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Application And Prospect Of Orthogonal On-Off Keying As An Error Control Coding In Laser Communication

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APPLICATION AND PROSPECT OF ORTHOGONAL ON-OFF KEYING AS AN ERROR CONTROL CODING IN LASER COMMUNICATION

By

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Tasbirun Nahian Upal

March 14th, 2014

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To my Mom - my idol of Strength and Courage

To my Dad – my idol of Creativity and Patience

ABSTRACT

In this thesis work, a bandwidth efficient coded modulation technique has been proposed for LASER based communication. It offers reliable error correction and bandwidth optimization for free space connectivity. Laser communication has been emerging as a potential alternative of Radio Frequency (RF) communication for long-haul connectivity. It provides several advantages over RF systems. Some of specific advantages are its high speed data transfer, higher bandwidth, robust security, immunity to electromagnetic interference, lower implementation cost. However, as any other communication system, it requires an error control system that detects and corrects error in the data transmission. The proposed technique blends well with the laser communication systems to provide a very good error correction capability. For a decent code length it can correct around 24 percent of error. The proposed method is named as Orthogonal On-Off Keying of LASER and uses a Bi-orthogonal matrix to generate the encoded data for laser. While decoding, it uses the cross correlation between two orthogonal codes to detect and correct any errors during transmission. Orthogonal codes also known as Walsh codes are used for error correction in Code Divisional Multiple Access of RF communication. But it has not been investigated for laser systems. Besides on-off keying this code also has enormous potential in other modulation techniques as well. Here in this thesis project, the error control performance has been verified using an experimental setup. Furthermore, a method for more bandwidth efficient transmission of data using laser have been proposed and discussed. This method of bit splitting offers bandwidth efficiency of unity code rate.

Altogether, the proposed technique is a promising solution for error detection and correction and at the same time a bandwidth efficient system.Another advantage of orthogonal coding is self-synchronization capability as the modulated signals share orthogonal space as well. All the codes in orthogonal matrix are unique as per their properties and can be identified separately. As a result, it does not require any synchronization bits while transmission. This results in reduction of complexity in implementation and thus yield savings economically.

Like orthogonal matrix, traditional block coding also uses a block of information bits. Say, they are segmented into a block of k bits. This block is transformed into a larger block of n bits by adding horizontal and vertical parity bits. This is denoted as (n,k) block code. The problem with this type of coding is, the added (n-k) bits carry no information and only helps in error detection and correction. However this bigger block of data can detect and correct only one error in the transmission and it fails, if more than one error occurs.

On the other hand, the data is mapped using an orthogonal table in this type of coding where codes have unique properties. No redundant bits are required to be added as they possess parity generation property with themselves. Also, the distance property of orthogonal codes makes it stronger for error detection. For codes of greater length in size, such approach is capable to correct more than one error.

The test bed is implemented using a LASER transmitter and hardware interface that includes a computer to receive the data and transmit. The operations such as data capture, modulation, coding and injection of error are carried by a software written in MATLAB®. On the receiver side, a high speed photo-detector is placed with a hardware interface with another computer. This one has the other part of the program to receive the bits and decode to extract the transmitted data. To test the error control capability, errors are intentionally transmitted by altering number of bits in the modulated signal. Upon reception, the data is compared with the transmitted bits and evaluated. This test goes through 8, 16, 32 and 64 bits of orthogonally mapped data, several different speed of transmission and a range of error percentage. All the results were compared and investigated for prediction and error tolerance.

CHAPTER 1

COMMUNICATION AND CODING

1.1 Introduction

Since the dawn of civilization, the field of communication can be identified as the strongest means of development. Whether it was oral, written or even in the form of sign language, the purpose is to convey the message and expression to the other individuals. Nowadays by the word ‘Communication’ generally we refer to the state of the art technology and most advanced engineering to carry voice, text, picture or any forms of data to the desired destination. This advanced technology includes wired and wireless infrastructure. In the wireless communication system, radio signals, ultrasonic, infrasonic or optical systems are the typical platforms. Lately the communication using Light Amplification by Stimulated Emission of Radiation (LASER) in the wireless advancement has become one of the most promising and reliable tool for long distance line of sight interface. My thesis topic addresses challenges in LASER communication technology.

1.2 Importance of Coding

To overcome the primary hurdles of digital communication, coding is the solution for it. The importance of coding does not only reflect that fact that it makes a reliable data transfer over the channel, it also plays a significant role for error detection and correction.

One of the issues in digital data transfer is the security of the data. Data security and source validation must be ensured in many of those important communications. For thatpurpose, encrypted data is used and reliable encryption is confirmed by proper coding scheme.

Another purpose of coding is data compression. This is to make sure that the channel is best used for its capacity and helps to send more useful data over a limited bandwidth channel [**1**]. At the same time, data integrity and validity must be assured. With proper coding, the best performance to send high volume of data on any channel can be achieved while the unity of the data need not be compromised.

For data translation, coding plays an important role. It helps to represent the data in different forms. The significant role of coding in communication is the role of error detection and correction. Due to channel attenuation, interference and all other parameters, there are many interruptions and noise introduced to the data while travelling along the channel. These issues can result in corrupted data, invalid data, irrecoverable data, damaged data or no data at all. Consequently this causes slower transmission of data, more repeat requests, and potentially results in a slower communication system. Proper coding scheme is badly necessary for all these issues to be dealt with. For correction, detection of error is the first step. So there are schemes that detect the error and send a repeat request. Also there are coding schemes that can detect and correct the error by itself. This saves time, channel bandwidth and makes the communication faster. This thesis is about a coding scheme that we are thinking to apply on LASER communication system which may show the potential of correcting almost 25% of error by itself.

1.3 Typical coding schemes

There are many coding schemes currently applied in communication systems. Depending on the channel, bandwidth, noise level, available data compression option, transmitter, receiver, medium and/or parameters like these the right coding scheme is chosen for a certain channel. Typical basic categories are source coding and channel coding [**2**].

In source coding, the data is translated into a stream of bits. ASCII code can be an example of that. But as this coding scheme has equal length code for all the characters, it is not considered as efficient as should be. Because in case of characters that have higher occurrence rate in the communication will take the same space in channel as the lower occurring ones. Now, by reducing the code length of higher occurring ones, the performance can be upgraded. So, variable length coding came out to be a choice. Huffman coding scheme is an example of that.

1.4 LASER communication over RF

Here in this research exploration, we are looking forward to find a reliable, promising and better solution over existing RF communication system. Especially when a high volume of data transfer is the point of interest and the bandwidth requirement is high. Also in a long distance communication where no physical infrastructure is a feasible solution laser can come up to play a big role. LASER communication has many advantages over RF systems to get over these points.

In terms of data security, laser offers more protection [**3**]. As the radio frequency is radiated mostly Omni directional, it can be detected by any receiver in the range. On the other hand, laser being highly focused and unidirectional, it can be pointed straight to the receiver and much less likely to be intercept by any invaders. And even if there is an interception in the middle, it can be easily detectable at the receiver end.

The other promising property of laser transmission is that it can support very high frequency data transfer. This can go up to gigabits per second which is much higher when compared to RF data speed. Commercial product is available to support 10 gigabits per second data transfer in the range of 8200feet [**4**]. On the other hand for deep space communication, Lunar Laser Communication Demonstration (LLCD) of The National Aeronautics and Space Administration (NASA) has proven a laser data transfer of 622 megabits per second. This communication was established between earth and moon which was a distance of around 239,000 miles [**5**]. It shows although the laser can offer high speed connectivity, very long distance may compromise the speed to some extent. In the RF world, lately offered 4G wireless data speed mentions 50 to 100 megabits per second of speed for Long Term Evolution (LTE) technology. But outside the lab it showed capacity of 5-12 megabits per second data transfer [**6**] [**7**]. For a wired interface in data transfer, a gigabit Ethernet network offers 1000 megabits per second transmission rate. Also a laser system seems to be more cost effective as it does not require any hardwired infrastructure. A lot of power in RF communication is dissipated in the ambient even if there is no receiver, whereas laser takes much less power for point to point communication.

Laser is immune to many typical interferences problems that are common issues for RF systems. Electric discharge, lightning conditions, electromagnetic waves or issues like these are not a threat on laser beam transmission.

In long range communication, where sending an RF signal can be a costly, unreliable mean, a laser can be robust solution for it [**8**]. For an example, deep space communications or data transfer between space to earth, space to space or even between air and ground, laser is a promising one to be considered [**9**].

1.5 Prospect of O^3K in LASER

For the modulation of laser to transmit data, on off keying is the most common technique. In this thesis I am going to review the prospect of the idea of Orthogonal On-Off Keying to modulate the laser beam. This is a new coding scheme for data transmission. Because we are looking for a robust data transfer option through laser that will have less error at the receiver end; The Orthogonal On-Off Keying also written as O^3K here in short is considered as a promising coding scheme to have the self-error correction capability of around 25%.

This new coding scheme uses code correlation to match data with a look up table and find if there is any error introduced during transmission. If the number of errors introduced are within the threshold limit it can correct itself and do not need the data to be retransmitted. The tradeoff here is that there will be more bits to transmit over the channel. But when we have a high bandwidth channel like laser, it is better to have some robust means of transmission in exchange of a few more bits [**10**].

