	1320	4744	3489	4241	4558
1098	2002	6777	1345	4769	3514	4266	4583
1123	2027	6802	1370	4794	3539	4291	4608
1148	2052	6827	1395	4819	3564	4316	4633
1173	2077	6852	1420	4844	3589	4341	4658
1198	2102	6877	1445	4869	3614	4366	4683
1223	2127	6902	1470	4894	3639	4391	4708
1248	2152	6927	1495	4919	3664	4416	4733
1273	2177	6952	1520	4944	3689	4441	4758
1298	2202	6977	1545	4969	3714	4466	4783
1323	2227	7002	1570	4994	3739	4491	4808
1348	2252	7027	1595	5019	3764	4516	4833
1373	2277	7052	1620	5044	3789	4541	4858
1398	2302	7077	1645	5069	3814	4566	4883
1423	2327	7102	1670	5094	3839	4591	4908
1448	2352	7127	1695	5119	3864	4616	4933
1473	2377	7152	1720	5144	3889	4641	4958
1498	2402	7177	1745	5169	3914	4666	4983
1523	2427	7202	1770	5194	3939	4691	5008
1548	2452	7227	1795	5219	3964	4716	5033
1573	2477	7252	1820	5244	3989	4741	5058
1598	2502	7277	1845	5269	4014	4766	5083
1623	2527	7302	1870	5294	4039	4791	5108
1648	2552	7327	1895	5319	4064	4816	5133
1673	2577	7352	1920	5344	4089	4841	5158
1698	2602	7377	1945	5369	4114	4866	5183
1723	2627	7402	1970	5394	4139	4891	5208
1748	2652	7427	1995	5419	4164	4916	5233
1773	2677	7452	2020	5444	4189	4941	5258
1798	2702	7477	2045	5469	4214	4966	5283
1823	2727	7502	2070	5494	4239	4991	5308
1848	2752	7527	2095	5519	4264	5016	5333
1873	2777	7552	2120	5544	4289	5041	5358
1898	2802	7577	2145	5569	4314	5066	5383
1923	2827	7602	2170	5594	4339	5091	5408
1948	2852	7627	2195	5619	4364	5116	5433
1973	2877	7652	2220	5644	4389	5141	5458
1998	2902	7677	2245	5669	4414	5166	5483
2023	2927	7702	2270	5694	4439	5191	5508
2048	2952	7727	2295	5719	4464	5216	5533
2073	2977	7752	2320	5744	4489	5241	5558
2098	3002	7777	2345	5769	4514	5266	5583
2123	3027	7802	2370	5794	4539	5291	5608
2148	3052	7827	2395	5819	4564	5316	5633
2173	3077	7852	2420	5844	4589	5341	5658
2198	3102	7877	2445	5869	4614	5366	5683
2223	3127	7902	2470	5894	4639	5391	5708
2248	3152	7927	2495	5919	4664	5416	5733
2273	3177	7952	2520	5944	4689	5441	5758
2298	3202	7977	2545	5969	4714	5466	5783
2323	3227	8002	2570	5994	4739	5491	5808
2348	3252	8027	2595	6019	4764	5516	5833
2373	3277	8052	2620	6044	4789	5541	5858
2398	3302	8077	2645	6069	4814	5566	5883
2423	3327	8102	2670	6094	4839	5591	5908
2448	3352	8127	2695	6119	4864	5616	5933
2473	3377	8152	2720	6144	4889	5641	5958
2498	3402	8177	2745	6169	4914	5666	5983
2523	3427	8202	2770	6194	4939	5691	6008
2548	3452	8227	2795	6219	4964	5716	6033
2573	3477	8252	2820	6244	4989	5741	6058
2598	3502	8277	2845	6269	5014	5766	6083
2623	3527	8302	2870	6294	5039	5791	6108
2648	3552	8327	2895	6319	5064	5816	6133
2673	3577	8352	2920	6344	5089	5841	6158
2698	3602	8377	2945	6369	5114	5866	6183
2723	3627	8402	2970	6394	5139	5891	6208
2748	3652	8427	2995	6419	5164	5916	6233
2773	3677	8452	3020	6444	5189	5941	6258
2798	3702	8477	3045	6469	5214	5966	6283

2823	3727	8502	3070	6494	5239	5991	6308
2848	3752	8527	3095	6519	5264	6016	6333
2873	3777	8552	3120	6544	5289	6041	6358
2898	3802	8577	3145	6569	5314	6066	6383
2923	3827	8602	3170	6594	5339	6091	6408
2948	3852	8627	3195	6619	5364	6116	6433
2973	3877	8652	3220	6644	5389	6141	6458
2998	3902	8677	3245	6669	5414	6166	6483
3023	3927	8702	3270	6694	5439	6191	6508
3048	3952	8727	3295	6719	5464	6216	6533
3073	3977	8752	3320	6744	5489	6241	6558
3098	4002	8777	3345	6769	5514	6266	6583
3123	4027	8802	3370	6794	5539	6291	6608
3148	4052	8827	3395	6819	5564	6316	6633
3173	4077	8852	3420	6844	5589	6341	6658
3198	4102	8877	3445	6869	5614	6366	6683
3223	4127	8902	3470	6894	5639	6391	6708
3248	4152	8927	3495	6919	5664	6416	6733
3273	4177	8952	3520	6944	5689	6441	6758
3298	4202	8977	3545	6969	5714	6466	6783
3323	4227	2	3570	6994	5739	6491	6808
3348	4252	27	3595	7019	5764	6516	6833
3373	4277	52	3620	7044	5789	6541	6858
3398	4302	77	3645	7069	5814	6566	6883
3423	4327	102	3670	7094	5839	6591	6908
3448	4352	127	3695	7119	5864	6616	6933
3473	4377	152	3720	7144	5889	6641	6958
3498	4402	177	3745	7169	5914	6666	6983
3523	4427	202	3770	7194	5939	6691	7008
3548	4452	227	3795	7219	5964	6716	7033
3573	4477	252	3820	7244	5989	6741	7058
3598	4502	277	3845	7269	6014	6766	7083
3623	4527	302	3870	7294	6039	6791	7108
3648	4552	327	3895	7319	6064	6816	7133
3673	4577	352	3920	7344	6089	6841	7158
3698	4602	377	3945	7369	6114	6866	7183
3723	4627	402	3970	7394	6139	6891	7208
3748	4652	427	3995	7419	6164	6916	7233
3773	4677	452	4020	7444	6189	6941	7258
3798	4702	477	4045	7469	6214	6966	7283
3823	4727	502	4070	7494	6239	6991	7308
3848	4752	527	4095	7519	6264	7016	7333
3873	4777	552	4120	7544	6289	7041	7358
3898	4802	577	4145	7569	6314	7066	7383
3923	4827	602	4170	7594	6339	7091	7408
3948	4852	627	4195	7619	6364	7116	7433
3973	4877	652	4220	7644	6389	7141	7458
3998	4902	677	4245	7669	6414	7166	7483
4023	4927	702	4270	7694	6439	7191	7508
4048	4952	727	4295	7719	6464	7216	7533
4073	4977	752	4320	7744	6489	7241	7558
4098	5002	777	4345	7769	6514	7266	7583
4123	5027	802	4370	7794	6539	7291	7608
4148	5052	827	4395	7819	6564	7316	7633
4173	5077	852	4420	7844	6589	7341	7658
4198	5102	877	4445	7869	6614	7366	7683
4223	5127	902	4470	7894	6639	7391	7708
4248	5152	927	4495	7919	6664	7416	7733
4273	5177	952	4520	7944	6689	7441	7758
4298	5202	977	4545	7969	6714	7466	7783
4323	5227	1002	4570	7994	6739	7491	7808
4348	5252	1027	4595	8019	6764	7516	7833
4373	5277	1052	4620	8044	6789	7541	7858
4398	5302	1077	4645	8069	6814	7566	7883
4423	5327	1102	4670	8094	6839	7591	7908
4448	5352	1127	4695	8119	6864	7616	7933
4473	5377	1152	4720	8144	6889	7641	7958
4498	5402	1177	4745	8169	6914	7666	7983
4523	5427	1202	4770	8194	6939	7691	8008
4548	5452	1227	4795	8219	6964	7716	8033



4573	5477	1252	4820	8244	6989	7741	8058
4598	5502	1277	4845	8269	7014	7766	8083
4623	5527	1302	4870	8294	7039	7791	8108
4648	5552	1327	4895	8319	7064	7816	8133
4673	5577	1352	4920	8344	7089	7841	8158
4698	5602	1377	4945	8369	7114	7866	8183
4723	5627	1402	4970	8394	7139	7891	8208
4748	5652	1427	4995	8419	7164	7916	8233
4773	5677	1452	5020	8444	7189	7941	8258
4798	5702	1477	5045	8469	7214	7966	8283
4823	5727	1502	5070	8494	7239	7991	8308
4848	5752	1527	5095	8519	7264	8016	8333
4873	5777	1552	5120	8544	7289	8041	8358
4898	5802	1577	5145	8569	7314	8066	8383
4923	5827	1602	5170	8594	7339	8091	8408
4948	5852	1627	5195	8619	7364	8116	8433
4973	5877	1652	5220	8644	7389	8141	8458
4998	5902	1677	5245	8669	7414	8166	8483
5023	5927	1702	5270	8694	7439	8191	8508
5048	5952	1727	5295	8719	7464	8216	8533
5073	5977	1752	5320	8744	7489	8241	8558
5098	6002	1777	5345	8769	7514	8266	8583
5123	6027	1802	5370	8794	7539	8291	8608
5148	6052	1827	5395	8819	7564	8316	8633
5173	6077	1852	5420	8844	7589	8341	8658
5198	6102	1877	5445	8869	7614	8366	8683
5223	6127	1902	5470	8894	7639	8391	8708
5248	6152	1927	5495	8919	7664	8416	8733
5273	6177	1952	5520	8944	7689	8441	8758
5298	6202	1977	5545	8969	7714	8466	8783
5323	6227	2002	5570	8994	7739	8491	8808
5348	6252	2027	5595	19	7764	8516	8833
5373	6277	2052	5620	44	7789	8541	8858
5398	6302	2077	5645	69	7814	8566	8883
5423	6327	2102	5670	94	7839	8591	8908
5448	6352	2127	5695	119	7864	8616	8933
5473	6377	2152	5720	144	7889	8641	8958
5498	6402	2177	5745	169	7914	8666	8983
5523	6427	2202	5770	194	7939	8691	8
5548	6452	2227	5795	219	7964	8716	33
5573	6477	2252	5820	244	7989	8741	58
5598	6502	2277	5845	269	8014	8766	83
5623	6527	2302	5870	294	8039	8791	108
5648	6552	2327	5895	319	8064	8816	133
5673	6577	2352	5920	344	8089	8841	158
5698	6602	2377	5945	369	8114	8866	183
5723	6627	2402	5970	394	8139	8891	208
5748	6652	2427	5995	419	8164	8916	233
5773	6677	2452	6020	444	8189	8941	258
5798	6702	2477	6045	469	8214	8966	283
5823	6727	2502	6070	494	8239	8991	308
5848	6752	2527	6095	519	8264	16	333
5873	6777	2552	6120	544	8289	41	358
5898	6802	2577	6145	569	8314	66	383
5923	6827	2602	6170	594	8339	91	408
5948	6852	2627	6195	619	8364	116	433
5973	6877	2652	6220	644	8389	141	458
5998	6902	2677	6245	669	8414	166	483
6023	6927	2702	6270	694	8439	191	508
6048	6952	2727	6295	719	8464	216	533
6073	6977	2752	6320	744	8489	241	558
6098	7002	2777	6345	769	8514	266	583
6123	7027	2802	6370	794	8539	291	608
6148	7052	2827	6395	819	8564	316	633
6173	7077	2852	6420	844	8589	341	658
6198	7102	2877	6445	869	8614	366	683
6223	7127	2902	6470	894	8639	391	708
6248	7152	2927	6495	919	8664	416	733
6273	7177	2952	6520	944	8689	441	758
6298	7202	2977	6545	969	8714	466	783

6323	7227	3002	6570	994	8739	491	808
6348	7252	3027	6595	1019	8764	516	833
6373	7277	3052	6620	1044	8789	541	858
6398	7302	3077	6645	1069	8814	566	883
6423	7327	3102	6670	1094	8839	591	908
6448	7352	3127	6695	1119	8864	616	933
6473	7377	3152	6720	1144	8889	641	958
6498	7402	3177	6745	1169	8914	666	983
6523	7427	3202	6770	1194	8939	691	1008
6548	7452	3227	6795	1219	8964	716	1033
6573	7477	3252	6820	1244	8989	741	1058
6598	7502	3277	6845	1269	14	766	1083
6623	7527	3302	6870	1294	39	791	1108
6648	7552	3327	6895	1319	64	816	1133
6673	7577	3352	6920	1344	89	841	1158
6698	7602	3377	6945	1369	114	866	1183
6723	7627	3402	6970	1394	139	891	1208
6748	7652	3427	6995	1419	164	916	1233
6773	7677	3452	7020	1444	189	941	1258
6798	7702	3477	7045	1469	214	966	1283
6823	7727	3502	7070	1494	239	991	1308
6848	7752	3527	7095	1519	264	1016	1333
6873	7777	3552	7120	1544	289	1041	1358
6898	7802	3577	7145	1569	314	1066	1383
6923	7827	3602	7170	1594	339	1091	1408
6948	7852	3627	7195	1619	364	1116	1433
6973	7877	3652	7220	1644	389	1141	1458
6998	7902	3677	7245	1669	414	1166	1483
7023	7927	3702	7270	1694	439	1191	1508
7048	7952	3727	7295	1719	464	1216	1533
7073	7977	3752	7320	1744	489	1241	1558
7098	8002	3777	7345	1769	514	1266	1583
7123	8027	3802	7370	1794	539	1291	1608
7148	8052	3827	7395	1819	564	1316	1633
7173	8077	3852	7420	1844	589	1341	1658
7198	8102	3877	7445	1869	614	1366	1683
7223	8127	3902	7470	1894	639	1391	1708
7248	8152	3927	7495	1919	664	1416	1733
7273	8177	3952	7520	1944	689	1441	1758
7298	8202	3977	7545	1969	714	1466	1783
7323	8227	4002	7570	1994	739	1491	1808
7348	8252	4027	7595	2019	764	1516	1833
7373	8277	4052	7620	2044	789	1541	1858
7398	8302	4077	7645	2069	814	1566	1883
7423	8327	4102	7670	2094	839	1591	1908
7448	8352	4127	7695	2119	864	1616	1933
7473	8377	4152	7720	2144	889	1641	1958
7498	8402	4177	7745	2169	914	1666	1983
7523	8427	4202	7770	2194	939	1691	2008
7548	8452	4227	7795	2219	964	1716	2033
7573	8477	4252	7820	2244	989	1741	2058
7598	8502	4277	7845	2269	1014	1766	2083
7623	8527	4302	7870	2294	1039	1791	2108
7648	8552	4327	7895	2319	1064	1816	2133
7673	8577	4352	7920	2344	1089	1841	2158
7698	8602	4377	7945	2369	1114	1866	2183
7723	8627	4402	7970	2394	1139	1891	2208
7748	8652	4427	7995	2419	1164	1916	2233
7773	8677	4452	8020	2444	1189	1941	2258
7798	8702	4477	8045	2469	1214	1966	2283
7823	8727	4502	8070	2494	1239	1991	2308
7848	8752	4527	8095	2519	1264	2016	2333
7873	8777	4552	8120	2544	1289	2041	2358
7898	8802	4577	8145	2569	1314	2066	2383
7923	8827	4602	8170	2594	1339	2091	2408
7948	8852	4627	8195	2619	1364	2116	2433
7973	8877	4652	8220	2644	1389	2141	2458
7998	8902	4677	8245	2669	1414	2166	2483
8023	8927	4702	8270	2694	1439	2191	2508
8048	8952	4727	8295	2719	1464	2216	2533

8073	8977	4752	8320	2744	1489	2241	2558
8098	2	4777	8345	2769	1514	2266	2583
8123	27	4802	8370	2794	1539	2291	2608
8148	52	4827	8395	2819	1564	2316	2633
8173	77	4852	8420	2844	1589	2341	2658
8198	102	4877	8445	2869	1614	2366	2683
8223	127	4902	8470	2894	1639	2391	2708
8248	152	4927	8495	2919	1664	2416	2733
8273	177	4952	8520	2944	1689	2441	2758
8298	202	4977	8545	2969	1714	2466	2783
8323	227	5002	8570	2994	1739	2491	2808
8348	252	5027	8595	3019	1764	2516	2833
8373	277	5052	8620	3044	1789	2541	2858
8398	302	5077	8645	3069	1814	2566	2883
8423	327	5102	8670	3094	1839	2591	2908
8448	352	5127	8695	3119	1864	2616	2933
8473	377	5152	8720	3144	1889	2641	2958
8498	402	5177	8745	3169	1914	2666	2983
8523	427	5202	8770	3194	1939	2691	3008
8548	452	5227	8795	3219	1964	2716	3033
8573	477	5252	8820	3244	1989	2741	3058
8598	502	5277	8845	3269	2014	2766	3083
8623	527	5302	8870	3294	2039	2791	3108
8648	552	5327	8895	3319	2064	2816	3133
8673	577	5352	8920	3344	2089	2841	3158
8698	602	5377	8945	3369	2114	2866	3183
8723	627	5402	8970	3394	2139	2891	3208
8748	652	5427	8995	3419	2164	2916	3233
8773	677	5452	20	3444	2189	2941	3258
8798	702	5477	45	3469	2214	2966	3283
8823	727	5502	70	3494	2239	2991	3308
8848	752	5527	95	3519	2264	3016	3333
8873	777	5552	120	3544	2289	3041	3358
8898	802	5577	145	3569	2314	3066	3383
8923	827	5602	170	3594	2339	3091	3408
8948	852	5627	195	3619	2364	3116	3433
8973	877	5652	220	3644	2389	3141	3458
8998	902	5677	245	3669	2414	3166	3483
24	2803	4521	3578	5325	1092	4668	4450
49	2828	4546	3603	5350	1117	4693	4475
74	2853	4571	3628	5375	1142	4718	4500
99	2878	4596	3653	5400	1167	4743	4525
124	2903	4621	3678	5425	1192	4768	4550
149	2928	4646	3703	5450	1217	4793	4575
174	2953	4671	3728	5475	1242	4818	4600
199	2978	4696	3753	5500	1267	4843	4625
224	3003	4721	3778	5525	1292	4868	4650
249	3028	4746	3803	5550	1317	4893	4675
274	3053	4771	3828	5575	1342	4918	4700
299	3078	4796	3853	5600	1367	4943	4725
324	3103	4821	3878	5625	1392	4968	4750
349	3128	4846	3903	5650	1417	4993	4775
374	3153	4871	3928	5675	1442	5018	4800
399	3178	4896	3953	5700	1467	5043	4825
424	3203	4921	3978	5725	1492	5068	4850
449	3228	4946	4003	5750	1517	5093	4875
474	3253	4971	4028	5775	1542	5118	4900
499	3278	4996	4053	5800	1567	5143	4925
524	3303	5021	4078	5825	1592	5168	4950
549	3328	5046	4103	5850	1617	5193	4975
574	3353	5071	4128	5875	1642	5218	5000
599	3378	5096	4153	5900	1667	5243	5025
624	3403	5121	4178	5925	1692	5268	5050
649	3428	5146	4203	5950	1717	5293	5075
674	3453	5171	4228	5975	1742	5318	5100
699	3478	5196	4253	6000	1767	5343	5125
724	3503	5221	4278	6025	1792	5368	5150
749	3528	5246	4303	6050	1817	5393	5175
774	3553	5271	4328	6075	1842	5418	5200
799	3578	5296	4353	6100	1867	5443	5225

824	3603	5321	4378	6125	1892	5468	5250
849	3628	5346	4403	6150	1917	5493	5275
874	3653	5371	4428	6175	1942	5518	5300
899	3678	5396	4453	6200	1967	5543	5325
924	3703	5421	4478	6225	1992	5568	5350
949	3728	5446	4503	6250	2017	5593	5375
974	3753	5471	4528	6275	2042	5618	5400
999	3778	5496	4553	6300	2067	5643	5425
1024	3803	5521	4578	6325	2092	5668	5450
1049	3828	5546	4603	6350	2117	5693	5475
1074	3853	5571	4628	6375	2142	5718	5500
1099	3878	5596	4653	6400	2167	5743	5525
1124	3903	5621	4678	6425	2192	5768	5550
1149	3928	5646	4703	6450	2217	5793	5575
1174	3953	5671	4728	6475	2242	5818	5600
1199	3978	5696	4753	6500	2267	5843	5625
1224	4003	5721	4778	6525	2292	5868	5650
1249	4028	5746	4803	6550	2317	5893	5675
1274	4053	5771	4828	6575	2342	5918	5700
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1324	4103	5821	4878	6625	2392	5968	5750
1349	4128	5846	4903	6650	2417	5993	5775
1374	4153	5871	4928	6675	2442	6018	5800
1399	4178	5896	4953	6700	2467	6043	5825
1424	4203	5921	4978	6725	2492	6068	5850
1449	4228	5946	5003	6750	2517	6093	5875
1474	4253	5971	5028	6775	2542	6118	5900
1499	4278	5996	5053	6800	2567	6143	5925
1524	4303	6021	5078	6825	2592	6168	5950
1549	4328	6046	5103	6850	2617	6193	5975
1574	4353	6071	5128	6875	2642	6218	6000
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1624	4403	6121	5178	6925	2692	6268	6050
1649	4428	6146	5203	6950	2717	6293	6075
1674	4453	6171	5228	6975	2742	6318	6100
1699	4478	6196	5253	7000	2767	6343	6125
1724	4503	6221	5278	7025	2792	6368	6150
1749	4528	6246	5303	7050	2817	6393	6175
1774	4553	6271	5328	7075	2842	6418	6200
1799	4578	6296	5353	7100	2867	6443	6225
1824	4603	6321	5378	7125	2892	6468	6250
1849	4628	6346	5403	7150	2917	6493	6275
1874	4653	6371	5428	7175	2942	6518	6300
1899	4678	6396	5453	7200	2967	6543	6325
1924	4703	6421	5478	7225	2992	6568	6350
1949	4728	6446	5503	7250	3017	6593	6375
1974	4753	6471	5528	7275	3042	6618	6400
1999	4778	6496	5553	7300	3067	6643	6425
2024	4803	6521	5578	7325	3092	6668	6450
2049	4828	6546	5603	7350	3117	6693	6475
2074	4853	6571	5628	7375	3142	6718	6500
2099	4878	6596	5653	7400	3167	6743	6525
2124	4903	6621	5678	7425	3192	6768	6550
2149	4928	6646	5703	7450	3217	6793	6575
2174	4953	6671	5728	7475	3242	6818	6600
2199	4978	6696	5753	7500	3267	6843	6625
2224	5003	6721	5778	7525	3292	6868	6650
2249	5028	6746	5803	7550	3317	6893	6675
2274	5053	6771	5828	7575	3342	6918	6700
2299	5078	6796	5853	7600	3367	6943	6725
2324	5103	6821	5878	7625	3392	6968	6750
2349	5128	6846	5903	7650	3417	6993	6775
2374	5153	6871	5928	7675	3442	7018	6800
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2424	5203	6921	5978	7725	3492	7068	6850
2449	5228	6946	6003	7750	3517	7093	6875
2474	5253	6971	6028	7775	3542	7118	6900
2499	5278	6996	6053	7800	3567	7143	6925
2524	5303	7021	6078	7825	3592	7168	6950
2549	5328	7046	6103	7850	3617	7193	6975

2574	5353	7071	6128	7875	3642	7218	7000
2599	5378	7096	6153	7900	3667	7243	7025
2624	5403	7121	6178	7925	3692	7268	7050
2649	5428	7146	6203	7950	3717	7293	7075
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2699	5478	7196	6253	8000	3767	7343	7125
2724	5503	7221	6278	8025	3792	7368	7150
2749	5528	7246	6303	8050	3817	7393	7175
2774	5553	7271	6328	8075	3842	7418	7200
2799	5578	7296	6353	8100	3867	7443	7225
2824	5603	7321	6378	8125	3892	7468	7250
2849	5628	7346	6403	8150	3917	7493	7275
2874	5653	7371	6428	8175	3942	7518	7300
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2924	5703	7421	6478	8225	3992	7568	7350
2949	5728	7446	6503	8250	4017	7593	7375
2974	5753	7471	6528	8275	4042	7618	7400
2999	5778	7496	6553	8300	4067	7643	7425
3024	5803	7521	6578	8325	4092	7668	7450
3049	5828	7546	6603	8350	4117	7693	7475
3074	5853	7571	6628	8375	4142	7718	7500
3099	5878	7596	6653	8400	4167	7743	7525
3124	5903	7621	6678	8425	4192	7768	7550
3149	5928	7646	6703	8450	4217	7793	7575
3174	5953	7671	6728	8475	4242	7818	7600
3199	5978	7696	6753	8500	4267	7843	7625
3224	6003	7721	6778	8525	4292	7868	7650
3249	6028	7746	6803	8550	4317	7893	7675
3274	6053	7771	6828	8575	4342	7918	7700
3299	6078	7796	6853	8600	4367	7943	7725
3324	6103	7821	6878	8625	4392	7968	7750
3349	6128	7846	6903	8650	4417	7993	7775
3374	6153	7871	6928	8675	4442	8018	7800
3399	6178	7896	6953	8700	4467	8043	7825
3424	6203	7921	6978	8725	4492	8068	7850
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3474	6253	7971	7028	8775	4542	8118	7900
3499	6278	7996	7053	8800	4567	8143	7925
3524	6303	8021	7078	8825	4592	8168	7950
3549	6328	8046	7103	8850	4617	8193	7975
3574	6353	8071	7128	8875	4642	8218	8000
3599	6378	8096	7153	8900	4667	8243	8025
3624	6403	8121	7178	8925	4692	8268	8050
3649	6428	8146	7203	8950	4717	8293	8075
3674	6453	8171	7228	8975	4742	8318	8100
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3724	6503	8221	7278	25	4792	8368	8150
3749	6528	8246	7303	50	4817	8393	8175
3774	6553	8271	7328	75	4842	8418	8200
3799	6578	8296	7353	100	4867	8443	8225
3824	6603	8321	7378	125	4892	8468	8250
3849	6628	8346	7403	150	4917	8493	8275
3874	6653	8371	7428	175	4942	8518	8300
3899	6678	8396	7453	200	4967	8543	8325
3924	6703	8421	7478	225	4992	8568	8350
3949	6728	8446	7503	250	5017	8593	8375
3974	6753	8471	7528	275	5042	8618	8400
3999	6778	8496	7553	300	5067	8643	8425
4024	6803	8521	7578	325	5092	8668	8450
4049	6828	8546	7603	350	5117	8693	8475
4074	6853	8571	7628	375	5142	8718	8500
4099	6878	8596	7653	400	5167	8743	8525
4124	6903	8621	7678	425	5192	8768	8550
4149	6928	8646	7703	450	5217	8793	8575
4174	6953	8671	7728	475	5242	8818	8600
4199	6978	8696	7753	500	5267	8843	8625
4224	7003	8721	7778	525	5292	8868	8650
4249	7028	8746	7803	550	5317	8893	8675
4274	7053	8771	7828	575	5342	8918	8700
4299	7078	8796	7853	600	5367	8943	8725

4324	7103	8821	7878	625	5392	8968	8750
4349	7128	8846	7903	650	5417	8993	8775
4374	7153	8871	7928	675	5442	18	8800
4399	7178	8896	7953	700	5467	43	8825
4424	7203	8921	7978	725	5492	68	8850
4449	7228	8946	8003	750	5517	93	8875
4474	7253	8971	8028	775	5542	118	8900
4499	7278	8996	8053	800	5567	143	8925
4524	7303	21	8078	825	5592	168	8950
4549	7328	46	8103	850	5617	193	8975
4574	7353	71	8128	875	5642	218	9000
4599	7378	96	8153	900	5667	243	25
4624	7403	121	8178	925	5692	268	50
4649	7428	146	8203	950	5717	293	75
4674	7453	171	8228	975	5742	318	100
4699	7478	196	8253	1000	5767	343	125
4724	7503	221	8278	1025	5792	368	150
4749	7528	246	8303	1050	5817	393	175
4774	7553	271	8328	1075	5842	418	200
4799	7578	296	8353	1100	5867	443	225
4824	7603	321	8378	1125	5892	468	250
4849	7628	346	8403	1150	5917	493	275
4874	7653	371	8428	1175	5942	518	300
4899	7678	396	8453	1200	5967	543	325
4924	7703	421	8478	1225	5992	568	350
4949	7728	446	8503	1250	6017	593	375
4974	7753	471	8528	1275	6042	618	400
4999	7778	496	8553	1300	6067	643	425
5024	7803	521	8578	1325	6092	668	450
5049	7828	546	8603	1350	6117	693	475
5074	7853	571	8628	1375	6142	718	500
5099	7878	596	8653	1400	6167	743	525
5124	7903	621	8678	1425	6192	768	550
5149	7928	646	8703	1450	6217	793	575
5174	7953	671	8728	1475	6242	818	600
5199	7978	696	8753	1500	6267	843	625
5224	8003	721	8778	1525	6292	868	650
5249	8028	746	8803	1550	6317	893	675
5274	8053	771	8828	1575	6342	918	700
5299	8078	796	8853	1600	6367	943	725
5324	8103	821	8878	1625	6392	968	750
5349	8128	846	8903	1650	6417	993	775
5374	8153	871	8928	1675	6442	1018	800
5399	8178	896	8953	1700	6467	1043	825
5424	8203	921	8978	1725	6492	1068	850
5449	8228	946	3	1750	6517	1093	875
5474	8253	971	28	1775	6542	1118	900
5499	8278	996	53	1800	6567	1143	925
5524	8303	1021	78	1825	6592	1168	950
5549	8328	1046	103	1850	6617	1193	975
5574	8353	1071	128	1875	6642	1218	1000
5599	8378	1096	153	1900	6667	1243	1025
5624	8403	1121	178	1925	6692	1268	1050
5649	8428	1146	203	1950	6717	1293	1075
5674	8453	1171	228	1975	6742	1318	1100
5699	8478	1196	253	2000	6767	1343	1125
5724	8503	1221	278	2025	6792	1368	1150
5749	8528	1246	303	2050	6817	1393	1175
5774	8553	1271	328	2075	6842	1418	1200
5799	8578	1296	353	2100	6867	1443	1225
5824	8603	1321	378	2125	6892	1468	1250
5849	8628	1346	403	2150	6917	1493	1275
5874	8653	1371	428	2175	6942	1518	1300
5899	8678	1396	453	2200	6967	1543	1325
5924	8703	1421	478	2225	6992	1568	1350
5949	8728	1446	503	2250	7017	1593	1375
5974	8753	1471	528	2275	7042	1618	1400
5999	8778	1496	553	2300	7067	1643	1425
6024	8803	1521	578	2325	7092	1668	1450
6049	8828	1546	603	2350	7117	1693	1475