Another advantage of this coding scheme is it is self-synchronized, and does not require any parity generator. It reduces the complexity of the implementation and makes it more cost effective. The following Figure 1.1 (a) and 1.1 (b) shows two block diagrams for comparison between conventional block coding and bi-orthogonal coding for transmission.

Figure: 1.1 (a) Block diagram of conventional block coding transmission

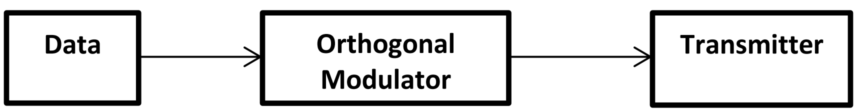

Figure: 1.1 (b) Block diagram of orthogonal transmission

CHAPTER 2

COMMUNICATION USING LASER

2.1 Introduction

Since the discovery of Light Amplification by Stimulated Emission of Radiation (LASER) there have been numerous applications of LASER [**11**]. This includes the fields of research, medical science, data storage, industrial application, law enforcement and so forth [**3**]. Some application examples are of printing, compact disc players, surgery, range measurements, visual displays etc. and are not only limited to those. As the development of laser forwards and the size of the equipment decreases, the more and more applications were invented. The significant reduction of the cost due to the invention of solid state laser also fueled to propel the number of applications. Application in the communication field is one of the most optimistic and promising fields of laser application [**12**].

2.2 Laser communication

Wireless communication is a very important mean of data transfer in the current world. For long haul communication, remote operations, and deep space data transfer, radio frequency (RF) based systems have been used for long time. The field of laser communication has come out to be a reliable alternative to that as it offers a lot of advantages over it. It is capable to provide very high transfer rate, better security, easy implementation and maintenance. It does not require any Federal Communication

Commission license or frequency allocation in this regard [**3**]. As long as there is line of sight available, the implementation of laser communication is feasible. It can be a Local Area Network(LAN) of a campus or a city, quick replacement or emergency response, or even air to air or air to ground communication [**3**].

2.3 Transmitter

In this experiment, for the transmission an off the shelf laser product have been chosen. It is a class IIIa laser and has a modulated/variable power drive circuit. This laser can be operated by varying power or sending a modulating signal to the control terminal. It can support up to 400 KHz of bandwidth with the beam of a 635nm of wavelength. The input from the data source is amplified by an amplifier as the level of control signal has to be in the range of 3.0-3.5 Volts. The amplified signal is used to drive the laser and performs the On-Off keying of the laser.

2.4 Receiver

For the reception unit, a simple PIN diode is used. The response at terminal when illuminated with the laser can range up to 400 millivolts. This voltage is recorded at the time domain as it is the data stream. If necessary the voltage is amplified using software after acquiring the whole signal and storing into the computer. Detailed process is explained in the experiment section.

If there is a lot of ambient light and probability of saturating the photodetector is high, the detector may fail to identify the laser signal. To overcome such incidents, a differential receiver can be designed for better detection [**13**]. Although in the lab experiment the ambient light saturation was not a concern, but as a future development of the system it can be considered.

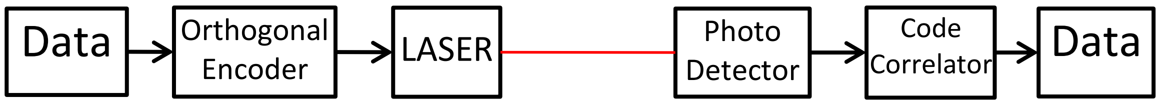

Figure 2.1: Block Diagram of experimental setup

Figure 2.1 illustrates the apparatus settings for the experiment. This a fairly simple setup to transmit and receive data and record the reception. The received data is compared and analyzed to calculate the result. Primary setup of the experiment uses LASER transmission in the air. The wired medium has also been introduced and data have been collected for analysis.

2.5 Intensity Modulation

In the area of communication, modulation refers to changing one or more properties of a wave. The modulation technique for the data transfer in optical domain involves intensity variation. Therefore the power of the optical source which is the LASER in this case is changed with the deviation of the modulating signal. Although optical heterodyning is possible for communication, it is usually more common to use laser for intensity modulation at the transmission end and direct detection in the receiving end [**14**]. At present typical optical communication system uses On-Off Keying (OOK) and direct detection. Differential phase shift keying and interferometric detection is also a rising modulation scheme in this field [**15**].

2.6 Analog Modulation

Analog modulation system refers to the continuous modulation of carrier signal with respect to the information. Some common examples of analog modulations are Amplitude Modulation (AM), Frequency Modulation (FM), Phase Modulation (PM) etc. Analog modulation is welcome in short-haul communication and the data can be retrieved easily. Due to the significant lower cost in implementation and less requirement for sophisticated equipment, analog modulation is popular in many cases. However in long distance communication, as there is higher attenuation in the channel it causes more noise. As such the Signal to Noise Ratio (SNR) for analog modulation becomes less satisfactory. In those cases digital modulation comes into play [**16**].

2.7 Digital Modulation

In Digital modulation systems, the carrier signal is modulated using a discrete signal. As often or most of the time at the user end, the information is an analog distribution, the system involves analog to digital conversion at the transmission end and digital to analog conversion at the receiving end. The advantage of digital modulation over the analog one is discrete change in the states of modulating signal which yields easily detectable binary states i.e. 0 and 1. Unlike the continuous analog signal, the discrete changes are more immune to the channel attenuation over the long-haul communication. There are a number of digital modulation schemes exist. Some examples include but not limited to Phase Shift Keying (PSK), Frequency Shift Keying (FSK), Amplitude Shift Keying (ASK), Continuous Phase Modulation (CPM) [**16**].

CHAPTER 3

ERROR CORRECTION METHODS AND PROPOSED RESEARCH

3.1 Introduction

Errors introduced in the channel during the transmission is most obvious and in case of longhaul communication the error generated is higher due to the attenuation, interference, impurity, noise and other parameters in the channel. The reliability of data transfer in a non-ideal channel depends on proper detection and correction of errors. This is also referred to as the error control technique in the area of communication. Error detection process identifies the presence of error in the received data and error correction technique helps to retrieve the original bits and thus confirms the integrity of the received data.

3.2 Error detection processes

Code repetitions: Same set of codes are repeated certain number of time over the channel and the receiver compares between the repeat blocks. If there is any mismatch found that blocks are not identical it is certain that errors have been introduced in the channel. This process is inefficient and if the error occurs in the same manner for all the repeated blocks, the error is undetectable.

Parity check: In this method a parity bit is added to the block of codes being transmitted. The count of 1s in the string is predefined as ‘even’ or ‘odd’. Parity bit is attached to maintain the preselected parity check, and at the receiving end the integrity of the data is checked by verifying the even or odd parity. It is a very simple form of detection and fails to work if there happens to be even number of errors in the same string which keeps the parity same.

Checksum: Checksum is computed from the data and can use different algorithms to generate it. At the receiver the checksum is verified to trace if the data transmitted with it is error free. Some checksum schemes are parity bits, check digits, and longitudinal redundancy checks etc. If there is a minor change in the input, a well-built checksum algorithm should generate significantly different value.

Cyclic redundancy check (CRC): Cyclic redundancy check is not the best to detect severely generated errors in the channel. It is more likely to be useful in accidental changes to digital data in computer networks. For detection of burst errors, they work well. This is hardware friendly in implementation and more common in digital network and storage media.

3.3 Error correction processes

For error correction it detects and corrects error at the receiver end. Commonly, there are two methods used in the current communication systems. They are Automatic Repeat Request (ARQ) and Forward Error Correction (FEC) that approaches use of Error Correcting Codes (ECC). In case of communications where low latency is not acceptable, the ARQ is not a feasible option. ARQ requires having a return channel to work so simplex system is not supported. For a communication like broadcasting or so, ARQ is less preferred whereas ECC is used.

3.4 Automatic Repeat Request (ARQ)

Automatic Repeat Request uses error detection codes along with acknowledgement, negative acknowledgement and timeout. Upon receiving the data without an error the receiver sends a positive acknowledgment or otherwise the transmission end gets a negative response. Negative response triggers to resend the data till it is delivered error free. Also there is a timeout period if no acknowledgment is received by that time, it is resent. This type of correction requires duplex communication. And depending on the channel attenuation and noise the number of repeat request can be fairly high.

3.5 Forward Error Correction (FEC)

In this method upon detection of an error, it is corrected at the receiver end without the data being resend. Redundant data bits are introduced and attached to the desired data before transmission. If there is an error introduced in the channel, the receiver can correct up to certain number of errors (depending on the code) by matching the received bits with a lookup table. FEC codes can be distinguished in to major categories.

Convolutional code: Data is coded in bit by bit process.

Block code: Data is coded in block by block process.

The experiment here is focused on the Orthogonal coding for error correction which is a block code for forward error correction.