6074	8853	1571	628	2375	7142	1718	1500
6099	8878	1596	653	2400	7167	1743	1525
6124	8903	1621	678	2425	7192	1768	1550
6149	8928	1646	703	2450	7217	1793	1575
6174	8953	1671	728	2475	7242	1818	1600
6199	8978	1696	753	2500	7267	1843	1625
6224	3	1721	778	2525	7292	1868	1650
6249	28	1746	803	2550	7317	1893	1675
6274	53	1771	828	2575	7342	1918	1700
6299	78	1796	853	2600	7367	1943	1725
6324	103	1821	878	2625	7392	1968	1750
6349	128	1846	903	2650	7417	1993	1775
6374	153	1871	928	2675	7442	2018	1800
6399	178	1896	953	2700	7467	2043	1825
6424	203	1921	978	2725	7492	2068	1850
6449	228	1946	1003	2750	7517	2093	1875
6474	253	1971	1028	2775	7542	2118	1900
6499	278	1996	1053	2800	7567	2143	1925
6524	303	2021	1078	2825	7592	2168	1950
6549	328	2046	1103	2850	7617	2193	1975
6574	353	2071	1128	2875	7642	2218	2000
6599	378	2096	1153	2900	7667	2243	2025
6624	403	2121	1178	2925	7692	2268	2050
6649	428	2146	1203	2950	7717	2293	2075
6674	453	2171	1228	2975	7742	2318	2100
6699	478	2196	1253	3000	7767	2343	2125
6724	503	2221	1278	3025	7792	2368	2150
6749	528	2246	1303	3050	7817	2393	2175
6774	553	2271	1328	3075	7842	2418	2200
6799	578	2296	1353	3100	7867	2443	2225
6824	603	2321	1378	3125	7892	2468	2250
6849	628	2346	1403	3150	7917	2493	2275
6874	653	2371	1428	3175	7942	2518	2300
6899	678	2396	1453	3200	7967	2543	2325
6924	703	2421	1478	3225	7992	2568	2350
6949	728	2446	1503	3250	8017	2593	2375
6974	753	2471	1528	3275	8042	2618	2400
6999	778	2496	1553	3300	8067	2643	2425
7024	803	2521	1578	3325	8092	2668	2450
7049	828	2546	1603	3350	8117	2693	2475
7074	853	2571	1628	3375	8142	2718	2500
7099	878	2596	1653	3400	8167	2743	2525
7124	903	2621	1678	3425	8192	2768	2550
7149	928	2646	1703	3450	8217	2793	2575
7174	953	2671	1728	3475	8242	2818	2600
7199	978	2696	1753	3500	8267	2843	2625
7224	1003	2721	1778	3525	8292	2868	2650
7249	1028	2746	1803	3550	8317	2893	2675
7274	1053	2771	1828	3575	8342	2918	2700
7299	1078	2796	1853	3600	8367	2943	2725
7324	1103	2821	1878	3625	8392	2968	2750
7349	1128	2846	1903	3650	8417	2993	2775
7374	1153	2871	1928	3675	8442	3018	2800
7399	1178	2896	1953	3700	8467	3043	2825
7424	1203	2921	1978	3725	8492	3068	2850
7449	1228	2946	2003	3750	8517	3093	2875
7474	1253	2971	2028	3775	8542	3118	2900
7499	1278	2996	2053	3800	8567	3143	2925
7524	1303	3021	2078	3825	8592	3168	2950
7549	1328	3046	2103	3850	8617	3193	2975
7574	1353	3071	2128	3875	8642	3218	3000
7599	1378	3096	2153	3900	8667	3243	3025
7624	1403	3121	2178	3925	8692	3268	3050
7649	1428	3146	2203	3950	8717	3293	3075
7674	1453	3171	2228	3975	8742	3318	3100
7699	1478	3196	2253	4000	8767	3343	3125
7724	1503	3221	2278	4025	8792	3368	3150
7749	1528	3246	2303	4050	8817	3393	3175
7774	1553	3271	2328	4075	8842	3418	3200
7799	1578	3296	2353	4100	8867	3443	3225

7824	1603	3321	2378	4125	8892	3468	3250
7849	1628	3346	2403	4150	8917	3493	3275
7874	1653	3371	2428	4175	8942	3518	3300
7899	1678	3396	2453	4200	8967	3543	3325
7924	1703	3421	2478	4225	8992	3568	3350
7949	1728	3446	2503	4250	17	3593	3375
7974	1753	3471	2528	4275	42	3618	3400
7999	1778	3496	2553	4300	67	3643	3425
8024	1803	3521	2578	4325	92	3668	3450
8049	1828	3546	2603	4350	117	3693	3475
8074	1853	3571	2628	4375	142	3718	3500
8099	1878	3596	2653	4400	167	3743	3525
8124	1903	3621	2678	4425	192	3768	3550
8149	1928	3646	2703	4450	217	3793	3575
8174	1953	3671	2728	4475	242	3818	3600
8199	1978	3696	2753	4500	267	3843	3625
8224	2003	3721	2778	4525	292	3868	3650
8249	2028	3746	2803	4550	317	3893	3675
8274	2053	3771	2828	4575	342	3918	3700
8299	2078	3796	2853	4600	367	3943	3725
8324	2103	3821	2878	4625	392	3968	3750
8349	2128	3846	2903	4650	417	3993	3775
8374	2153	3871	2928	4675	442	4018	3800
8399	2178	3896	2953	4700	467	4043	3825
8424	2203	3921	2978	4725	492	4068	3850
8449	2228	3946	3003	4750	517	4093	3875
8474	2253	3971	3028	4775	542	4118	3900
8499	2278	3996	3053	4800	567	4143	3925
8524	2303	4021	3078	4825	592	4168	3950
8549	2328	4046	3103	4850	617	4193	3975
8574	2353	4071	3128	4875	642	4218	4000
8599	2378	4096	3153	4900	667	4243	4025
8624	2403	4121	3178	4925	692	4268	4050
8649	2428	4146	3203	4950	717	4293	4075
8674	2453	4171	3228	4975	742	4318	4100
8699	2478	4196	3253	5000	767	4343	4125
8724	2503	4221	3278	5025	792	4368	4150
8749	2528	4246	3303	5050	817	4393	4175
8774	2553	4271	3328	5075	842	4418	4200
8799	2578	4296	3353	5100	867	4443	4225
8824	2603	4321	3378	5125	892	4468	4250
8849	2628	4346	3403	5150	917	4493	4275
8874	2653	4371	3428	5175	942	4518	4300
8899	2678	4396	3453	5200	967	4543	4325
8924	2703	4421	3478	5225	992	4568	4350
8949	2728	4446	3503	5250	1017	4593	4375
8974	2753	4471	3528	5275	1042	4618	4400
8999	2778	4496	3553	5300	1067	4643	4425
25	5141	2004	1264	4743	6498	1186	6203
50	5166	2029	1289	4768	6523	1211	6228
75	5191	2054	1314	4793	6548	1236	6253
100	5216	2079	1339	4818	6573	1261	6278
125	5241	2104	1364	4843	6598	1286	6303
150	5266	2129	1389	4868	6623	1311	6328
175	5291	2154	1414	4893	6648	1336	6353
200	5316	2179	1439	4918	6673	1361	6378
225	5341	2204	1464	4943	6698	1386	6403
250	5366	2229	1489	4968	6723	1411	6428
275	5391	2254	1514	4993	6748	1436	6453
300	5416	2279	1539	5018	6773	1461	6478
325	5441	2304	1564	5043	6798	1486	6503
350	5466	2329	1589	5068	6823	1511	6528
375	5491	2354	1614	5093	6848	1536	6553
400	5516	2379	1639	5118	6873	1561	6578
425	5541	2404	1664	5143	6898	1586	6603
450	5566	2429	1689	5168	6923	1611	6628
475	5591	2454	1714	5193	6948	1636	6653
500	5616	2479	1739	5218	6973	1661	6678
525	5641	2504	1764	5243	6998	1686	6703
550	5666	2529	1789	5268	7023	1711	6728



575	5691	2554	1814	5293	7048	1736	6753
600	5716	2579	1839	5318	7073	1761	6778
625	5741	2604	1864	5343	7098	1786	6803
650	5766	2629	1889	5368	7123	1811	6828
675	5791	2654	1914	5393	7148	1836	6853
700	5816	2679	1939	5418	7173	1861	6878
725	5841	2704	1964	5443	7198	1886	6903
750	5866	2729	1989	5468	7223	1911	6928
775	5891	2754	2014	5493	7248	1936	6953
800	5916	2779	2039	5518	7273	1961	6978
825	5941	2804	2064	5543	7298	1986	7003
850	5966	2829	2089	5568	7323	2011	7028
875	5991	2854	2114	5593	7348	2036	7053
900	6016	2879	2139	5618	7373	2061	7078
925	6041	2904	2164	5643	7398	2086	7103
950	6066	2929	2189	5668	7423	2111	7128
975	6091	2954	2214	5693	7448	2136	7153
1000	6116	2979	2239	5718	7473	2161	7178
1025	6141	3004	2264	5743	7498	2186	7203
1050	6166	3029	2289	5768	7523	2211	7228
1075	6191	3054	2314	5793	7548	2236	7253
1100	6216	3079	2339	5818	7573	2261	7278
1125	6241	3104	2364	5843	7598	2286	7303
1150	6266	3129	2389	5868	7623	2311	7328
1175	6291	3154	2414	5893	7648	2336	7353
1200	6316	3179	2439	5918	7673	2361	7378
1225	6341	3204	2464	5943	7698	2386	7403
1250	6366	3229	2489	5968	7723	2411	7428
1275	6391	3254	2514	5993	7748	2436	7453
1300	6416	3279	2539	6018	7773	2461	7478
1325	6441	3304	2564	6043	7798	2486	7503
1350	6466	3329	2589	6068	7823	2511	7528
1375	6491	3354	2614	6093	7848	2536	7553
1400	6516	3379	2639	6118	7873	2561	7578
1425	6541	3404	2664	6143	7898	2586	7603
1450	6566	3429	2689	6168	7923	2611	7628
1475	6591	3454	2714	6193	7948	2636	7653
1500	6616	3479	2739	6218	7973	2661	7678
1525	6641	3504	2764	6243	7998	2686	7703
1550	6666	3529	2789	6268	8023	2711	7728
1575	6691	3554	2814	6293	8048	2736	7753
1600	6716	3579	2839	6318	8073	2761	7778
1625	6741	3604	2864	6343	8098	2786	7803
1650	6766	3629	2889	6368	8123	2811	7828
1675	6791	3654	2914	6393	8148	2836	7853
1700	6816	3679	2939	6418	8173	2861	7878
1725	6841	3704	2964	6443	8198	2886	7903
1750	6866	3729	2989	6468	8223	2911	7928
1775	6891	3754	3014	6493	8248	2936	7953
1800	6916	3779	3039	6518	8273	2961	7978
1825	6941	3804	3064	6543	8298	2986	8003
1850	6966	3829	3089	6568	8323	3011	8028
1875	6991	3854	3114	6593	8348	3036	8053
1900	7016	3879	3139	6618	8373	3061	8078
1925	7041	3904	3164	6643	8398	3086	8103
1950	7066	3929	3189	6668	8423	3111	8128
1975	7091	3954	3214	6693	8448	3136	8153
2000	7116	3979	3239	6718	8473	3161	8178
2025	7141	4004	3264	6743	8498	3186	8203
2050	7166	4029	3289	6768	8523	3211	8228
2075	7191	4054	3314	6793	8548	3236	8253
2100	7216	4079	3339	6818	8573	3261	8278
2125	7241	4104	3364	6843	8598	3286	8303
2150	7266	4129	3389	6868	8623	3311	8328
2175	7291	4154	3414	6893	8648	3336	8353
2200	7316	4179	3439	6918	8673	3361	8378
2225	7341	4204	3464	6943	8698	3386	8403
2250	7366	4229	3489	6968	8723	3411	8428
2275	7391	4254	3514	6993	8748	3436	8453
2300	7416	4279	3539	7018	8773	3461	8478

2325	7441	4304	3564	7043	8798	3486	8503
2350	7466	4329	3589	7068	8823	3511	8528
2375	7491	4354	3614	7093	8848	3536	8553
2400	7516	4379	3639	7118	8873	3561	8578
2425	7541	4404	3664	7143	8898	3586	8603
2450	7566	4429	3689	7168	8923	3611	8628
2475	7591	4454	3714	7193	8948	3636	8653
2500	7616	4479	3739	7218	8973	3661	8678
2525	7641	4504	3764	7243	8998	3686	8703
2550	7666	4529	3789	7268	23	3711	8728
2575	7691	4554	3814	7293	48	3736	8753
2600	7716	4579	3839	7318	73	3761	8778
2625	7741	4604	3864	7343	98	3786	8803
2650	7766	4629	3889	7368	123	3811	8828
2675	7791	4654	3914	7393	148	3836	8853
2700	7816	4679	3939	7418	173	3861	8878
2725	7841	4704	3964	7443	198	3886	8903
2750	7866	4729	3989	7468	223	3911	8928
2775	7891	4754	4014	7493	248	3936	8953
2800	7916	4779	4039	7518	273	3961	8978
2825	7941	4804	4064	7543	298	3986	3
2850	7966	4829	4089	7568	323	4011	28
2875	7991	4854	4114	7593	348	4036	53
2900	8016	4879	4139	7618	373	4061	78
2925	8041	4904	4164	7643	398	4086	103
2950	8066	4929	4189	7668	423	4111	128
2975	8091	4954	4214	7693	448	4136	153
3000	8116	4979	4239	7718	473	4161	178
3025	8141	5004	4264	7743	498	4186	203
3050	8166	5029	4289	7768	523	4211	228
3075	8191	5054	4314	7793	548	4236	253
3100	8216	5079	4339	7818	573	4261	278
3125	8241	5104	4364	7843	598	4286	303
3150	8266	5129	4389	7868	623	4311	328
3175	8291	5154	4414	7893	648	4336	353
3200	8316	5179	4439	7918	673	4361	378
3225	8341	5204	4464	7943	698	4386	403
3250	8366	5229	4489	7968	723	4411	428
3275	8391	5254	4514	7993	748	4436	453
3300	8416	5279	4539	8018	773	4461	478
3325	8441	5304	4564	8043	798	4486	503
3350	8466	5329	4589	8068	823	4511	528
3375	8491	5354	4614	8093	848	4536	553
3400	8516	5379	4639	8118	873	4561	578
3425	8541	5404	4664	8143	898	4586	603
3450	8566	5429	4689	8168	923	4611	628
3475	8591	5454	4714	8193	948	4636	653
3500	8616	5479	4739	8218	973	4661	678
3525	8641	5504	4764	8243	998	4686	703
3550	8666	5529	4789	8268	1023	4711	728
3575	8691	5554	4814	8293	1048	4736	753
3600	8716	5579	4839	8318	1073	4761	778
3625	8741	5604	4864	8343	1098	4786	803
3650	8766	5629	4889	8368	1123	4811	828
3675	8791	5654	4914	8393	1148	4836	853
3700	8816	5679	4939	8418	1173	4861	878
3725	8841	5704	4964	8443	1198	4886	903
3750	8866	5729	4989	8468	1223	4911	928
3775	8891	5754	5014	8493	1248	4936	953
3800	8916	5779	5039	8518	1273	4961	978
3825	8941	5804	5064	8543	1298	4986	1003
3850	8966	5829	5089	8568	1323	5011	1028
3875	8991	5854	5114	8593	1348	5036	1053
3900	16	5879	5139	8618	1373	5061	1078
3925	41	5904	5164	8643	1398	5086	1103
3950	66	5929	5189	8668	1423	5111	1128
3975	91	5954	5214	8693	1448	5136	1153
4000	116	5979	5239	8718	1473	5161	1178
4025	141	6004	5264	8743	1498	5186	1203
4050	166	6029	5289	8768	1523	5211	1228