3.6 Conventional Block Coding

For block coding of the data, the information bits are first segmented into a block of k bits. Then horizontal and vertical parity bits are generated and a new block is formed. The number of bits in the new block is n and the segment is called (n,k) block code.

Obviously n>k here and a term ‘code rate’ denotes the k/n ratio. Therefore this new block of codes is transmitted through the channel. Included parity bits (n-k) only participate to detect and correct errors and do not contain any information [**17**].

For an example, let us consider a stream of 9 bit data which can be arranged in a block of 3x3 arrays. I.e. the data is 110010011. After arranging them into a block of data, vertical and horizontal parity (referred as Pv and Ph respectively) are generated and placed in the adjacent row and column. This results in the increment of the block size and looks like Figure 3.11(b). A set of registers combined with multiplexer or a random access memory can perform the task. An XOR operation is used to calculate the parity bits which are shown in Figure 3.1(a).

XOR operation
$0 \oplus 0 = 0$
$0 \oplus 1 = 1$
$1 \oplus 0 = 1$
$1 \oplus 1 = 0$

(a)

	Data			Ph
	1	1	0	0
	0	1	0	1
	0	1	1	0
Pv	1	1	1	0

(b)

	Data			Ph	*Ph
	1	1	0	0	0
	0	1	0	1	0
	0	1	1	0	0
Pv	1	1	1	0	0
*Pv	0	0	0	0	0

(c)

Figure: 3.1. (a) XOR operation, (b) (n,k) block code, (c) Parity check for encoded block

After encoding the result is a 4x4 block of codes made of 16bits. Number of parity bits included is P = n-k = 16-9 = 7. If the initial dimension of data block were M by N, then MN = k = 9. After encoding the new dimension in this case is (M+1)(N+1) = n = 16.

So the calculated coding rate is $r = \frac{MN}{(M+1)(N+1)} = \frac{9}{16}$ (3.1)

Receiver of this encoded block generates new horizontal parity *Ph and a new vertical parity *Pv which are shown in Figure 3.1(c). If the there was an error introduced during the transmission, these bits work to detect and correct the error. Occurrence of error will result parity check failure at the respective column and row and will show 1 instead of 0. The following figure explains it more.

	Data			Ph
	1	1	0	0
	0	1	0	1
	0	1	1	0
Pv	1	1	1	0

(a)

	Data			Ph	*Ph
	1	1	0	0	0
	0	0	0	1	1
	0	1	1	0	0
Pv	1	1	1	0	0
*Pv	0	1	0	0	0

(b)

Figure: 3.2: (a) Encoded block, (b) Error correction by parity bits

It is shown from the Figure 3.2 (b) that if an error was there in the data it would generate parity bits in the respective row and column and the receiver will be able to locate the position of error and can correct it.

Pros and Cons: In case of block codes the receiver can locate the error easily and can correct it. But if the noise in the channel is too high, it may not be a very effective scheme. This method can only correct a single bit error in the block. If there is more than one error, it fails to work. More over adding redundant bits grows the volume of the data which costs bandwidth.

If we consider a block of M-rows and N-columns, the number of information bits D is given by, $$D = M \times N \quad (3.2)$$

After the encoding, $$D + P = (M + 1) \times (N + 1) \quad (3.3)$$

Where P is the number of parity bits appended to the block.

$$P = M + N + 1 \quad (3.3)$$

Table 3.1 below shows how the number of parity bits increases with the size of the block.

Table: 3.1 Parity bits estimation.

M (Bits)	N (Bits)	P (Bits)
4	4	9
8	8	17
16	16	33
32	32	65

For a block of 32x32 bits, 65 parity bits are generated and attached to correct a single error. No information are carried by those additional bits and only used for error correction. This causes more bandwidth occupation and sometimes slower transmission over a noisy channel. Optimizing the channel and making it more efficient is always a challenge improved coding techniques are required to make it better. The project in this thesis is the investigation of finding a reliable error control solution using orthogonal codes.

3.7 Orthogonal codes

In communication systems, Orthogonal codes like Walsh codes are used for long time as spreading codes. Besides as spreading codes, it also serves as forward error control (FEC) code [**18**]. Systematic block codes like Walsh codes have been proven to be more efficient and reliable as it is capable to correct more than one error. If an n-bit orthogonal code is chosen, it can detect and correct up to $\left(\frac{n}{4} - 1\right)$ errors. For a comparison with the last one in the above table, a 64-bit orthogonal code is able to correct up to 15 errors. The performance of orthogonal code for FEC is not widely investigated [**19**] [**20**]. In this thesis the application of orthogonal code in LASER communication for FEC is investigated. To the best of our knowledge, this method has not been checked for LASER so far and can be a very promising error correction technique for optical communication as higher bandwidth are available. Also different methods have been discussed to propose even more bandwidth efficient modulation. The experiment uses Amplitude Shift Keying (ASK) modulation of LASER and a bi-orthogonal mapping for data encoding.

3.8 Decoding of Orthogonal Code and Error Correction

At the receiver, the incoming encoded data is compared to the lookup table that contains the mapping structure. Upon the closest approximation (if not a 100 percent match which is the result of error in transmission) corresponding data bits are stored.

If the orthogonal code is n-bit long, it has n/2 1s and n/2 0s. The only exceptions are all 0s and all 1s. Other than those the distance 'd' between the codes become d = n/2. In exceptional cases it is even higher. This distance property helps to detect and correct the error in the channel [**21**] [**22**]. To apply this distance property, a threshold point at the midway between two orthogonal codes is set. The Figure 3.3 below shows the received code as dotted line falling between to orthogonal codes.

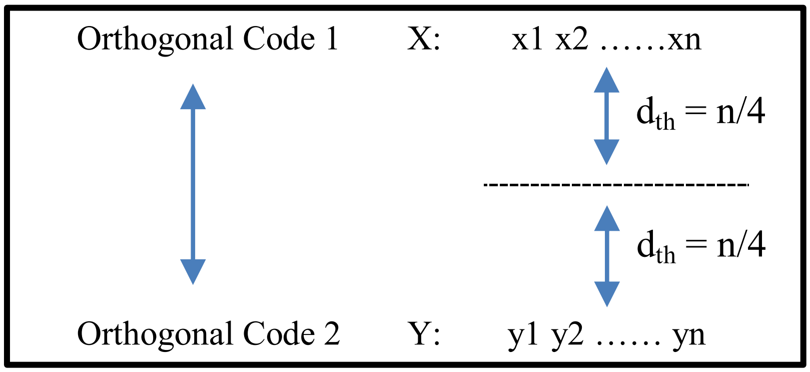

Figure 3.3: Decoding process of orthogonal code [**21**] [**19**]

If n is the code length and d_{th} is denoted as the threshold, the relation between can be expressed as

$$d_{th} = \frac{n}{4} \qquad (3.4)$$

The threshold falls at the midway between two orthogonal codes and provides the option to make the correct decision. The received encoded data is accepted as a valid code if the n-bit comparison yields a good cross correlation value. The correlation process below is followed when an impaired orthogonally coded data is compared with a couple of n-bit orthogonal codes.

$$R(x,y) = \sum_{i=1}^{n} x_i y_i \geq (n - d_{th}) + 1 \qquad (3.5)$$

Provided R(x,y) is the cross-correlation function, n = code length, dth = threshold. Since the threshold is right in the middle between two valid codes, an 1 bit offset is added to the equation above to avoid ambiguity.

The expected number of error correction from this process can be calculated by combining equations (3.4) and (3.5). We get

$$t = n - R(x, y) = \frac{n}{4} - 1 \qquad (3.6)$$

Here t = number of errors that can be corrected using n-bit orthogonal coding.

So, we can find that using an 8-bit code will correct 1 error where as a 16-bit code will give us 3 errors corrected. Table 3.2 shows further error correction capabilities for longer codes.

Table: 3.2 Relation between code length and number of corrected errors

Code Length ‘n’	Number of Errors Corrected ‘t’
8	**1**
16	**3**
32	**7**
64	**15**
128	**31**

We can see longer code length offers more than linear increment in number of errors corrected. This makes it a good choice in specific fields of applications for convenient error correction.

CHAPTER 4

ERROR CONTROL AND BANDWIDTH OPTIMIZATION USING ORTHOGONAL CODE

4.1 Introduction

J. L. Walsh in 1923 developed the aforementioned orthogonal codes. They are also well known as Walsh codes [**23**] [**19**]. Although these codes have been broadly used in Code Divisional Multiple Access (CDMA) for spreading data, it has been less inquired in other fields.

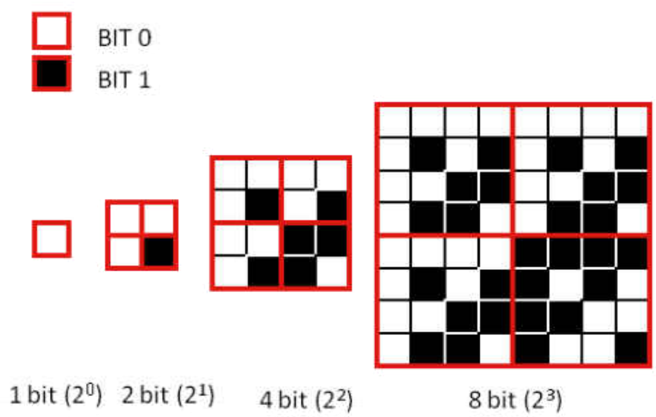

Figure **4**.1: Expansion of Hadamard Matrix [**19**] [**20**]

For orthogonal code generation, Hadamard matrix is the most well- technique. The following generalized equation is given for the mapping of Walsh sequences [**24**].

$$h2 = \begin{bmatrix} h1 & h1 \\ h1 & \overline{h1} \end{bmatrix} \qquad (4.1)$$

Figure **4**.1. shows the generation of orthogonal code using Hadamard matrix. Any Hadamard matrix can be generated of order N, when N = 2^n (2, 4, 8, 16, 32 . . .).

4.2 Properties of Orthogonal Code

Two standalone properties of orthogonal code make them unique as well as a very efficient for error control coding. These are: Parity generation and Distance properties.

Parity Generation Properties: An orthogonal code in every row generated using Hadamard matrix has equal number of 1s and 0s in it and the scalar product of the code is always to be ‘0’. But there is exception as well- when all the bits are 0s or 1s. If the generated codes are inversed, they are called antipodal codes and they are orthogonal amongst themselves. That infers an n-bit orthogonal code has an n-bit antipodal code of its own and all together there is a 2n bi-orthogonal code set. 8 bit orthogonal code set and the antipodal codes are shown in the Table **4**.1

Table: 4.1 n = 8 bit orthogonal and antipodal codes

Orthogonal code									Antipodal Code							
0	0	0	0	0	0	0	0		1	1	1	1	1	1	1	1
0	1	0	1	0	1	0	1		1	0	1	0	1	0	1	0
0	0	1	1	0	0	1	1		1	1	0	0	1	1	0	0
0	1	1	0	0	1	1	0		1	0	0	1	1	0	0	1
0	0	0	0	1	1	1	1		1	1	1	1	0	0	0	0
0	1	0	1	1	0	1	0		1	0	1	0	0	1	0	1
0	0	1	1	1	1	0	0		1	1	0	0	0	0	1	1
0	1	1	0	1	0	0	1		1	0	0	1	0	1	1	0

Antipodal Codes: Inverted regular orthogonal codes produce antipodal codes and possess the same properties. These codes can be generated in hardware level simply by passing the orthogonal codes through an in inverter buffer like a NOT gate. Orthogonal codes combined with antipodal codes forms the bi-orthogonal matrix which possesses all the orthogonal properties for all the sequences. Following table shows the set of bi-orthogonal codes using orthogonal and antipodal codes.

Table 4.2: Bi orthogonal code set by combining Orthogonal and Antipodal codes

Orthogonal Code	0	0	0	0	0	0	0	0
	0	1	0	1	0	1	0	1
	0	0	1	1	0	0	1	1
	0	1	1	0	0	1	1	0
	0	0	0	0	1	1	1	1
	0	1	0	1	1	0	1	0
	0	0	1	1	1	1	0	0
	0	1	1	0	1	0	0	1
Antipodal Code	1	1	1	1	1	1	1	1
	1	0	1	0	1	0	1	0
	1	1	0	0	1	1	0	0
	1	0	0	1	1	0	0	1
	1	1	1	1	0	0	0	0
	1	0	1	0	0	1	0	1
	1	1	0	0	0	0	1	1
	1	0	0	1	0	1	1	0

Bi Orthogonal code

Distance Properties: The other property that an orthogonal code set has is the cross correlation is zero between a pair of them [**25**]. This relation is given as [**21**] [**22**]

$$R_{xy}(0) = \sum_{i=1}^{m} x_i y_i = 0 \qquad (4.2)$$

Here two sets of m-bit codes are considered as X1, X2….Xm and Y1, Y2….Ym. In reality, when the offset between two Walsh code sequences is zero, they show zero cross correlation between them. The offset can be achieved by synchronization of all the users of the code which makes it well suitable for CDMA applications [**26**].

Other properties of orthogonal code include:

- If the code length is n-bit, the minimum length of the orthogonal code for the respective data is 2^n.
- 2^n different orthogonal code combinations are available for 2^n bits of code length.
- There are 2^{n+1} different bi-orthogonal code combinations are available for 2^n bits of code length.
- If orthogonal code modulates a carrier signal, the modulated signal also shares the orthogonal space.

4.3 Encoding of the data

An orthogonal encoding can be performed in both hardware level or in the software interface. The primary purpose here is to map the data using a table and transmit the data over the channel. In the Table: 4.3(a) a mapping table is shown for an n=3 bit data and the respective orthogonal codes, and in the Table: 4.3(b) a mapping table for n=4 bit data.

Table: 4.3: (a) mapping table for n = 2, (b) mapping table for n = 4

Data, 2^3 =8	**8*4 Mapped result**
000	0000
001	0101
010	0011
011	0110
100	1111
101	1010
110	1100
111	1001

(a)

Data, 2^4 =16	**16*8 Mapped result**
0000	0000 0000
0001	0101 0101
0010	0011 0011
0011	0110 0110
0100	0000 1111
0101	0101 1010
0110	0011 1100
0111	0110 1001
1000	1111 1111
1001	1010 1010
1010	1100 1100
1011	1001 1001
1100	1111 0000
1101	1010 0101
1110	1100 0011
1111	1001 0110

(b)

These data are mapped using a bi-orthogonal coding scheme. For higher values of n, the table expands accordingly. For the fulfillment of the experiment, mapping table for n = 4, 5, 6 and 7 are generated and used for generating coded data.

The code rate for this orthogonal code is calculated as:

$$r = \frac{n+1}{2^n} \quad (4.3)$$

Where r = code rate, and n = number of bits

4.4 Preparation of test bed

The experimental setup features a transmitting station and a receiving station which are two computers here to serve the purpose. The data is transferred using a LASER which is ASK modulated by the coded data. The audio output and input ports of the computers are used to send the bits to the laser and receive the signal from the photodetector respectively. The laser module used here has its own controller circuit and can operate while a control signal of 3.0-3.5 volt signal is present. To amplify the output signal from the computer a high frequency amplifier circuit has been introduced to interface the LASER. This makes sure that it receives the proper voltage level to drive the beam.

The mapping of data, introduction of the errors, receiving the coded data and extracting the information using the lookup table and calculation of error is performed by a program. The program is written using MATLAB®.

The flowchart for the program is given below.