4075	191	6054	5314	8793	1548	5236	1253
4100	216	6079	5339	8818	1573	5261	1278
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4575	691	6554	5814	293	2048	5736	1753
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4675	791	6654	5914	393	2148	5836	1853
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4775	891	6754	6014	493	2248	5936	1953
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227	3081	292
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6956	3875	7241
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7556	4475	7841
7581	4500	7866
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7631	4550	7916
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432	1893	4475
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632	2093	4675
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682	2143	4725
707	2168	4750
732	2193	4775
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782	2243	4825
807	2268	4850
832	2293	4875
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907	2368	4950
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383	8196	2618
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6413	429	7165
6438	454	7190
6463	479	7215
6488	504	7240
6513	529	7265
6538	554	7290
6563	579	7315
6588	604	7340
6613	629	7365
6638	654	7390
6663	679	7415
6688	704	7440
6713	729	7465
6738	754	7490
6763	779	7515
6788	804	7540
6813	829	7565
6838	854	7590
6863	879	7615
6888	904	7640
6913	929	7665
6938	954	7690
6963	979	7715
6988	1004	7740
7013	1029	7765
7038	1054	7790
7063	1079	7815
7088	1104	7840
7113	1129	7865
7138	1154	7890
7163	1179	7915
7188	1204	7940
7213	1229	7965
7238	1254	7990
7263	1279	8015
7288	1304	8040
7313	1329	8065
7338	1354	8090
7363	1379	8115
7388	1404	8140
7413	1429	8165
7438	1454	8190
7463	1479	8215
7488	1504	8240
7513	1529	8265
7538	1554	8290
7563	1579	8315
7588	1604	8340
7613	1629	8365
7638	1654	8390
7663	1679	8415
7688	1704	8440
7713	1729	8465
7738	1754	8490
7763	1779	8515
7788	1804	8540

7813	1829	8565
7838	1854	8590
7863	1879	8615
7888	1904	8640
7913	1929	8665
7938	1954	8690
7963	1979	8715
7988	2004	8740
8013	2029	8765
8038	2054	8790
8063	2079	8815
8088	2104	8840
8113	2129	8865
8138	2154	8890
8163	2179	8915
8188	2204	8940
8213	2229	8965
8238	2254	8990
8263	2279	15
8288	2304	40
8313	2329	65
8338	2354	90
8363	2379	115
8388	2404	140
8413	2429	165
8438	2454	190
8463	2479	215
8488	2504	240
8513	2529	265
8538	2554	290
8563	2579	315
8588	2604	340
8613	2629	365
8638	2654	390
8663	2679	415
8688	2704	440
8713	2729	465
8738	2754	490
8763	2779	515
8788	2804	540
8813	2829	565
8838	2854	590
8863	2879	615
8888	2904	640
8913	2929	665
8938	2954	690
8963	2979	715
8988	3004	740
14	5989	1058
39	6014	1083
64	6039	1108
89	6064	1133
114	6089	1158
139	6114	1183
164	6139	1208
189	6164	1233
214	6189	1258
239	6214	1283
264	6239	1308
289	6264	1333
314	6289	1358
339	6314	1383
364	6339	1408
389	6364	1433
414	6389	1458
439	6414	1483
464	6439	1508
489	6464	1533
514	6489	1558
539	6514	1583



564	6539	1608
589	6564	1633
614	6589	1658
639	6614	1683
664	6639	1708
689	6664	1733
714	6689	1758
739	6714	1783
764	6739	1808
789	6764	1833
814	6789	1858
839	6814	1883
864	6839	1908
889	6864	1933
914	6889	1958
939	6914	1983
964	6939	2008
989	6964	2033
1014	6989	2058
1039	7014	2083
1064	7039	2108
1089	7064	2133
1114	7089	2158
1139	7114	2183
1164	7139	2208
1189	7164	2233
1214	7189	2258
1239	7214	2283
1264	7239	2308
1289	7264	2333
1314	7289	2358
1339	7314	2383
1364	7339	2408
1389	7364	2433
1414	7389	2458
1439	7414	2483
1464	7439	2508
1489	7464	2533
1514	7489	2558
1539	7514	2583
1564	7539	2608
1589	7564	2633
1614	7589	2658
1639	7614	2683
1664	7639	2708
1689	7664	2733
1714	7689	2758
1739	7714	2783
1764	7739	2808
1789	7764	2833
1814	7789	2858
1839	7814	2883
1864	7839	2908
1889	7864	2933
1914	7889	2958
1939	7914	2983
1964	7939	3008
1989	7964	3033
2014	7989	3058
2039	8014	3083
2064	8039	3108
2089	8064	3133
2114	8089	3158
2139	8114	3183
2164	8139	3208
2189	8164	3233
2214	8189	3258
2239	8214	3283
2264	8239	3308
2289	8264	3333

2314	8289	3358
2339	8314	3383
2364	8339	3408
2389	8364	3433
2414	8389	3458
2439	8414	3483
2464	8439	3508
2489	8464	3533
2514	8489	3558
2539	8514	3583
2564	8539	3608
2589	8564	3633
2614	8589	3658
2639	8614	3683
2664	8639	3708
2689	8664	3733
2714	8689	3758
2739	8714	3783
2764	8739	3808
2789	8764	3833
2814	8789	3858
2839	8814	3883
2864	8839	3908
2889	8864	3933
2914	8889	3958
2939	8914	3983
2964	8939	4008
2989	8964	4033
3014	8989	4058
3039	14	4083
3064	39	4108
3089	64	4133
3114	89	4158
3139	114	4183
3164	139	4208
3189	164	4233
3214	189	4258
3239	214	4283
3264	239	4308
3289	264	4333
3314	289	4358
3339	314	4383
3364	339	4408
3389	364	4433
3414	389	4458
3439	414	4483
3464	439	4508
3489	464	4533
3514	489	4558
3539	514	4583
3564	539	4608
3589	564	4633
3614	589	4658
3639	614	4683
3664	639	4708
3689	664	4733
3714	689	4758
3739	714	4783
3764	739	4808
3789	764	4833
3814	789	4858
3839	814	4883
3864	839	4908
3889	864	4933
3914	889	4958
3939	914	4983
3964	939	5008
3989	964	5033
4014	989	5058
4039	1014	5083

4064	1039	5108
4089	1064	5133
4114	1089	5158
4139	1114	5183
4164	1139	5208
4189	1164	5233
4214	1189	5258
4239	1214	5283
4264	1239	5308
4289	1264	5333
4314	1289	5358
4339	1314	5383
4364	1339	5408
4389	1364	5433
4414	1389	5458
4439	1414	5483
4464	1439	5508
4489	1464	5533
4514	1489	5558
4539	1514	5583
4564	1539	5608
4589	1564	5633
4614	1589	5658
4639	1614	5683
4664	1639	5708
4689	1664	5733
4714	1689	5758
4739	1714	5783
4764	1739	5808
4789	1764	5833
4814	1789	5858
4839	1814	5883
4864	1839	5908
4889	1864	5933
4914	1889	5958
4939	1914	5983
4964	1939	6008
4989	1964	6033
5014	1989	6058
5039	2014	6083
5064	2039	6108
5089	2064	6133
5114	2089	6158
5139	2114	6183
5164	2139	6208
5189	2164	6233
5214	2189	6258
5239	2214	6283
5264	2239	6308
5289	2264	6333
5314	2289	6358
5339	2314	6383
5364	2339	6408
5389	2364	6433
5414	2389	6458
5439	2414	6483
5464	2439	6508
5489	2464	6533
5514	2489	6558
5539	2514	6583
5564	2539	6608
5589	2564	6633
5614	2589	6658
5639	2614	6683
5664	2639	6708
5689	2664	6733
5714	2689	6758
5739	2714	6783
5764	2739	6808
5789	2764	6833

5814	2789	6858
5839	2814	6883
5864	2839	6908
5889	2864	6933
5914	2889	6958
5939	2914	6983
5964	2939	7008
5989	2964	7033
6014	2989	7058
6039	3014	7083
6064	3039	7108
6089	3064	7133
6114	3089	7158
6139	3114	7183
6164	3139	7208
6189	3164	7233
6214	3189	7258
6239	3214	7283
6264	3239	7308
6289	3264	7333
6314	3289	7358
6339	3314	7383
6364	3339	7408
6389	3364	7433
6414	3389	7458
6439	3414	7483
6464	3439	7508
6489	3464	7533
6514	3489	7558
6539	3514	7583
6564	3539	7608
6589	3564	7633
6614	3589	7658
6639	3614	7683
6664	3639	7708
6689	3664	7733
6714	3689	7758
6739	3714	7783
6764	3739	7808
6789	3764	7833
6814	3789	7858
6839	3814	7883
6864	3839	7908
6889	3864	7933
6914	3889	7958
6939	3914	7983
6964	3939	8008
6989	3964	8033
7014	3989	8058
7039	4014	8083
7064	4039	8108
7089	4064	8133
7114	4089	8158
7139	4114	8183
7164	4139	8208
7189	4164	8233
7214	4189	8258
7239	4214	8283
7264	4239	8308
7289	4264	8333
7314	4289	8358
7339	4314	8383
7364	4339	8408
7389	4364	8433
7414	4389	8458
7439	4414	8483
7464	4439	8508
7489	4464	8533
7514	4489	8558
7539	4514	8583

7564	4539	8608
7589	4564	8633
7614	4589	8658
7639	4614	8683
7664	4639	8708
7689	4664	8733
7714	4689	8758
7739	4714	8783
7764	4739	8808
7789	4764	8833
7814	4789	8858
7839	4814	8883
7864	4839	8908
7889	4864	8933
7914	4889	8958
7939	4914	8983
7964	4939	8
7989	4964	33
8014	4989	58
8039	5014	83
8064	5039	108
8089	5064	133
8114	5089	158
8139	5114	183
8164	5139	208
8189	5164	233
8214	5189	258
8239	5214	283
8264	5239	308
8289	5264	333
8314	5289	358
8339	5314	383
8364	5339	408
8389	5364	433
8414	5389	458
8439	5414	483
8464	5439	508
8489	5464	533
8514	5489	558
8539	5514	583
8564	5539	608
8589	5564	633
8614	5589	658
8639	5614	683
8664	5639	708
8689	5664	733
8714	5689	758
8739	5714	783
8764	5739	808
8789	5764	833
8814	5789	858
8839	5814	883
8864	5839	908
8889	5864	933
8914	5889	958
8939	5914	983
8964	5939	1008
8989	5964	1033
15	7412	3451
40	7437	3476
65	7462	3501
90	7487	3526
115	7512	3551
140	7537	3576
165	7562	3601
190	7587	3626
215	7612	3651
240	7637	3676
265	7662	3701
290	7687	3726

315	7712	3751
340	7737	3776
365	7762	3801
390	7787	3826
415	7812	3851
440	7837	3876
465	7862	3901
490	7887	3926
515	7912	3951
540	7937	3976
565	7962	4001
590	7987	4026
615	8012	4051
640	8037	4076
665	8062	4101
690	8087	4126
715	8112	4151
740	8137	4176
765	8162	4201
790	8187	4226
815	8212	4251
840	8237	4276
865	8262	4301
890	8287	4326
915	8312	4351
940	8337	4376
965	8362	4401
990	8387	4426
1015	8412	4451
1040	8437	4476
1065	8462	4501
1090	8487	4526
1115	8512	4551
1140	8537	4576
1165	8562	4601
1190	8587	4626
1215	8612	4651
1240	8637	4676
1265	8662	4701
1290	8687	4726
1315	8712	4751
1340	8737	4776
1365	8762	4801
1390	8787	4826
1415	8812	4851
1440	8837	4876
1465	8862	4901
1490	8887	4926
1515	8912	4951
1540	8937	4976
1565	8962	5001
1590	8987	5026
1615	12	5051
1640	37	5076
1665	62	5101
1690	87	5126
1715	112	5151
1740	137	5176
1765	162	5201
1790	187	5226
1815	212	5251
1840	237	5276
1865	262	5301
1890	287	5326
1915	312	5351
1940	337	5376
1965	362	5401
1990	387	5426
2015	412	5451
2040	437	5476

2065	462	5501
2090	487	5526
2115	512	5551
2140	537	5576
2165	562	5601
2190	587	5626
2215	612	5651
2240	637	5676
2265	662	5701
2290	687	5726
2315	712	5751
2340	737	5776
2365	762	5801
2390	787	5826
2415	812	5851
2440	837	5876
2465	862	5901
2490	887	5926
2515	912	5951
2540	937	5976
2565	962	6001
2590	987	6026
2615	1012	6051
2640	1037	6076
2665	1062	6101
2690	1087	6126
2715	1112	6151
2740	1137	6176
2765	1162	6201
2790	1187	6226
2815	1212	6251
2840	1237	6276
2865	1262	6301
2890	1287	6326
2915	1312	6351
2940	1337	6376
2965	1362	6401
2990	1387	6426
3015	1412	6451
3040	1437	6476
3065	1462	6501
3090	1487	6526
3115	1512	6551
3140	1537	6576
3165	1562	6601
3190	1587	6626
3215	1612	6651
3240	1637	6676
3265	1662	6701
3290	1687	6726
3315	1712	6751
3340	1737	6776
3365	1762	6801
3390	1787	6826
3415	1812	6851
3440	1837	6876
3465	1862	6901
3490	1887	6926
3515	1912	6951
3540	1937	6976
3565	1962	7001
3590	1987	7026
3615	2012	7051
3640	2037	7076
3665	2062	7101
3690	2087	7126
3715	2112	7151
3740	2137	7176
3765	2162	7201
3790	2187	7226

3815	2212	7251
3840	2237	7276
3865	2262	7301
3890	2287	7326
3915	2312	7351
3940	2337	7376
3965	2362	7401
3990	2387	7426
4015	2412	7451
4040	2437	7476
4065	2462	7501
4090	2487	7526
4115	2512	7551
4140	2537	7576
4165	2562	7601
4190	2587	7626
4215	2612	7651
4240	2637	7676
4265	2662	7701
4290	2687	7726
4315	2712	7751
4340	2737	7776
4365	2762	7801
4390	2787	7826
4415	2812	7851
4440	2837	7876
4465	2862	7901
4490	2887	7926
4515	2912	7951
4540	2937	7976
4565	2962	8001
4590	2987	8026
4615	3012	8051
4640	3037	8076
4665	3062	8101
4690	3087	8126
4715	3112	8151
4740	3137	8176
4765	3162	8201
4790	3187	8226
4815	3212	8251
4840	3237	8276
4865	3262	8301
4890	3287	8326
4915	3312	8351
4940	3337	8376
4965	3362	8401
4990	3387	8426
5015	3412	8451
5040	3437	8476
5065	3462	8501
5090	3487	8526
5115	3512	8551
5140	3537	8576
5165	3562	8601
5190	3587	8626
5215	3612	8651
5240	3637	8676
5265	3662	8701
5290	3687	8726
5315	3712	8751
5340	3737	8776
5365	3762	8801
5390	3787	8826
5415	3812	8851
5440	3837	8876
5465	3862	8901
5490	3887	8926
5515	3912	8951
5540	3937	8976