Flow chart of the transmission end

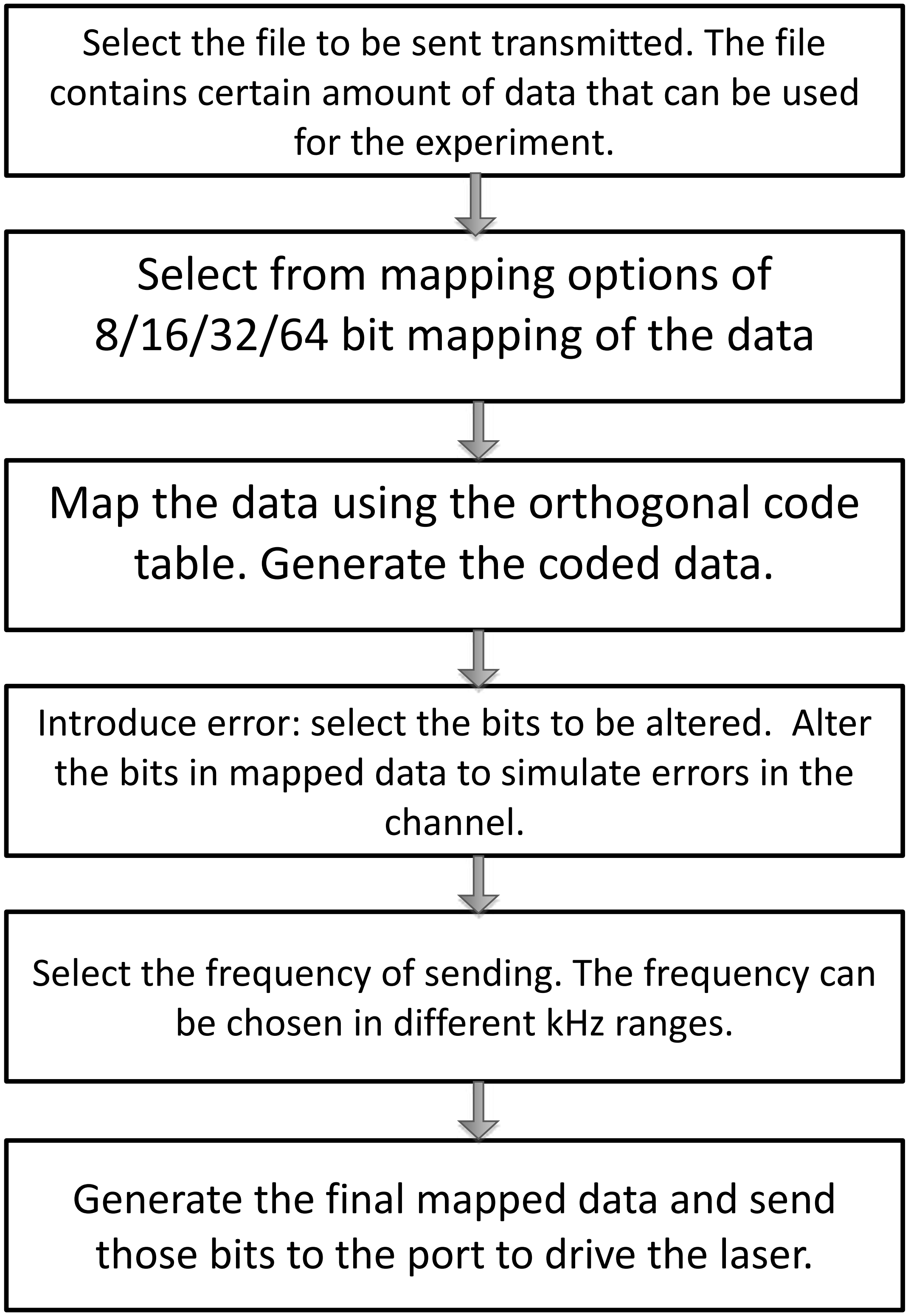

Figure **4**.2: Transmission end steps in flowchart

Flowchart of the receiving end

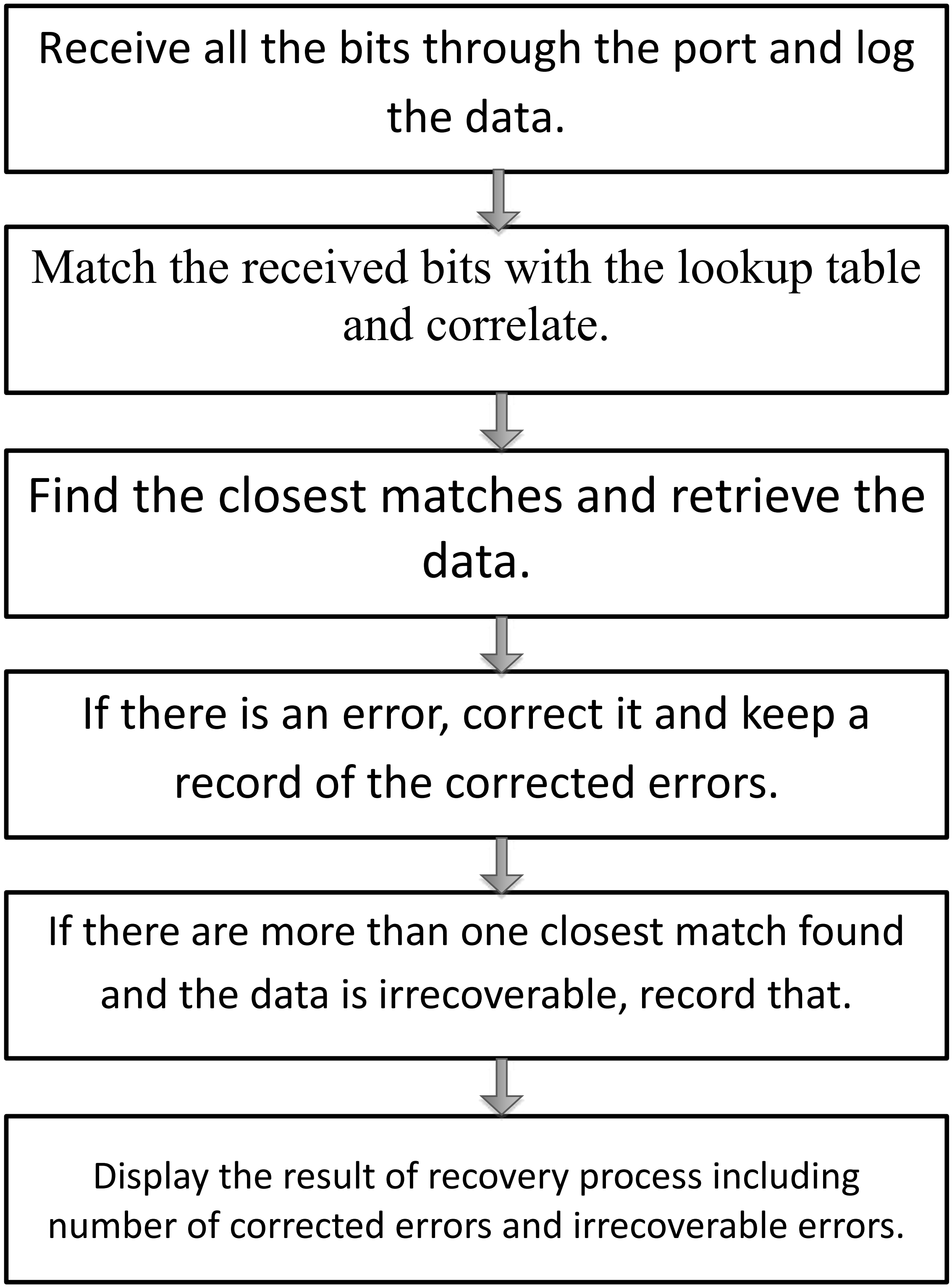

Figure **4**.3: Reception end steps in flowchart

4.5 Bandwidth Optimization

While using Bi-Orthogonal coding, there is a lot of room for bandwidth optimization. The dimension of the bi orthogonal code depends on the mapping sequence of input data bits. It follows the equation:

$$2^n = K \qquad (4.4)$$

Where n = number of bits and K*K/2 is the dimension of the bi-orthogonal matrix required for the data mapping

The Table 4.4 explains how the expansion of bi-orthogonal matrix moves with respect to number of bits:

Table 4.4: Expansion of bi-orthogonal matrix size respect to number of bits

Number of bits	**Number of combinations**	**Bi orthogonal matrix**
3	2^3=8	8*4
4	2^4=16	16*8
5	2^5=32	32*16
6	2^6=64	64*32
7	2^7=128	128*64
8	2^8=256	256*128

It is visible from the table that the requirement of the bigger matrix size of the bi orthogonal coding increases exponentially. This costs lots of bandwidth in this case. But it can be significantly reduced by bit splitting.

Bit Splitting: Bit splitting procedure means the input bits are divided into two or even smaller branches to map the data. While bigger chunk of data will use long matrix of bi orthogonal code, a smaller fraction of those bits will use it more efficiently as the bit rate will be lower.

For an example, an 8 bit data needs a matrix of 256*128 bi-orthogonal codes. But if the 8bit data is split in half and two of 4bit data are sent sequentially, it will only require a matrix of 16*8. Even further bit splitting possible to decompose it into smaller bit sequences. The following Table 4.5 shows some examples:

Table: 4.5: Bit splitting in orthogonal matrix

Number of bits	Number of combinations	Bi orthogonal matrix	Bit rate	Bi orthogonal matrix after half splitting	Bit rate
3	**2^3=8**	**8*4**	**(Rb/3)*4 = 4Rb/3**	**2*4*4**	**(Rb/4)*4 = Rb**
4	**2^4=16**	**16*8**	**(Rb/4)*8 = 2Rb**	**2*8*8**	**(Rb/6)*8 = 4Rb/3**
5	**2^5=32**	**32*16**	**(Rb/5)*16 = 16Rb/5**	**2*16*16**	**(Rb/8)*16 = 2Rb**
6	**2^6=64**	**64*32**	**(Rb/6)*32 = 16Rb/3**	**2*32*32**	**(Rb/10)*32 = 16Rb/5**
7	**2^7=128**	**128*64**	**(Rb/7)*64 = 64Rb/7**	**2*64*64**	**(Rb/12)*64 = 16Rb/3**
8	**2^8=256**	**256*128**	**(Rb/8)*128 = 32Rb**	**2*128*128**	**(Rb/14)*128 = 64Rb/7**

Following block diagrams will explain the hardware level implementation of bit splitting.