5565	3962	1
5590	3987	26
5615	4012	51
5640	4037	76
5665	4062	101
5690	4087	126
5715	4112	151
5740	4137	176
5765	4162	201
5790	4187	226
5815	4212	251
5840	4237	276
5865	4262	301
5890	4287	326
5915	4312	351
5940	4337	376
5965	4362	401
5990	4387	426
6015	4412	451
6040	4437	476
6065	4462	501
6090	4487	526
6115	4512	551
6140	4537	576
6165	4562	601
6190	4587	626
6215	4612	651
6240	4637	676
6265	4662	701
6290	4687	726
6315	4712	751
6340	4737	776
6365	4762	801
6390	4787	826
6415	4812	851
6440	4837	876
6465	4862	901
6490	4887	926
6515	4912	951
6540	4937	976
6565	4962	1001
6590	4987	1026
6615	5012	1051
6640	5037	1076
6665	5062	1101
6690	5087	1126
6715	5112	1151
6740	5137	1176
6765	5162	1201
6790	5187	1226
6815	5212	1251
6840	5237	1276
6865	5262	1301
6890	5287	1326
6915	5312	1351
6940	5337	1376
6965	5362	1401
6990	5387	1426
7015	5412	1451
7040	5437	1476
7065	5462	1501
7090	5487	1526
7115	5512	1551
7140	5537	1576
7165	5562	1601
7190	5587	1626
7215	5612	1651
7240	5637	1676
7265	5662	1701
7290	5687	1726

7315	5712	1751
7340	5737	1776
7365	5762	1801
7390	5787	1826
7415	5812	1851
7440	5837	1876
7465	5862	1901
7490	5887	1926
7515	5912	1951
7540	5937	1976
7565	5962	2001
7590	5987	2026
7615	6012	2051
7640	6037	2076
7665	6062	2101
7690	6087	2126
7715	6112	2151
7740	6137	2176
7765	6162	2201
7790	6187	2226
7815	6212	2251
7840	6237	2276
7865	6262	2301
7890	6287	2326
7915	6312	2351
7940	6337	2376
7965	6362	2401
7990	6387	2426
8015	6412	2451
8040	6437	2476
8065	6462	2501
8090	6487	2526
8115	6512	2551
8140	6537	2576
8165	6562	2601
8190	6587	2626
8215	6612	2651
8240	6637	2676
8265	6662	2701
8290	6687	2726
8315	6712	2751
8340	6737	2776
8365	6762	2801
8390	6787	2826
8415	6812	2851
8440	6837	2876
8465	6862	2901
8490	6887	2926
8515	6912	2951
8540	6937	2976
8565	6962	3001
8590	6987	3026
8615	7012	3051
8640	7037	3076
8665	7062	3101
8690	7087	3126
8715	7112	3151
8740	7137	3176
8765	7162	3201
8790	7187	3226
8815	7212	3251
8840	7237	3276
8865	7262	3301
8890	7287	3326
8915	7312	3351
8940	7337	3376
8965	7362	3401
8990	7387	3426

## Appendix B: Indexes of nonzero elements in the parity-check matrix H (9000 x 16200)

### B1: Row-wised row index:

{0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 2, 2, 2, 2, 2, 2, 3, 3, 3, 3, 3, 3, 4, 4, 4, 4, 5, 5, 5, 5, 5, 6, 6, 6, 6, 7, 7, 7, 7, 8, 8, 8, 8, 8, 8, 9, 9, 9, 9, 10, 10, 10, 10, 10, 11, 11, 11, 11, 11, 11, 12, 12, 12, 12, 12, 12, 13, 13, 13, 13, 13, 13, 14, 14, 14, 14, 14, 14, 15, 15, 15, 15, 16, 16, 16, 16, 17, 17, 17, 17, 17, 17, 18, 18, 18, 18, 18, 19, 19, 19, 19, 20, 20, 20, 20, 20, 20, 21, 21, 21, 21, 21, 22, 22, 22, 22, 23, 23, 23, 23, 23, 24, 24, 24, 24, 24, 24, 25, 25, 25, 25, 26, 26, 26, 26, 26, 26, 27, 27, 27, 27, 27, 27, 28, 28, 28, 28, 28, 29, 29, 29, 29, 30, 30, 30, 30, 30, 31, 31, 31, 31, 32, 32, 32, 32, 32, 33, 33, 33, 33, 33, 33, 34, 34, 34, 34, 35, 35, 35, 35, 36, 36, 36, 36, 36, 36, 37, 37, 37, 37, 37, 38, 38, 38, 38, 38, 38, 39, 39, 39, 39, 39, 39, 40, 40, 40, 40, 41, 41, 41, 41, 42, 42, 42, 42, 42, 43, 43, 43, 43, 43, 44, 44, 44, 44, 45, 45, 45, 45, 45, 46, 46, 46, 46, 46, 47, 47, 47, 48, 48, 48, 48, 49, 49, 49, 49, 49, 49, 50, 50, 50, 50, 51, 51, 51, 51, 51, 52, 52, 52, 52, 52, 53, 53, 53, 53, 54, 54, 54, 54, 55, 55, 55, 55, 56, 56, 56, 56, 57, 57, 57, 57, 58, 58, 58, 58, 58, 59, 59, 59, 59, 60, 60, 60, 60, 61, 61, 61, 61, 62, 62, 62, 62, 62, 63, 63, 63, 63, 64, 64, 64, 64, 64, 65, 65, 65, 65, 66, 66, 66, 67, 67, 67, 68, 68, 68, 68, 69, 69, 69, 70, 70, 70, 70, 71, 71, 71, 71, 72, 72, 72, 72, 73, 73, 73, 73, 74, 74, 74, 74, 75, 75, 75, 76, 76, 76, 76, 77, 77, 77, 78, 78, 78, 78, 79, 79, 79, 80, 80, 80, 80, 81, 81, 81, 82, 82, 82, 82, 83, 83, 83, 83, 83, 84, 84, 84, 84, 85, 85, 85, 86, 86, 86, 86, 87, 87, 87, 87, 87, 88, 88, 88, 88, 89, 89, 89, 89, 89, 90, 90, 90, 90, 91, 91, 91, 92, 92, 92, 93, 93, 93, 94, 94, 94, 95, 95, 95, 95, 96, 96, 96, 96, 97, 97, 97, 97, 98, 98, 98, 99, 99, 99, 99, 99, 99, 100, 100, 100, 100, 101, 101, 101, 101, 101, 102, 102, 102, 102, 103, 103, 103, 103, 104, 104, 104, 105, 105, 105, 105, 106, 106, 106, 107, 107, 107, 108, 108, 108, 108, 109, 109, 109, 109, 110, 110, 110, 110, 111, 111, 111, 111, 112, 112, 112, 112, 113, 113, 113, 113, 114, 114, 114, 115, 115, 115, 116, 116, 116, 117, 117, 117, 117, 118, 118, 118, 118, 119, 119, 119, 120, 120, 120, 120, 121, 121, 121, 122, 122, 122, 122, 123, 123, 123, 123, 124, 124, 124, 124, 125, 125, 125, 125, 126, 126, 126, 126, 127, 127, 127, 127, 128, 128, 128, 128, 129, 129, 129, 130, 130, 130, 131, 131, 131, 132, 132, 132, 133, 133, 133, 133, 134, 134, 134, 135, 135, 135, 136, 136, 136, 137, 137, 137, 138, 138, 138, 139, 139, 139, 140, 140, 140, 141, 141, 141, 142, 142, 142, 143, 143, 143, 144, 144, 144, 145, 145, 145, 146, 146, 146, 147, 147, 147, 148, 148, 148, 149, 149, 150, 150, 150, 151, 151, 151, 152, 152, 152, 153, 153, 153, 154, 154, 155, 155, 156, 156, 157, 157, 157, 158, 158, 158, 159, 159, 159, 160, 160, 160, 161, 161, 161, 162, 162, 162, 163, 163, 163, 164, 164, 164, 165, 165, 166, 166, 167, 167, 167, 168, 168, 168, 169, 169, 170, 170, 170, 171, 171, 171, 172, 172, 172, 173, 173, 173, 174, 174, 174, 175, 175, 175, 176, 176, 176, 177, 177, 177, 177, 178, 178, 178, 179, 179, 180, 180, 180, 181, 181, 181, 182, 182, 182, 183, 183, 183, 184, 184, 184, 185, 185, 185, 186, 186, 186, 187, 187, 187, 188, 188, 188, 189, 189, 189, 190, 190, 190, 191, 191, 192, 192, 192, 193, 193, 193, 194, 194, 195, 195, 195, 196, 196, 196, 197, 197, 197, 198, 198, 198, 199, 199, 199, 200, 200, 200, 201, 201, 201, 202, 202, 202, 203, 203, 203, 204, 204, 205, 205, 205, 206, 206, 207, 207, 208, 208, 208, 209, 209, 210, 210, 210, 211, 211, 211, 212, 212, 212, 213, 213, 213, 214, 214, 214, 215, 215, 215, 216, 216, 217, 217, 217, 218, 218, 218, 219, 219, 220, 220, 220, 221, 221, 221, 222, 222, 222, 223, 223, 223, 224, 224, 224, 225, 225, 225, 226, 226, 226, 227, 227, 227, 228, 228, 228, 229, 229, 230, 230, 230, 231, 231, 231, 232, 232, 232, 233, 233, 233, 234, 234, 234, 235, 235, 235, 236, 236, 236, 237, 237, 237, 238, 238, 238, 239, 239, 240, 240, 240, 241, 241, 241, 242, 242, 242, 243, 243, 244, 244, 245, 245, 245, 246, 246, 246, 247, 247, 247, 248, 248, 248, 249, 249, 250, 250, 250, 251, 251, 251, 252, 252, 252, 253, 253, 253, 254, 254, 255, 255, 255, 256, 256, 257, 257, 258, 258, 258, 259, 259, 259, 260, 260, 260, 261, 261, 261, 262, 262, 262, 263, 263, 263, 264, 264, 264, 265, 265, 265, 266, 266, 267, 267, 267, 268, 268, 268, 269, 269, 270, 270, 270, 271, 271, 271, 272, 272, 272, 273, 273, 273, 274, 274, 274, 274, 275, 275, 276, 276, 276, 277, 277, 277, 278, 278, 278, 279, 279, 280, 280, 280, 281, 281, 281, 282, 282, 282, 283, 283, 283, 284, 284, 284, 285, 285, 286, 286, 286, 287, 287, 287, 288, 288, 288, 289, 289, 289, 290, 290, 291, 291, 291, 292, 292, 292, 293, 293, 293, 294, 294, 295, 295, 295, 296, 296, 296, 297, 297, 297, 298, 298, 298, 299, 299, 299, 300, 300, 300, 301, 301, 301, 301, 301,







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8993, 8993, 8993, 8994, 8994, 8994, 8994, 8995, 8995, 8995, 8995, 8995, 8995, 8996, 8996, 8996, 8996, 8996, 8997, 8997, 8997, 8997, 8997, 8998, 8998, 8998, 8998, 8999, 8999, 8999, 8999, 8999, 8999, 8999, 8999};