In the following Figure 4.2, we can see the Code rate r=1/2, Transmit bit rate = 2Rb, Bandwidth BW = 2*2Rb = 4Rb Hz

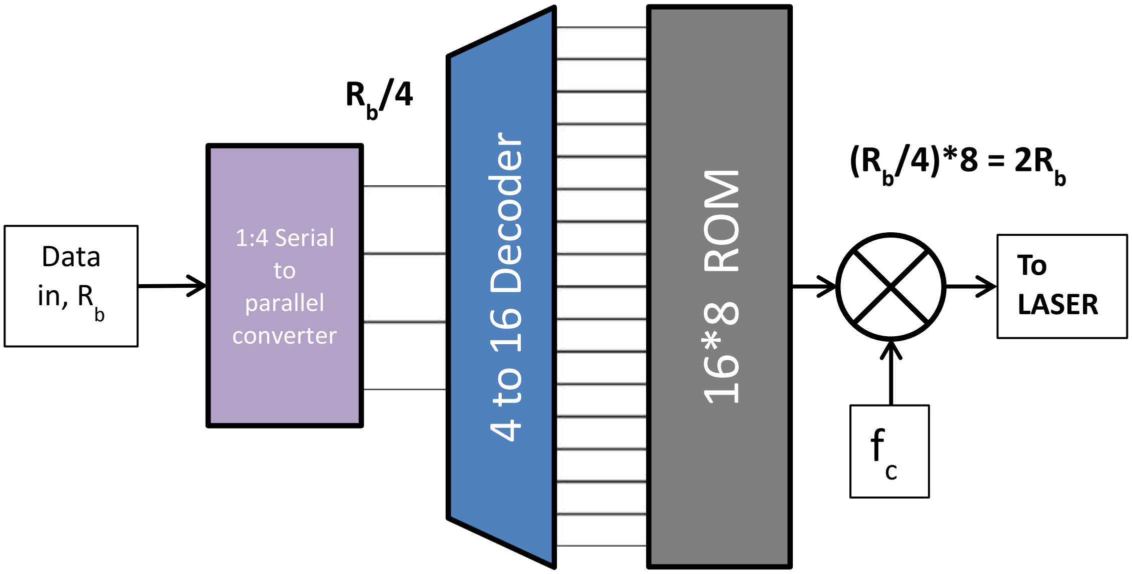

Figure: 4.4 Bit Splitting, 4-bit input and 16x8 mapping

When 16 bit inputs are split into two 8 bit inputs, the change is shown in the following Figure 4.3. Here Code rate r=3/4, Transmit bit rate = 4Rb/3, Bandwidth BW = 2*4R_b/3 Rb = 8Rb/3 Hz

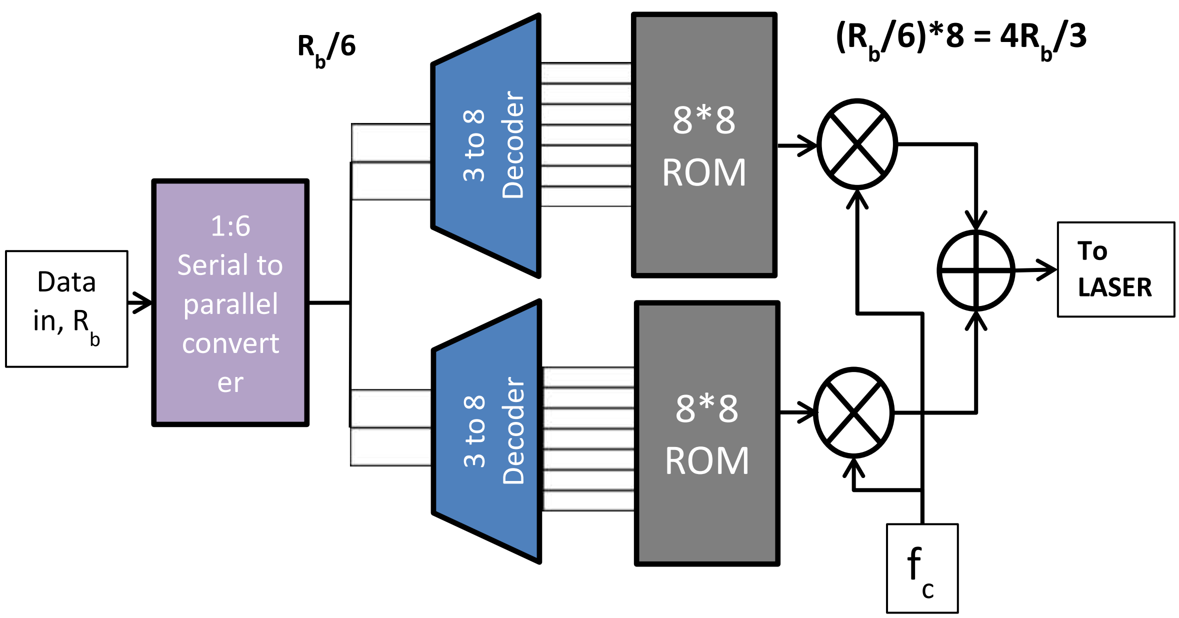

Figure: 4.5 Bit Splitting, 2*3-bit input and 2*(8x8) mapping

After splitting further, the fixture would look like the one in the Figure 4.4. Here Code rate r=1, Transmit bit rate = Rb, Bandwidth BW = 2***R_b** = 2Rb Hz

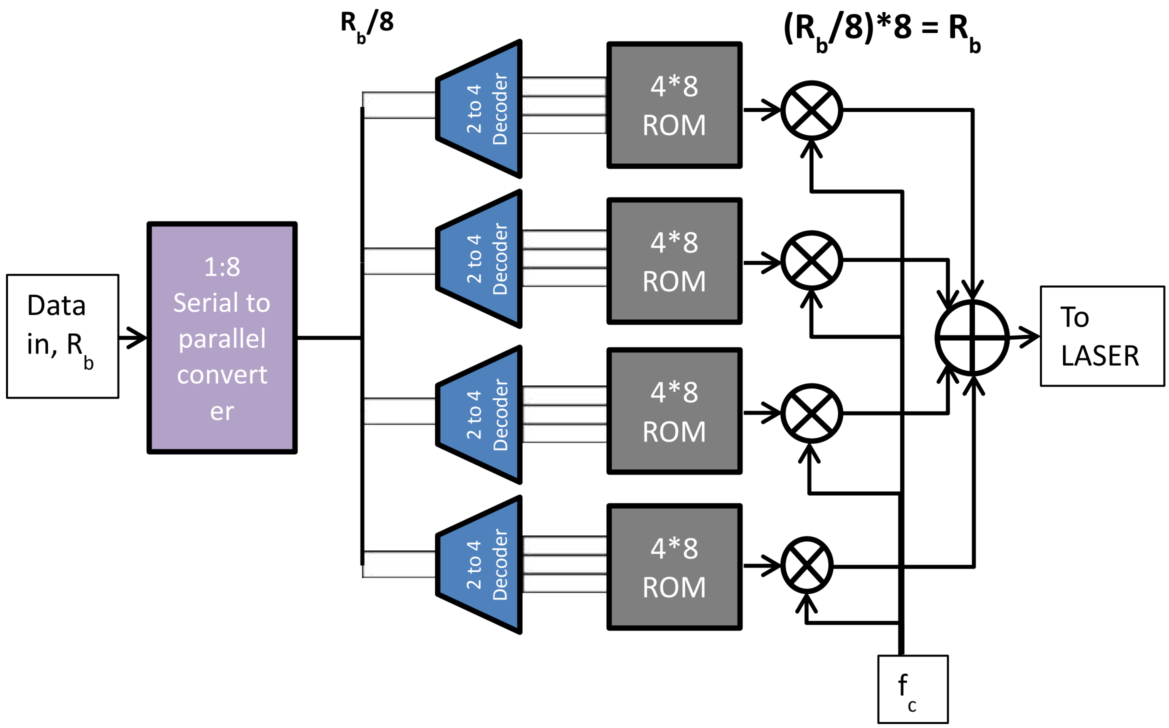

Figure: 4.6 Bit Splitting, 4*2-bit input and 4*(4x8) mapping

Error control and bandwidth optimization options are two major advantages of Orthogonal coding schemes. In LASER communication, the orthogonal coding performance is verified using On-Off Keying modulation and experiments and results are discussed in the following chapter.

CHAPTER 5

EXPERIMENTAL RESULT

5.1 Introduction

The experimental verification process of the error correction capability of Orthogonal On-Off Keying (O^3K) has been discussed in this chapter and the results are presented. The setup required a combination of hardware and software. Transmissions of data were performed and checked between two computers acting as transmitter and receiver. The medium was a LASER beam operating in the air. And data transmission through a wired interface was also performed. Both the results are presented and discussed.

5.2 Hardware and Software

LASER: Class IIIa LASER product has been used. It is a red laser of 635nm wavelength. Product vendor is COHERENT®. Control of the laser can be a voltage signal ranging up to 3.5volts but suggested typical value is 3.2volts. Figure 5.1 (a) shows a picture of the laser that has been used.

Photo-detector: a high-speed photodiode has been used for the detection of the laser beam. The working range of this photo-detector extends from 450 to 1100 nm. Low rise and fall time typically around 5nS makes it very much suitable for the experiment. Product vendor is Industrial Fiber Optics, Inc. and manufacturer id is IF-D91. Figure 5.1 (b) shows the pictures of the photo-detector illuminated by laser and 5.1 (c) shows the response when the laser is off.

Transceiver computers: Any computer that is capable to run MATLAB® R2012a or R2010a is good to work as the transmitter or receiver end of the experiment. These two versions of MATLAB® are confirmed to perform as it has been tested. But other versions are expected to support as well.

Signal amplifier: A TL071 high frequency operational amplifier was used for the amplification of the signal. Received signal is magnified to the required level, here in this case signal raised to 3.2 volts to drive the laser.

Software: Programming Language: MATLAB™ 2012a used to prepare the software.

Audio software: Audacity 2.0.5 and Windows Media Player are used to record the received data and send the data to laser by playing the audio file respectively.

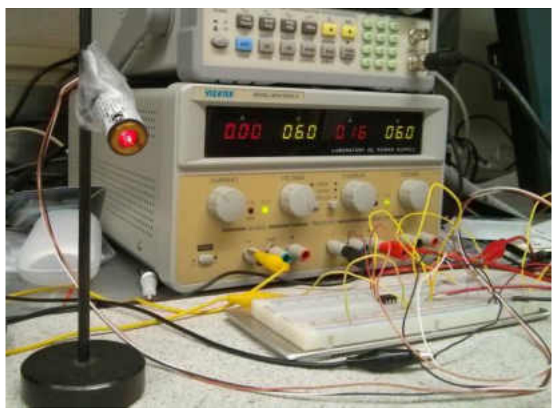

Figure: 5.1(a) LASER for data transmission

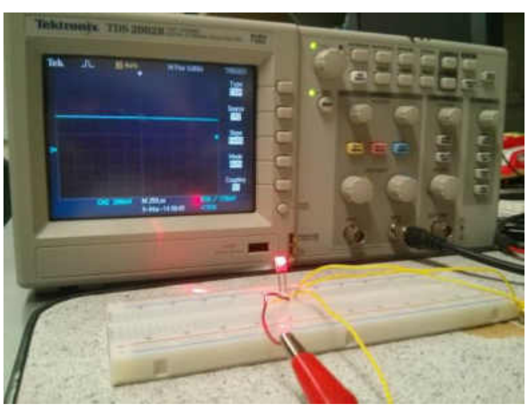

Figure: 5.1(b) Photo-detector (LASER on)

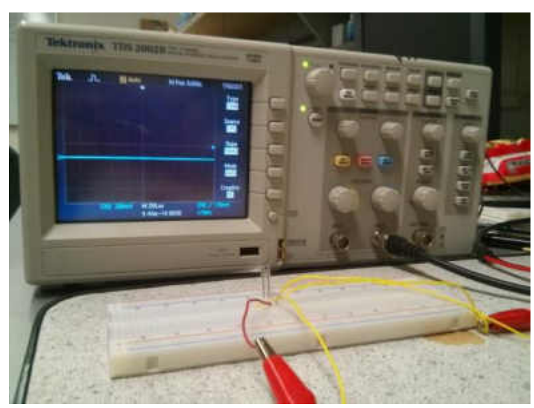

Figure: 5.1(c) Photo-detector (LASER off)

5.3 Construction of the Experiment

The purpose of the whole experiment in this project to test the orthogonal coding scheme applied to a set of data that is transferred through a laser channel. The channel attenuation and noise can interfere with the data transfer and create error in the bits. For the experimental purpose, random bits were altered to simulate the error in the channel. The receiver end will log the data bits and use the mapping table for correction and confirm the performance orthogonal codes in forward error correction. The expected error correction ability is given by the following equation

$$t = n/4 - 1 \qquad (5.1)$$

Where t = number of errors corrected and n = number of bits

Table 5.1 shows the number of error correction for n = 8, 16, 32, 64

Table: 5.1 Percentage of error correction and code length

Code Length 'n'	Number of Errors Corrected 't'	Percentage or error correction
8	**1**	**12.50%**
16	**3**	**18.75%**
32	**7**	**21.87%**
64	**15**	**23.43%**

5.3.1 Selection of data file: At first, a file is prepared to send over the channel and because it is an experiment the number of the bits in the file has been selected carefully to suite the program written in MATLAB®. For this, a common multiple of selected n values (4,5,6,7) were taken and that many number of bits were placed in the file to make sure the program can map all the bits inside. If not a multiple of the given n values, the program will have unmatched size of array and will not proceed.

5.3.2 Mapping of the data: There have been options created to map the data for four different lengths of the bi-orthogonal code, which are 8, 16, 32 and 64 bits. Upon the choice of the user, any mapping option can be selected. The higher dimension of the mapping table is chosen, the more correction of error is possible. But it will increase the volume of the mapped result as well.

5.3.3 Introduction of errors: To simulate the errors in the channel, the program is prepared to introduce errors in the bit stream. User can choose any number of errors to be in the file from zero to all. Selected bits will be altered from the generated orthogonally coded data. For an example, altering 16 bits in every 64 bits will result creating 25% of error in the data. Both the numbers are variable and can be chosen independently. Such as, it can be chosen to be 2 bits out of every 16 bits. If no error to be introduced, simply putting 0 out of every 16 bits will do it.

5.3.4 Choice of bit rate: The user can choose the frequency at which the data will be sent out. This forms the bit rate of the transmission.

5.3.5 Conversion into wave file: Last step of the program is to convert the binary file into a wave file also known as wav file format. Because in this file format data is stored in linear pulse coded modulation, the data bit stream of 0s and 1s become discrete voltage levels in the time domain. This file can be executed from any audio player software.

5.3.6 Sending out the bits: The bits are sent out simply by playing the wav file. Any audio playing software can do that. In this experiment the Windows Media Player has been used. From the audio output port of the computer the bit stream will be available as the wave file executed.

5.3.7 Amplification: As the audio port gives away the signal of our interest, it is fed into the amplifier circuit. A high frequency operational amplifier performs the amplification and raises the peak voltage up to 3.2 volts.

5.3.8 Operation of laser: The output signal of the amplifier has two discrete levels to denote 0 and 1. For 0 the voltage level is ~0volt and for 1, it is ~3.2 volts. The control input of the laser is directly connected to the output of the amplifier. The On operation of the laser takes place between the ranges of 3.0-3.5volts. So, the laser is On-Off modulated by the 0s and 1s of the data file created earlier.

5.3.9 Detection and logging of the signal: LASER beam is pointed at the photodetector and generates responses according to the laser illumination. The signal produces a response of ~400mV when fully brightened by the laser and ~0volt when no beam is falling upon its lens. This range of voltage is adequate for the detection of bits. So as a result a stream of data bits is produced from the terminals of the photodetector. This signal is fed into the ‘line in’ audio recording port of the receiver end computer.

5.3.10 Recording of the data: The line in audio port of is typically used to collect and record signals from audio sources. It is capable to collect and store the change in the voltage of a source in time domain. So this option has been used here to record all the signals and analyze later one. The software Audacity 2.0.5 has been used to record the reception and store it as a wav file.

5.3.11 Data retrieval and error correction: The recorded wav file contains the received bits in the time domain. 0s and 1s are represented as the ~0Volt and ~400mVolt respectively. The receiver part of the MATLAB® program now analyzes the file and determines the bits using a threshold value. After recognition of the bits, it is matched with the lookup table. User can define which lookup table to be used here and can select from the 8, 16, 32 or 64bit options to check. Upon correct selection, the program will pick bits from the file and match with the lookup table. When a perfect match is found, it will store the respective data bits as the retrieved data. If it is not matched all the way along the length of the data, the closest matches are picked for analysis.
Mismatched bits in the code length are counted as errors in the transmission. If the number of errors in the transmission falls in the range of error correction ability of the coding, there should be only one closest match to any one of the rows in the lookup table. For an example, if 10 error bits were found in a 64 bit long code, in the lookup table there should be only one match that is closest to the bits received. On the other hand, if there are 16 or more errors found in a 64bit long code, there will be more than one closest match in the lookup table. In that case, the program will be unable to correct the number of errors as more than one match is found say it is 3 or 4 matches. There is no way to

confirm which one is the right match. But if it falls in the range of correctable number of errors, it will take the closest match and correct it. Will record the number of corrected bits as well, retrieve the data and display the result.

For the experiment, multiple combinations of mapping table along with the numbers of introduced errors and the rate of transmission were checked. Various permutations and combinations using all the parameters were tried over the channel using laser and wired transmission. All the results are collected and used for the verification of the error correction ability of the coding.

The following figures from Figure 5.2 to Figure 5.9 show the pattern of transmitted and received data by LASER and wired transmission. All the responses show the signal transmitted and received in time domain. Each section includes the transmission bits and reception signals by laser as well as wired interface. The responses are properly aligned to compare between the same bits for transmission and reception.