## B2: Row-wised column index:

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941, 4321, 6799, 7231, 7232, 155, 3195, 4681, 5216, 7232, 7233, 1884, 5041, 5606, 7233, 7234, 1754, 5401, 5764, 7234, 7235, 199, 266, 5761, 6905, 7235, 7236, 319, 333, 2873, 6121, 7236, 7237, 984, 1751, 6481, 6602, 7237, 7238, 598, 3104, 6451, 6841, 7238, 7239, 954, 1596, 3950, 7239, 7240, 1398, 2519, 7240, 7241, 1255, 1612, 4263, 4592, 7241, 7242, 620, 934, 5487, 7242, 7243, 1071, 2614, 7243, 7244, 1, 160, 1261, 4369, 7244, 7245, 361, 2000, 5922, 7245, 7246, 529, 721, 1542, 3425, 7246, 7247, 492, 628, 1081, 7247, 7248, 1229, 1264, 1441, 3725, 4160, 7248, 7249, 1802, 3448, 7064, 7249, 7250, 487, 854, 1045, 2162, 7250, 7251, 1299, 1330, 1554, 2522, 5087, 7251, 7252, 469, 1722, 2882, 6361, 7252, 7253, 108, 3242, 7253, 7254, 2408, 3602, 4919, 7254, 7255, 3962, 4858, 7255, 7256, 942, 4322, 6800, 7256, 7257, 156, 3196, 4682, 5217, 7257, 7258, 1885, 5042, 5607, 7258, 7259, 1755, 5402, 5765, 7259, 7260, 200, 267, 5762, 6906, 7260, 7261, 320, 334, 2874, 6122, 7261, 7262, 985, 1752, 6482, 6603, 7262, 7263, 599, 3105, 6452, 6842, 7263, 7264, 955, 1597, 3951, 7264, 7265, 1399, 2160, 7265, 7266, 1256, 1613, 4264, 4593, 7266, 7267, 621, 935, 5488, 7267, 7268, 1072, 2615, 7268, 7269, 2, 161, 1262, 4370, 7269, 7270, 362, 2001, 5923, 7270, 7271, 530, 722, 1543, 3426, 7271, 7272, 493, 629, 1082, 7272, 7273, 1230, 1265, 1442, 3726, 4161, 7273, 7274, 1803, 3449, 7065, 7274, 7275, 488, 855, 1046, 2163, 7275, 7276, 1300, 1331, 1555, 2523, 5088, 7276, 7277, 470, 1723, 2883, 6362, 7277, 7278, 109, 3243, 7278, 7279, 2409, 3603, 4920, 7279, 7280, 3963, 4859, 7280, 7281, 943, 4323, 6801, 7281, 7282, 157, 3197, 4683, 5218, 7282, 7283, 1886, 5043, 5608, 7283, 7284, 1756, 5403, 5766, 7284, 7285, 201, 268, 5763, 6907, 7285, 7286, 321, 335, 2875, 6123, 7286, 7287, 986, 1753, 6483, 6604, 7287, 7288, 600, 3106, 6453, 6843, 7288, 7289, 956, 1598, 3952, 7289, 7290, 1400, 2161, 7290, 7291, 1257, 1614, 4265, 4594, 7291, 7292, 622, 936, 5489, 7292, 7293, 1073, 2616, 7293, 7294, 3, 162, 1263, 4371, 7294, 7295, 363, 2002, 5924, 7295, 7296, 531, 723, 1544, 3427, 7296, 7297, 494, 630, 1083, 7297, 7298, 1231, 1266, 1443, 3727, 4162, 7298, 7299, 1804, 3450, 7066, 7299, 7300, 489, 856, 1047, 2164, 7300, 7301, 1301, 1332, 1556, 2524, 5089, 7301, 7302, 471, 1724, 2884, 6363, 7302, 7303, 110, 3244, 7303, 7304, 2410, 3604, 4921, 7304, 7305, 3964, 4860, 7305, 7306, 944, 4324, 6802, 7306, 7307, 158, 3198, 4684, 5219, 7307, 7308, 1887, 5044, 5609, 7308, 7309, 1757, 5404, 5767, 7309, 7310, 202, 269, 5764, 6908, 7310, 7311, 322, 336, 2876, 6124, 7311, 7312, 987, 1754, 6484, 6605, 7312, 7313, 601, 3107, 6454, 6844, 7313, 7314, 957, 1599, 3953, 7314, 7315, 1401, 2162, 7315, 7316, 1258, 1615, 4266, 4595, 7316, 7317, 623, 937, 5490, 7317, 7318, 1074, 2617, 7318, 7319, 4, 163, 1264, 4372, 7319, 7320, 364, 2003, 5925, 7320, 7321, 532, 724, 1545, 3428, 7321, 7322, 495, 631, 1084, 7322, 7323, 1232, 1267, 1444, 3728, 4163, 7323, 7324, 1805, 3451, 7067, 7324, 7325, 490, 857, 1048, 2165, 7325, 7326, 1302, 1333, 1557, 2525, 5090, 7326, 7327, 472, 1725, 2885, 6364, 7327, 7328, 111, 3245, 7328, 7329, 2411, 3605, 4922, 7329, 7330, 3965, 4861, 7330, 7331, 945, 4325, 6803, 7331, 7332, 159, 3199, 4685, 5220, 7332, 7333, 1888, 5045, 5610, 7333, 7334, 1758, 5405, 5768, 7334, 7335, 203, 270, 5765, 6909, 7335, 7336, 323, 337, 2877, 6125, 7336, 7337, 988, 1755, 6485, 6606, 7337, 7338, 602, 3108, 6455, 6845, 7338, 7339, 958, 1600, 3954, 7339, 7340, 1402, 2163, 7340, 7341, 1259, 1616, 4267, 4596, 7341, 7342, 624, 938, 5491, 7342, 7343, 1075, 2618, 7343, 7344, 5, 164, 1265, 4373, 7344, 7345, 365, 2004, 5926, 7345, 7346, 533, 725, 1546, 3429, 7346, 7347, 496, 632, 1085, 7347, 7348, 1233, 1268, 1445, 3729, 4164, 7348, 7349, 1806, 3452, 7068, 7349, 7350, 491, 858, 1049, 2166, 7350, 7351, 1303, 1334, 1558, 2526, 5091, 7351, 7352, 473, 1726, 2886, 6365, 7352, 7353, 112, 3246, 7353, 7354, 2412, 3606, 4923, 7354, 7355, 3966, 4862, 7355, 7356, 946, 4326, 6804, 7356, 7357, 160, 3200, 4686, 5221, 7357, 7358, 1889, 5046, 5611, 7358, 7359, 1759, 5406, 5769, 7359, 7360, 204, 271, 5766, 6910, 7360, 7361, 324, 338, 2878, 6126, 7361, 7362, 989, 1756, 6486, 6607, 7362, 7363, 603, 3109, 6456, 6846, 7363, 7364, 959, 1601, 3955, 7364, 7365, 1403, 2164, 7365, 7366, 1260, 1617, 4268, 4597, 7366, 7367, 625, 939, 5492, 7367, 7368, 1076, 2619, 7368, 7369, 6, 165, 1266, 4374, 7369, 7370, 366, 2005, 5927, 7370, 7371, 534, 726, 1547, 3430, 7371, 7372, 497, 633, 1086, 7372, 7373, 1234, 1269, 1446, 3730, 4165, 7373, 7374, 1807, 3453, 7069, 7374, 7375, 492, 859, 1050, 2167, 7375, 7376, 1304, 1335, 1559, 2527, 5092, 7376, 7377, 474, 1727, 2887, 6366, 7377, 7378, 113, 3247, 7378, 7379, 2413, 3607, 4924, 7379, 7380, 3967, 4863, 7380, 7381, 947, 4327, 6805, 7381, 7382, 161, 3201, 4687, 5222, 7382, 7383, 1890, 5047, 5612, 7383, 7384, 1760, 5407, 5770, 7384, 7385, 205, 272, 5767, 6911, 7385, 7386, 325, 339, 2879, 6127, 7386, 7387, 990, 1757, 6487, 6608, 7387, 7388, 604, 3110, 6457, 6847, 7388, 7389, 960, 1602, 3956, 7389, 7390, 1404, 2165, 7390, 7391, 1261, 1618, 4269, 4598, 7391, 7392, 626, 940, 5493, 7392, 7393, 1077, 2620, 7393, 7394, 7, 166, 1267, 4375, 7394, 7395, 367, 2006, 5928, 7395, 7396, 535, 727, 1548, 3431, 7396, 7397, 498, 634, 1087, 7397, 7398, 1235, 1270, 1447, 3731, 4166, 7398, 7399, 1808, 3454, 7070, 7399, 7400, 493, 860, 1051, 2168, 7400, 7401, 1305, 1336, 1560, 2528, 5093, 7401, 7402, 475, 1728, 2888, 6367, 7402, 7403, 114, 3248, 7403, 7404, 2414, 3608, 4925, 7404, 7405, 3968, 4864, 7405, 7406, 948, 4328, 6806, 7406, 7407, 162, 3202, 4688, 5223, 7407, 7408, 1891, 5048, 5613, 7408, 7409, 1761, 5408, 5771, 7409, 7410, 206, 273, 5768, 6912, 7410, 7411, 326, 340, 2520, 6128, 7411, 7412, 991, 1758, 6488, 6609, 7412, 7413, 605, 3111, 6458, 6848, 7413, 7414, 961, 1603, 3957, 7414, 7415, 1405, 2166, 7415, 7416, 1262, 1619, 4270, 4599, 7416, 7417, 627, 941, 5494, 7417, 7418, 1078, 2621, 7418, 7419, 8, 167, 1268, 4376, 7419, 7420, 368, 2007, 5929, 7420, 7421, 536, 728, 1549, 3432, 7421, 7422, 499, 635, 1088, 7422, 7423, 1236, 1271, 1448, 3732, 4167, 7423, 7424, 1809, 3455, 7071, 7424, 7425, 494, 861, 1052, 2169, 7425, 7426, 1306, 1337, 1561, 2529, 5094, 7426, 7427, 476, 1729, 2889, 6368, 7427, 7428, 115, 3249, 7428, 7429, 2415, 3609, 4926, 7429, 7430, 3969, 4865, 7430, 7431, 949, 4329, 6807, 7431, 7432, 163, 3203, 4689, 5224, 7432, 7433, 1892, 5049, 5614, 7433, 7434, 1762, 5409, 5772, 7434, 7435, 207, 274, 5769, 6913, 7435, 7436, 327, 341, 2521, 6129, 7436, 7437, 992, 1759, 6489, 6610, 7437, 7438, 606, 3112, 6459, 6849, 7438, 7439, 962, 1604, 3958, 7439, 7440, 1406, 2167, 7440, 7441, 1263, 1620, 4271, 4600, 7441, 7442, 628, 942, 5495, 7442, 7443, 1079, 2622, 7443, 7444, 9, 168, 1269, 4377, 7444, 7445, 369, 2008, 5930, 7445, 7446, 537, 729, 1550, 3433, 7446, 7447, 500, 636, 1089, 7447, 7448, 1237, 1272, 1449, 3733, 4168, 7448, 7449, 1810, 3456, 7072, 7449, 7450, 495, 862, 1053, 2170, 7450, 7451, 1307, 1338, 1562, 2530, 5095, 7451, 7452, 477, 1730, 2890,

6369, 7452, 7453, 116, 3250, 7453, 7454, 2416, 3610, 4927, 7454, 7455, 3970, 4866, 7455, 7456, 950, 4330, 6808, 7456, 7457, 164, 3204, 4690, 5225, 7457, 7458, 1893, 5050, 5615, 7458, 7459, 1763, 5410, 5773, 7459, 7460, 208, 275, 5770, 6914, 7460, 7461, 328, 342, 2522, 6130, 7461, 7462, 993, 1760, 6490, 6611, 7462, 7463, 607, 3113, 6460, 6850, 7463, 7464, 963, 1605, 3959, 7464, 7465, 1407, 2168, 7465, 7466, 1264, 1621, 4272, 4601, 7466, 7467, 629, 943, 5496, 7467, 7468, 720, 2623, 7468, 7469, 10, 169, 1270, 4378, 7469, 7470, 370, 2009, 5931, 7470, 7471, 538, 730, 1551, 3434, 7471, 7472, 501, 637, 1090, 7472, 7473, 1238, 1273, 1450, 3734, 4169, 7473, 7474, 1811, 3457, 7073, 7474, 7475, 496, 863, 1054, 2171, 7475, 7476, 1308, 1339, 1563, 2531, 5096, 7476, 7477, 478, 1731, 2891, 6370, 7477, 7478, 117, 3251, 7478, 7479, 2417, 3611, 4928, 7479, 7480, 3971, 4867, 7480, 7481, 951, 4331, 6809, 7481, 7482, 165, 3205, 4691, 5226, 7482, 7483, 1894, 5051, 5616, 7483, 7484, 1764, 5411, 5774, 7484, 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2403, 3957, 4914, 16129, 16130, 4317, 4853, 16130, 16131, 937, 4677, 6795, 16131, 16132, 151, 3191, 5037, 5212, 16132, 16133, 1880, 5397, 5602, 16133, 16134, 1750, 5757, 5760, 16134, 16135, 195, 262, 6117, 6901, 16135, 16136, 315, 329, 2869, 6477, 16136, 16137, 980, 1747, 6598, 6837, 16137, 16138, 594, 3100, 6447, 7197, 16138, 16139, 950, 1592, 3946, 16139, 16140, 1394, 2515, 16140, 16141, 1251, 1608, 4259, 4588, 16141, 16142, 616, 930, 5483, 16142, 16143, 1067, 2610, 16143, 16144, 156, 357, 1257, 4365, 16144, 16145, 717, 1996, 5918, 16145, 16146, 525, 1077, 1538, 3421, 16146, 16147, 488, 624, 1437, 16147, 16148, 1225, 1260, 1797, 3721, 4156, 16148, 16149, 2158, 3444, 7060, 16149, 16150, 483, 850, 1041, 2518, 16150, 16151, 1295, 1326, 1550, 2878, 5083, 16151, 16152, 465, 1718, 3238, 6357, 16152, 16153, 104, 3598, 16153, 16154, 2404, 3958, 4915, 16154, 16155, 4318, 4854, 16155, 16156, 938, 4678, 6796, 16156, 16157, 152, 3192, 5038, 5213, 16157, 16158, 1881, 5398, 5603, 16158, 16159, 1751, 5758, 5761, 16159, 16160, 196, 263, 6118, 6902, 16160, 16161, 316, 330, 2870, 6478, 16161, 16162, 981, 1748, 6599, 6838, 16162, 16163, 595, 3101, 6448, 7198, 16163, 16164, 951, 1593, 3947, 16164, 16165, 1395, 2516, 16165, 16166, 1252, 1609, 4260, 4589, 16166, 16167, 617, 931, 5484, 16167, 16168, 1068, 2611, 16168, 16169, 157, 358, 1258, 4366, 16169, 16170, 718, 1997, 5919, 16170, 16171, 526, 1078, 1539, 3422, 16171, 16172, 489, 625, 1438, 16172, 16173, 1226, 1261, 1798, 3722, 4157, 16173, 16174, 2159, 3445, 7061, 16174, 16175, 484, 851, 1042, 2519, 16175, 16176, 1296, 1327, 1551, 2879, 5084, 16176, 16177, 466, 1719, 3239, 6358, 16177, 16178, 105, 3599, 16178, 16179, 2405, 3959, 4916, 16179, 16180, 4319, 4855, 16180, 16181, 939, 4679, 6797, 16181, 16182, 153, 3193, 5039, 5214, 16182, 16183, 1882, 5399, 5604, 16183, 16184, 1752, 5759, 5762, 16184, 16185, 197, 264, 6119, 6903, 16185, 16186, 317, 331, 2871, 6479, 16186, 16187, 982, 1749, 6600, 6839, 16187, 16188, 596, 3102, 6449, 7199, 16188, 16189, 952, 1594, 3948, 16189, 16190, 1396, 2517, 16190, 16191, 1253, 1610, 4261, 4590, 16191, 16192, 618, 932, 5485, 16192, 16193, 1069, 2612, 16193, 16194, 158, 359, 1259, 4367, 16194, 16195, 719, 1998, 5920, 16195, 16196, 527, 1079, 1540, 3423, 16196, 16197, 490, 626, 1439, 16197, 16198, 1227, 1262, 1799, 3723, 4158, 16198, 16199};

## B4: Column-wised column index:

{0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 2, 2, 2, 2, 2, 2, 2, 3, 3, 3, 3, 3, 3, 3, 4, 4, 4, 4, 4, 4, 4, 5, 5, 5, 5, 5, 5, 5, 6, 6, 6, 6, 6, 6, 6, 7, 7, 7, 7, 7, 7, 7, 8, 8, 8, 8, 8, 8, 8, 9, 9, 9, 9, 9, 9, 9, 10, 10, 10, 10, 10, 10, 10, 11, 11, 11, 11, 11, 11, 11, 12, 12, 12, 12, 12, 12, 12, 12, 13, 13, 13, 13, 13, 13, 13, 14, 14, 14, 14, 14, 14, 14, 15, 15, 15, 15, 15, 15, 15, 16, 16, 16, 16, 16, 16, 16, 17, 17, 17, 17, 17, 17, 17, 18, 18, 18, 18, 18, 18, 18, 19, 19, 19, 19, 19, 19, 19, 20, 20, 20, 20, 20, 20, 21, 21, 21, 21, 21, 21, 21, 22, 22, 22, 22, 22, 22, 22, 23, 23, 23, 23, 23, 23, 23, 24, 24, 24, 24, 24, 24, 24, 25, 25, 25, 25, 25, 25, 25, 26, 26, 26, 26, 26, 26, 26, 27, 27, 27, 27, 27, 27, 27, 28, 28, 28, 28, 28, 28, 28, 29, 29, 29, 29, 29, 29, 30, 30, 30, 30, 30, 30, 30, 31, 31, 31, 31, 31, 31, 31, 32, 32, 32, 32, 32, 32, 32, 33, 33, 33, 33, 33, 33, 33, 34, 34, 34, 34, 34, 34, 34, 35, 35, 35, 35, 35, 35, 35, 36, 36, 36, 36, 36, 36, 36, 37, 37, 37, 37, 37, 37, 38, 38, 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137, 137, 137, 137, 137, 138, 138, 138, 138, 138, 138, 138, 139, 139, 139, 139, 139, 139, 139, 140, 140, 140, 140, 140, 140, 140, 141, 141, 141, 141, 141, 141, 141, 142, 142, 142, 142, 142, 142, 142, 143, 143, 143, 143, 143, 143, 143, 144, 144, 144, 144, 144, 144, 144, 145, 145, 145, 145, 145, 145, 145, 146, 146, 146, 146, 146, 146, 146, 147, 147, 147, 147, 147, 147, 147, 148, 148, 148, 148, 148, 148, 148, 149, 149, 149, 149, 149, 149, 149, 150, 150, 150, 150, 150, 150, 150, 151, 151, 151, 151, 151, 151, 151, 152, 152, 152, 152, 152, 152, 152, 153, 153, 153, 153, 153, 153, 153, 154, 154, 154, 154, 154, 154, 154, 155, 155, 155, 155, 155, 155, 155, 156, 156, 156, 156, 156, 156, 156, 157, 157, 157, 157, 157, 157, 157, 158, 158, 158, 158, 158, 158, 158, 159, 159, 159, 159, 159, 159, 159, 160, 160, 160, 160, 160, 160, 160, 161, 161, 161, 161, 161, 161, 161, 162, 162, 162, 162, 162, 162, 162, 163, 163, 163, 163, 163, 163, 163, 164, 164, 164, 164, 164, 164, 164, 165, 165, 165, 165, 165, 165, 165, 166, 166, 166, 166, 166, 166, 166, 167, 167, 167, 167, 167, 167, 167, 168, 168, 168, 168, 168, 168, 168, 169, 169, 169, 169, 169, 169, 169, 170, 170, 170, 170, 170, 170, 170, 171, 171, 171, 171, 171, 171, 171, 172, 172, 172, 172, 172, 172, 172, 173, 173, 173, 173, 173, 173, 173, 174, 174, 174, 174, 174, 174, 174, 175, 175, 175, 175, 175, 175, 175,



[illegible]











































































## Appendix C: Swap Function of Encoder V1

```
//swap function
int swap (int *a,int *b)
{
    (*a)^=(*b);
    (*b)^=(*a);
    (*a)^=(*b);
    return 0;
}
```

## Appendix D: Function for Obtaining Transpose Matrix

```
void cofactor(int num[lengthi][lengthi], int f,int inv[][lengthi])
{
    int b[lengthi][lengthi], fac[lengthi][lengthi];
    int p, q, m, n, i, j;
    for (q = 0;q < f; q++)
    {
        for (p = 0;p < f; p++)
        {
            m = 0;
            n = 0;
            for (i = 0;i < f; i++)
            {
                for (j = 0;j < f; j++)
                {
                    if (i != q && j != p)
                    {
                        b[m][n] = num[i][j];
                        if (n < (f - 2))
                            n++;
                        else
                        {
                            n = 0;
                            m++;
                        }
                    }
                }
            }
            fac[q][p] = pow(-1, q + p) * determinant(b, f - 1);
        }
    }
    transpose(num, fac, f,inv);
}
/*For calculating Determinant of the Matrix */
int determinant(int a[lengthi][lengthi], int k)
{
    int s = 1, det = 0, b[lengthi][lengthi];
    int i, j, m, n, c;
    if (k == 1)
    {
        return (a[0][0]);
    }
    else
    {
        det = 0;
        for (c = 0; c < k; c++)
        {
            m = 0;
            n = 0;
            for (i = 0;i < k; i++)
            {
                for (j = 0 ;j < k; j++)
                {
                    b[i][j] = 0;
                    if (i != 0 && j != c)
```



```

        {
            b[m][n] = a[i][j];
            if (n < (k - 2))
                n++;
            else
            {
                n = 0;
                m++;
            }
        }
    }
    det = det + s * (a[0][c] * determinant(b, k - 1));
    s = -1 * s;
}
}

return (det);
}
/*Finding transpose of matrix*/
void transpose(int num[lengthi][lengthi], int fac[lengthi][lengthi], int r,int inverse[][lengthi])
{
    int i, j;
    int b[lengthi][lengthi], d;

    for (i = 0; i < r; i++)
    {
        for (j = 0; j < r; j++)
        {
            b[i][j] = fac[j][i];
        }
    }
    d = determinant(num, r);
    for (i = 0; i < r; i++)
    {
        for (j = 0; j < r; j++)
        {
            inverse[i][j] = b[i][j] / d;
            if(inverse[i][j]<0)
                inverse[i][j]*=-1;
        }
    }
}
}

```

## Appendix E: Function of Matrix Multiplication

```
/*matrix multiplication function*/
int multiplication(int a[][la],int b[][lb],int mult[][lb],int r1,int c1,int r2,int c2)
{
/* Initializing elements of matrix mult to 0.*/
for(i=0; i<r1; i++)
for(j=0; j<c2; j++)
{
    mult[i][j]=0;
}
/* Multiplying matrix a and b and storing in array mult. */
for(i=0; i<r1; i++)
for(j=0; j<c2; j++)
for(p=0; p<c1; p++)
{
    mult[i][j]+=a[i][p]*b[p][j];
    mult[i][j]= mult[i][j]%2;
}
}
```

## Appendix F: Function of Matrix Addition

```
/*matrix addition function*/
int addition(int a[][lengtha],int b[][lengtha],int add[][lengtha],int r,int c)
{
/* Initializing elements of matrix mult to 0.*/
    for(i=0; i<r; i++)
        for(j=0; j<c; j++)
        {
            add[i][j]=0;
        }
/* Add matrix a and b and storing in array add. */
    for(i=0; i<r; i++)
        for(j=0; j<c; j++)
        {
            add[i][j]=a[i][j]+b[i][j];
            add[i][j]= add[i][j]%2;
        }
}
```

## Appendix G: Encoder Version 1

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <time.h>
#include <string.h>
#include "dvbs2.h"

double gaussianRandom(void);
int lengthi,lengthm,lengtha,la,lb;
int swap(),determinant(),cofactor(),multiplication(),addition(),transpose();
int i,j,p,n,d;
#define K 7200
#define C 16200

void main()
{
    int M=C-K,Au[M][1];
    int ret;
    printf("CLocks per sec = %d\n", (int) CLOCKS_PER_SEC);
    double r_xb[K] = {0};
    int x[K];
    memset(r_xb, 0, sizeof r_xb);
    for (i = 0; i < K; i++)
        r_xb[i]=gaussianRandom();
    for(i=0;i<K;i++){
        if(r_xb[i]>0){x[i]=1;}
        else if(r_xb[i]<=0){x[i]=0;}
    }

    int xi[1][K];
    for(i=0;i<K;i++)
        xi[0][i]=x[i];

    int **A;
    A = malloc(K*sizeof(int*));
    for (i = 0; i < K; i++){
        A[i] = malloc(M*sizeof(int));
    }
    for(i=0;i<K;i++)
    {
        for(j=0;j<M;j++){ A[i][j]=0;}
    }

    int ** Addr;
    FILE *fp = fopen("Addr.txt","r");
    Addr = malloc(K*sizeof(int*));
    for (i = 0; i < K; i++){
        Addr[i] = malloc(8*sizeof(int));
    }
    for (i = 0; i < K; i++) {
        for (j = 0; j < 8; j++) {
            ret = fscanf(fp, "%d", &Addr[i][j]);
        }
    }
}
```

```

fclose(fp);
for (i=0;i<360*5;i++){
    for (j=0;j<8;j++){
        if((x[i]&&A[i][Addr[i][j]-1])||(x[i]==0&&A[i][Addr[i][j]-1]==0))
            A[i][Addr[i][j]-1]=0;
        else A[i][Addr[i][j]-1]=1;
    }
}
for (i=360*5;i<360*20;i++){
    for (j=0;j<3;j++){
        if((x[i]&&A[i][Addr[i][j]-1])||(x[i]==0&&A[i][Addr[i][j]-1]==0))
            A[i][Addr[i][j]-1]=0;
        else A[i][Addr[i][j]-1]=1;
    }
}
for(i=0;i<K;i++){
    for (j=0;j<M;j++){
        A[i][j]=(A[i][j]+A[i][j-1])%2;
    }
}

la=K;
lb=1;
/*calculate parity check bits*/
clock_t start1 = clock();
multiplication(xi,A,Au,1,K,M);
int Xx[C];
for (i=0;i<M;i++){
    Xx[i+K]=Au[i][0];
}
for (j=0;j<K;j++){
    Xx[j]=x[j];
}
clock_t end1 = clock();
printf("\nEncoding %ld (ms) elapsed.\n", (end1-start1)/1000);
/*Generate Parity Check Matrix*/
int **H;
H = malloc(M*sizeof(int*));
for (i = 0; i < M; i++){
    H[i] = malloc(C*sizeof(int));
}
for(i=0;i<M;i++){
    for(j=0;j<C;j++){
        if(j<K)
            H[i][j]=A[j][i];
        else
            H[i][j]=0;}
}
for(i=0;i<M;i++){
    H[i][i+K]=1;
}
printf("\nParity Check Matrix H generated.\n");

/*Check validity of Parith Check Matrix*/

int checksector[M][1];
int ck=0;
la=C;

```

```

lb=1;
multiplication(H,Xx,checksector,M,C,1);
for (i=0;i<M;i++)
if (checksector[i][0]==1)ck++;
printf("\nChecking parity check matrix H...: ");
if(ck==0)
printf("Valid (s=H*y=0) \n");
else printf("Invalid!!!\n");

//for a transmitted code "u", if and only if the encoded codeword "y" satisfies "H*y=0", thus "y" is a
valid codeword of the code "u"

}

/*****
*                               *
*          FUNCTIONS          *
*                               *
*****/
// Gaussian Random bit generator
double gaussianRandom(void){
    double v1, v2, s;

    do {
        v1 = 2 * ((double) rand() / RAND_MAX)-1;
        v2 = 2 * ((double) rand() / RAND_MAX)-1;
        s = v1 * v1 + v2 * v2;
    } while (s>=1||s==0);
    s = sqrt((-2*log(s))/s);
    return v1*s;
}
/*matrix multiplication function*/
int multiplication(int a[][la],int b[][lb],int mult[][lb],int r1,int cr,int c2)
{
    /* Initializing elements of matrix mult to 0.*/
    for(i=0; i<r1; i++)
    for(j=0; j<c2; j++)
    {
        mult[i][j]=0;
    }
    /* Multiplying matrix a and b and storing in array mult. */
    for(i=0; i<r1; i++)
    for(j=0; j<c2; j++)
    for(p=0; p<cr; p++)
    {
        if(a[i][p]&& b[p][j])
        {
            mult[i][j]=1;
        }
        else
        {
            mult[i][j]=0;
        }
    }
}
//swap function
int swap (int *a,int *b)

```

```

{
    (*a)^=(*b);
    (*b)^=(*a);
    (*a)^=(*b);
    return 0;
}
//Calculate Determinant of the Matrix
int determinant(int a[lengthi][lengthi], int k)
{
    int s = 1, det = 0, b[lengthi][lengthi];
    int i, j, m, n, c;
    if (k == 1)
    {
        return (a[0][0]);
    }
    else
    {
        det = 0;
        for (c = 0; c < k; c++)
        {
            m = 0;
            n = 0;
            for (i = 0; i < k; i++)
            {
                for (j = 0; j < k; j++)
                {
                    b[i][j] = 0;
                    if (i != 0 && j != c)
                    {
                        b[m][n] = a[i][j];
                        if (n < (k - 2))
                            n++;
                        else
                        {
                            n = 0;
                            m++;
                        }
                    }
                }
            }
            det = det + s * (a[0][c] * determinant(b, k - 1));
            s = -1 * s;
        }
    }

    return (det);
}

int cofactor(int num[lengthi][lengthi], int f, int inv[][lengthi])
{
    int b[lengthi][lengthi], fac[lengthi][lengthi];
    int p, q, m, n, i, j;
    for (q = 0; q < f; q++)
    {
        for (p = 0; p < f; p++)
        {
            m = 0;

```

```

n = 0;
for (i = 0; i < f; i++)
{
    for (j = 0; j < f; j++)
    {
        if (i != q && j != p)
        {
            b[m][n] = num[i][j];
            if (n < (f - 2))
                n++;
            else
            {
                n = 0;
                m++;
            }
        }
    }
}
fac[q][p] = pow(-1, q + p) * determinant(b, f - 1);
}
}
transpose(num, fac, f, inv);
}
//Finding transpose of matrix
int transpose(int num[lengthi][lengthi], int fac[lengthi][lengthi], int r, int inverse[][lengthi])
{
    int i, j;
    int b[lengthi][lengthi], d;

    for (i = 0; i < r; i++)
    {
        for (j = 0; j < r; j++)
        {
            b[i][j] = fac[j][i];
        }
    }
    d = determinant(num, r);
    for (i = 0; i < r; i++)
    {
        for (j = 0; j < r; j++)
        {
            inverse[i][j] = b[i][j] / d;
            if (inverse[i][j] < 0)
                inverse[i][j] *= -1;
        }
    }
}
}

```



## Appendix H:

### Sang's Sum-product Decoder & DVB-S2 Standard Encoder

```
// DVBS2_Sang.c
// Title: DVB-S2 short (16200bit) simulation
// Company: The Australian National University
// Author: SANGIKPARK
// This code is the main code of the DVB-S2 short simulation
// This code includes encoding part using DVB-S2 encoding standard
// After encoding process, decoding algorithm (Sum Product Algorithm) is applied to decode
// codeword with errors through AWGN channel.
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <time.h>
#include <string.h>
#include "dvbs2.h"

// Gaussian Random bit generator
double gaussianRandom(void);
int DVBS2DECODER(int *, double *);

#define Ndata 7200
#define Ncode 16200

int main(void){
    double SNR = 0.2; //Gives 0 BER DVBS2
    int Npar = Ncode-Ndata; //parity check bit length
    int iter;
    int c[Ncode] = {0};
    memset(c,0,Ncode*(sizeof(int)));
    double z[Ncode] = {0};
    int max_sim = 100; //Maximum number of simulations
    int i,j;
    int ret;
    int sim=0;
    double r_xb[Ndata] = {0};
    int xb[Ndata];
    int ** Addr;
    FILE *fp1 = fopen("Addr.txt","r");
    Addr = malloc(Ndata*sizeof(int*));
    for (i = 0; i < Ndata; i++){
        Addr[i] = malloc(8*sizeof(int));
    }
    for (i = 0; i < Ndata; i++) {
        for (j = 0; j < 8; j++) {
            ret = fscanf(fp1, "%d", &Addr[i][j]);
        }
    }
    fclose(fp1);

    clock_t startx = clock();
    while(sim < max_sim){
        srand((unsigned) time(NULL));
```

```

memset(r_xb, 0, sizeof r_xb);
for (i = 0; i < Ndata; i++){
    r_xb[i]=gaussianRandom();
}
for(i=0;i<Ndata;i++){
    if(r_xb[i]>0){xb[i]=1;}
    else if(r_xb[i]<=0){xb[i]=-1;}
}
int x[Ndata];
for(i=0;i<Ndata;i++){
    if(xb[i]>0){x[i]=1;}
    else if(xb[i]<=0){x[i]=0;}
}
int par[Npar];
for (i=0;i<Npar;i++){
    par[i]=0;
}
for (i=0;i<360*5;i++){
    for (j=0;j<8;j++){
        par[Addr[i][j]-1] = fmod(par[Addr[i][j]-1]+x[i],2);
    }
}
for (i=360*5;i<360*20;i++){
    for (j=0;j<3;j++){
        par[Addr[i][j]-1] = fmod(par[Addr[i][j]-1]+x[i],2);
    }
}
int Xx[Ncode];
for (i=0;i<Npar;i++){
    if(i>0){
        par[i]=fmod(par[i]+par[i-1],2);
    }
    Xx[i+Ndata]=par[i];
}
for (i=0;i<Ndata;i++){
    Xx[i]=x[i];
}
memset(z,0,Ncode*(sizeof(double)));
for(i=0;i<Ncode;i++){
    z[i] = 2 * Xx[i] -1;
}
double noise[Ncode];
for (i = 0; i < Ncode; i++){
    noise[i]=gaussianRandom();
}
double Npower=0;
for (i=0;i<Ncode;i++)Npower = Npower + noise[i]*noise[i];
double Spower=0;
for (i=0;i<Ncode;i++)Spower = Spower + z[i]*z[i];

for (i=0;i<Ncode;i++){
    noise[i]=noise[i]*pow(Spower/Npower,0.5)*pow(10,-SNR/20);
}
Npower = 0;
for (i=0;i<Ncode;i++) Npower = Npower + noise[i]*noise[i];
SNR = 10*log10(Spower/Npower);
for(i=0;i<Ncode;i++){

```

```

        z[i]=z[i]+noise[i];
    }
    //LLR decoder
    iter = DVBS2DECODER(c, z);
    sim++;
}
clock_t endx = clock();
printf("Number of iterations, sim = %d\t max_sim = %d\n", sim, max_sim);
printf("CLOCKS_PER_SEC = %f\n", (double) CLOCKS_PER_SEC);
double run_time = ((double) (endx-startx)) / (double) CLOCKS_PER_SEC;
printf("BPSK total run time - %f (ms), %f (s) elapsed.\n",run_time * 1000 , run_time);
printf("Average time elapsed per simulation = %f (ms)\n",run_time/(double) sim * 1000);
printf("Average time elapsed per iteration of decoding = %f (ms)\n",run_time/(double) sim *
1000/iter);
printf("Data rate = %f (MSPS)\n", (double) Ndata / run_time * (double) sim /1e6);
int x_hat[Ndata];
for(i=0;i<Ndata;i++){
    x_hat[i]=c[i];
}
int sign_z[Ndata];
for (i=0;i<Ndata;i++)sign_z[i] = (z[i]>0) ? 1:(-1);
double BER = 0;
for (i=0;i<Ndata;i++)BER = BER + abs(xb[i]-sign_z[i])/2;
double BER_RAW;
double BERDVBS2
BER_RAW = BER/Ndata; //Raw BER of transmitted codeword
double BER_x_hat=0; //The number of error bits in the decoded codeword
for(i=0;i<Ndata;i++) BER_x_hat = BER_x_hat + abs(xb[i]-2*x_hat[i]+1)/2;
BERDVBS2 = BER_x_hat/Ndata; // Bit error rate of the decoded codeword
printf("SNR = %g\n",SNR);
printf("BER_RAW = %f\n",BER_RAW);
printf("BERDVBS2 = %f\n",BERDVBS2); //Displaying BER
printf("Number of decoder iterations = %d\n",iter);
printf("\n");
return 0;
}
double gaussianRandom(void){
    double v1, v2, s;
    do {
        v1 = 2 * ((double) rand() / RAND_MAX)-1;
        v2 = 2 * ((double) rand() / RAND_MAX)-1;
        s = v1 * v1 + v2 * v2;
    } while (s>=1||s==0);
    s = sqrt((-2*log(s))/s);
    return v1*s;
}

// DVBS2DECODER.c
// Created on: Jan 4, 2012
// Author: SANGIKPARK
int DVBS2DECODER(int *c, double *z){
    unsigned int Npar = Ncode-Ndata;
    unsigned int i;
    double Ri[Ncode];
    unsigned int no_nonzero = 48599;
    double M[no_nonzero];
    double tanh_half[no_nonzero];

```

```

double oldM[no_nonzero];
double product[Npar];
unsigned int iter=0;
unsigned int success = 0;
unsigned int max_iter=150;
double E[no_nonzero];
double sumE[Ncode];
double product2[no_nonzero];
double L[Ncode];
unsigned int ss[Npar];
unsigned int s[Npar];
unsigned int false;
for (i=0;i<Ncode;i++){
    Ri[i] = (-2*(*(z+i)));
}
for(i=0;i<no_nonzero;i++){
    M[i]=Ri[cw_colindex[i]];
    tanh_half[i]=tanh(M[i]/2);
    oldM[i]=1;
    product[cw_rowindex[i]]=1;
}
while ((success ==0) & (iter<max_iter)){
    iter++;
    false = 0;
    for(i=0;i<no_nonzero;i++){
        product[cw_rowindex[i]]=product[cw_rowindex[i]]*tanh_half[i];
        sumE[cw_colindex[i]]=0;
    }
    for(i=0;i<no_nonzero;i++){
        E[i]=0;
        product2[i]=product[cw_rowindex[i]]/tanh_half[i];
        if(product2[i]>=0.99){
            product2[i]=0.99;
        }
        E[i]=log((1+product2[i])/(1-product2[i]));
        sumE[cw_colindex[i]] = sumE[cw_colindex[i]] + E[i];
    }
    for(i=0;i<Ncode;i++){
        L[i]=Ri[i]+sumE[i];
        *(c+i)=0;
        if(L[i]<0){*(c+i)=1;}
    }
    for(i=0;i<no_nonzero;i++){
        ss[rw_rowindex[i]]=ss[rw_rowindex[i]]+*(c+rw_colindex[i]);
    }
    for(i=0;i<Npar;i++){
        s[i]=ss[i]%2;
        ss[i]=0;
        if(s[i]==1){false++;}
        product[i]=1;
    }
    if (false ==0){success = 1;}
    else {
        for(i=0;i<no_nonzero;i++){
            M[i] = sumE[cw_colindex[i]] - E[i] + Ri[cw_colindex[i]];
            if(M[i]*oldM[i]<0){
                M[i]=M[i]+oldM[i];
            }
        }
    }
}

```

```

    }
    oldM[i]=M[i];
    tanh_half[i]=tanh(M[i]/2);
  }
}
return iter;
}

```

# Appendix I:

## MN Decoder with DVB-S2 Standard Encoder

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <time.h>
#include <string.h>
#include "dvbs2.h"

// Gaussian Random bit generator
double gaussianRandom(void);
int DVBS2DECODER(int *, double *);
#define Ndata 7200
#define Ncode 16200
double a;
double In_PR1[16200];
double In_PR0[16200];
double In_PdtR2[9000];

int main(void){
    double SNR = 0.2; //Gives 0 BER DVBS2
    int Npar = Ncode-Ndata; //parity check bit length
    int iter;

    int c[Ncode] = {0};
    memset(c,0,Ncode*(sizeof(int)));

    double z[Ncode] = {0};

    int max_sim = 100; //Maximum number of simulations

    printf("\n\n\nCLocks per sec = %d\n\n", (int) CLOCKS_PER_SEC);
    int i,j;
    int ret;

    for(i=0;i<Ncode;i++){
        In_PR1[i]=1;
        In_PR0[i]=1;
        if(i<Npar)
            In_PdtR2[i]=1;
    }

    int sim=0;
    double r_xb[Ndata] = {0};
    int xb[Ndata];

    int ** Addr;
    FILE *fp1 = fopen("Addr.txt","r");
    Addr = malloc(Ndata*sizeof(int*));
    for (i = 0; i < Ndata; i++){
        Addr[i] = malloc(8*sizeof(int));
    }
    for (i = 0; i < Ndata; i++) {
```

```

for (j = 0; j < 8; j++) {
    ret = fscanf(fp1, "%d", &Addr[i][j]);
}
}
fclose(fp1);

clock_t startx = clock();
while(sim<max_sim){
    srand((unsigned) time(NULL));
    memset(r_xb, 0, sizeof r_xb);

    for (i = 0; i < Ndata; i++){
        r_xb[i]=gaussianRandom();
    }

    for(i=0;i<Ndata;i++){
        if(r_xb[i]>0){xb[i]=1;}
        else if(r_xb[i]<=0){xb[i]=-1;}
    }

    int x[Ndata];

    for(i=0;i<Ndata;i++){
        if(xb[i]>0){x[i]=1;}
        else if(xb[i]<=0){x[i]=0;}
    }

    int par[Npar];
    for (i=0;i<Npar;i++){
        par[i]=0;
    }

    for (i=0;i<360*5;i++){
        for (j=0;j<8;j++){
            par[Addr[i][j]-1] = (par[Addr[i][j]-1]+x[i])%2;
        }
    }
    for (i=360*5;i<360*20;i++){
        for (j=0;j<3;j++){
            par[Addr[i][j]-1] = (par[Addr[i][j]-1]+x[i])%2;
        }
    }

    int Xx[Ncode];
    for (i=0;i<Npar;i++){
        if(i>0){
            par[i]=(par[i]+par[i-1])%2;
        }
        Xx[i+Ndata]=par[i];
    }

    for (i=0;i<Ndata;i++){
        Xx[i]=x[i];
    }
}

```

```

memset(z,0,Ncode*(sizeof(double)));
for(i=0;i<Ncode;i++){
    z[i] = 2 * Xx[i] -1;
}

double noise[Ncode];
for (i = 0; i < Ncode; i++){
    noise[i]=gaussianRandom();
}

double Npower=0;
for (i=0;i<Ncode;i++)Npower = Npower + noise[i]*noise[i];

double Spower=0;
for (i=0;i<Ncode;i++)Spower = Spower + z[i]*z[i];

for (i=0;i<Ncode;i++){
    noise[i]=noise[i]*pow(Spower/Npower,0.5)*pow(10,-SNR/20);
}

Npower = 0;
for (i=0;i<Ncode;i++) Npower = Npower + noise[i]*noise[i];

SNR = Spower/Npower;
a=sqrt(SNR); //a = square root of (2*Rate*SNR), where Rate = 0.5
SNR = 10*log10(SNR);

for(i=0;i<Ncode;i++){
    z[i]=z[i]+noise[i];
}

//MN Decoder
iter = DVBS2DECODER(c, z);

sim++;
}

clock_t endx = clock();

printf("Number of iterations, sim = %d\t max_sim = %d\n", sim, max_sim);
printf("CLOCKS_PER_SEC = %f\n", (double) CLOCKS_PER_SEC);
double run_time = ((double) (endx-startx)) / (double) CLOCKS_PER_SEC;

printf("BPSK total run time - %f (ms), %f (s) elapsed.\n",run_time * 1000 , run_time);
printf("Average time elapsed per simulation = %f (ms)\n",run_time/(double) sim * 1000);
printf("Average time elapsed per iteration of decoding = %f (ms)\n",run_time/(double) sim *
1000/iter);
printf("Data rate = %f (MSPS)\n", (double) Ndata / run_time * (double) sim /1e6);

int x_hat[Ndata];
for(i=0;i<Ndata;i++){
    x_hat[i]=c[i];
}

int sign_z[Ndata];

for (i=0;i<Ndata;i++)sign_z[i] = (z[i]>0) ? 1:(-1);

```



```

double BER = 0;
for (i=0;i<Ndata;i++)BER = BER + abs(xb[i]-sign_z[i])/2;

double BER_RAW;
double BERDVBS2;

BER_RAW = BER/Ndata; //Raw BER of transmitted codeword

double BER_x_hat=0; //The number of error bits in the decoded codeword
for(i=0;i<Ndata;i++) BER_x_hat = BER_x_hat + abs(xb[i]-2*x_hat[i]+1)/2;
BERDVBS2 = BER_x_hat/Ndata; // Bit error rate of the decoded codeword

printf("SNR = %g\n",SNR);
printf("BER_RAW = %f\n",BER_RAW);
printf("BERDVBS2 = %f \n",BERDVBS2); //Displaying BER
printf("Number of decoder iterations = %d\n",iter);
printf("\n");

return 0;
}

double gaussianRandom(void){
    double v1, v2, s;

    do {
        v1 = 2 * ((double) rand() / RAND_MAX)-1;
        v2 = 2 * ((double) rand() / RAND_MAX)-1;
        s = v1 * v1 + v2 * v2;
    } while (s>=1||s==0);
    s = sqrt((-2*log(s))/s);
    return v1*s;
}

int DVBS2DECODER(int *c, double *z){

    unsigned int Npar = Ncode-Ndata;
    unsigned int i;
    unsigned int no_nonzero = 48599;
    int iter=0;
    unsigned int success = 0;
    unsigned int max_iter=150;

    double sumQ;
    double sumq;
    double F1[Ncode],F0[Ncode];
    double Q1[no_nonzero],Q0[no_nonzero],dtQ[no_nonzero],q1[Ncode],q0[Ncode];
    double R1[no_nonzero],R0[no_nonzero],Updated_dtQ[no_nonzero],Prod_dtQ[Npar];
    double prod_R1[no_nonzero],prod_R0[no_nonzero],Prod_R1[Ncode],Prod_R0[Ncode];
    unsigned int ss[Npar];
    unsigned int s[Npar];
    unsigned int fail;
    for (i=0;i<Ncode;i++){
        F1[i]=1/(1+exp((-2)*a*z[i]));
        F0[i]=1-F1[i];
    }

```

```

//Initialization
memset(Q0,0x00,sizeof(Q0));
memset(Q1,0x00,sizeof(Q1));
for(i=0;i<no_nonzero;i++){
    Q1[i]=F1[cw_colindex[i]];
    Q0[i]=F0[cw_colindex[i]];
}

while ((success ==0) & (iter<max_iter)){
    iter++;
    fail = 0;

    //Horizontal step
    memset(R0,0x00,sizeof(R0));
    memset(R1,0x00,sizeof(R1));
    memset(q0,0x00,sizeof(q0));
    memset(q1,0x00,sizeof(q1));
    memset(dtQ,0x00,sizeof(dtQ));

    memcpy(Prod_R1,In_PR1,sizeof(In_PR1));
    memcpy(Prod_R0,In_PR0,sizeof(In_PR0));
    memcpy(Prod_dtQ,In_PdtR2,sizeof(In_PdtR2));

    for (i=0;i<no_nonzero;i++)
    {
        dtQ[i]=Q0[i]-Q1[i];
        Prod_dtQ[cw_rowindex[i]]=Prod_dtQ[cw_rowindex[i]]*dtQ[i];
    }

    //Horizontal step
    for (i=0;i<no_nonzero;i++)
    {
        Updated_dtQ[i]=Prod_dtQ[cw_rowindex[i]]/dtQ[i];
        R0[i]=0.5*(1+Updated_dtQ[i]);
        R1[i]=1-R0[i]; //0.5-0.5*Updated_dtQ

        Prod_R1[cw_colindex[i]]=Prod_R1[cw_colindex[i]]*R1[i];
        Prod_R0[cw_colindex[i]]=Prod_R0[cw_colindex[i]]*R0[i];
    }

    //Vertical step
    for (i=0;i<no_nonzero;i++)
    {
        sumQ=0;
        prod_R1[i]=Prod_R1[cw_colindex[i]]/R1[i];
        Q1[i]=F1[cw_colindex[i]]*prod_R1[i];
        prod_R0[i]=Prod_R0[cw_colindex[i]]/R0[i];
        Q0[i]=F0[cw_colindex[i]]*prod_R0[i];
        sumQ=Q1[i]+Q0[i];
        Q1[i]=Q1[i]/sumQ;
        Q0[i]=1-Q1[i];
        if(i<Ncode)
        {
            sumq=0;
            q0[i]=F0[i]*Prod_R0[i];
            q1[i]=F1[i]*Prod_R1[i];

```

```

        sumq=q1[i]+q0[i];
        q1[i]=q1[i]/sumq;
        q0[i]=1-q1[i];
        c[i]=0;
        if(q0[i]<=q1[i]){c[i]=1;}
    }
    ss[cw_rowindex[i]]=ss[cw_rowindex[i]]+(unsigned int)c[cw_colindex[i]];
}

for(i=0;i<Npar;i++){
    s[i]=ss[i]%2;
    ss[i]=0;
    if(s[i]==1){fail++;}
}
if (fail ==0){success = 1;}
}
return iter;
}

```

## Appendix J:

### Flowchart of the MN Decoder