5.3.12 Visual pattern of the 8 bit mapped transmission and reception

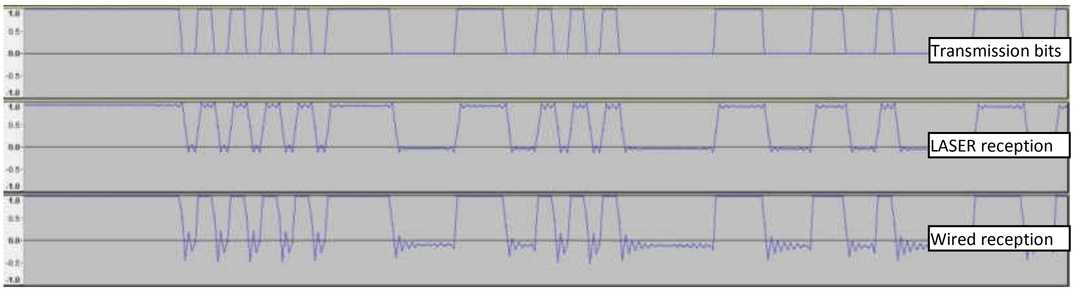

Figure: 5.2 (a): 8 bit mapping, 1 error in every 8 bit, 4 kHz transmission

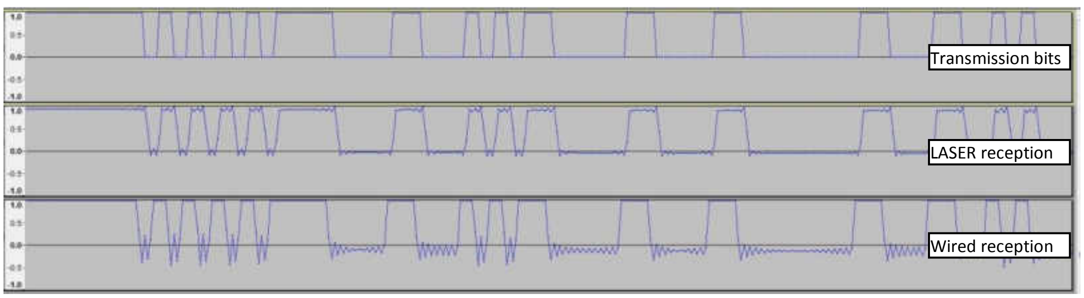

Figure: 5.2 (b): 8 bit mapping, 2 errors in every 8 bit, 4 kHz transmission

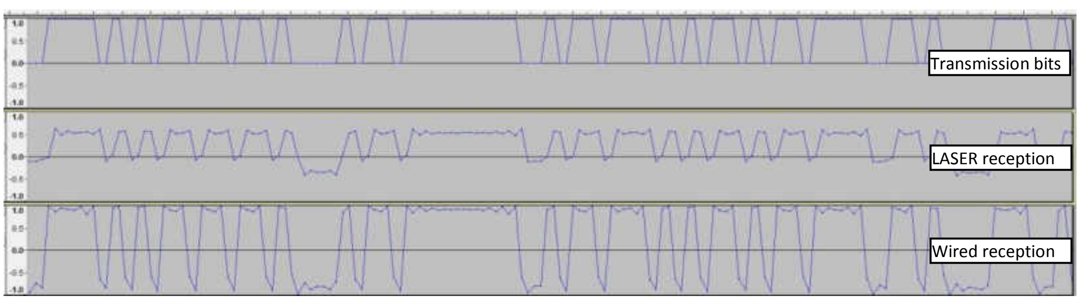

Figure: 5.3 (a): 8 bit mapping, 1 error in every 8 bit, 8 kHz transmission

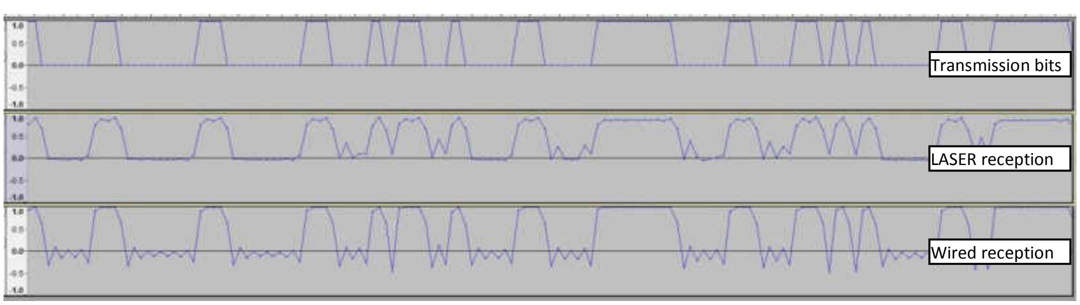

Figure: 5.3 (b): 8 bit mapping, 2 errors in every 8 bit, 8 kHz transmission

5.3.13 Visual pattern of the 16 bit mapped transmission and reception

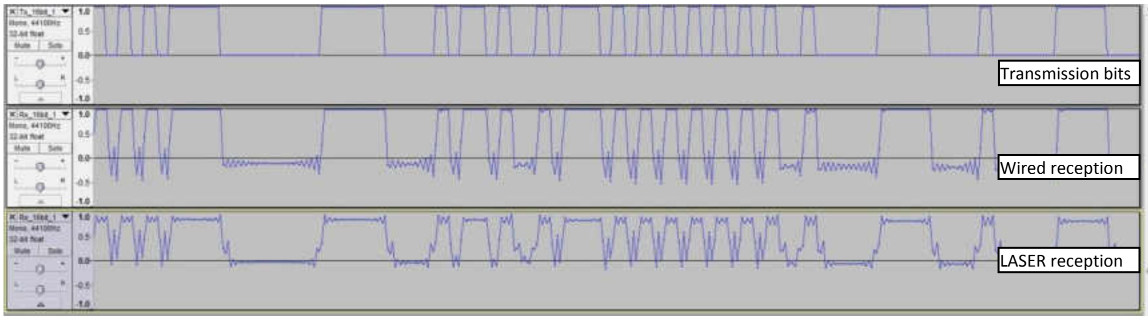

Figure: 5.4 (a): 16 bit mapping, 3 errors in every 16 bit, 4 kHz transmission

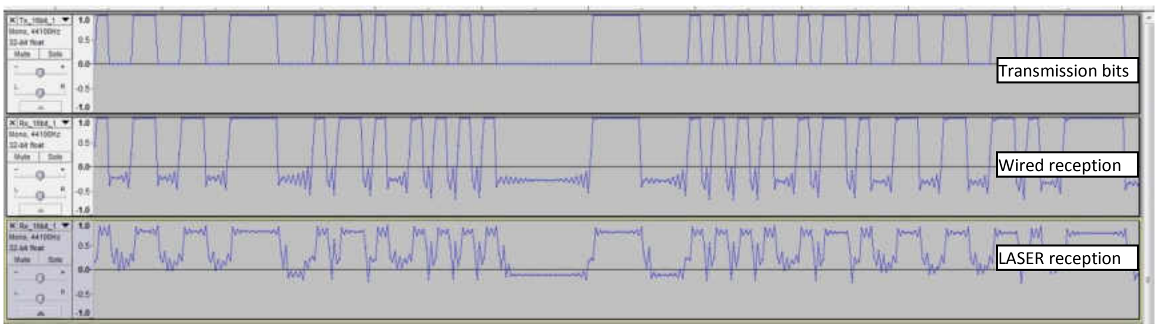

Figure: 5.4 (b): 16 bit mapping, 4 errors in every 16 bit, 4 kHz transmission

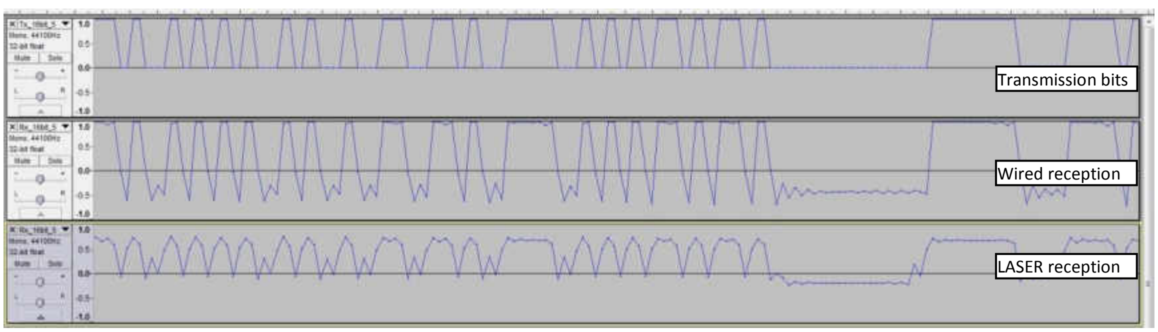

Figure: 5.5 (a): 16 bit mapping, 3 errors in every 16 bit, 8 kHz transmission

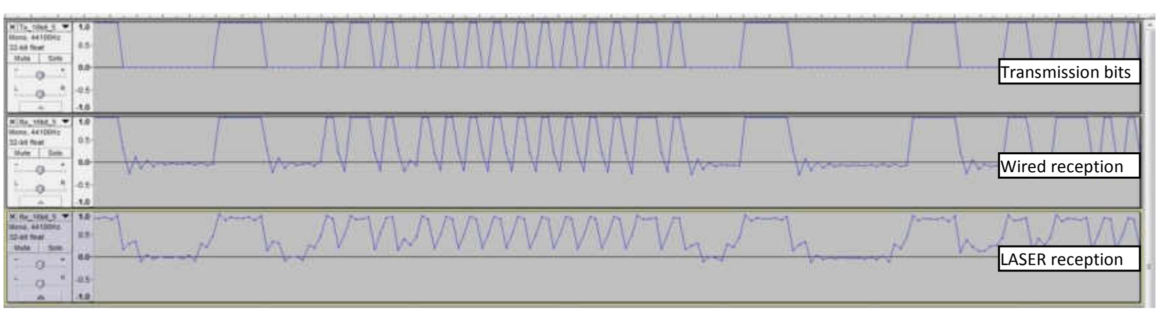

Figure: 5.5 (b): 16 bit mapping, 4 errors in every 16 bit, 8 kHz transmission

5.3.14 Visual pattern of the 32 bit mapped transmission and reception

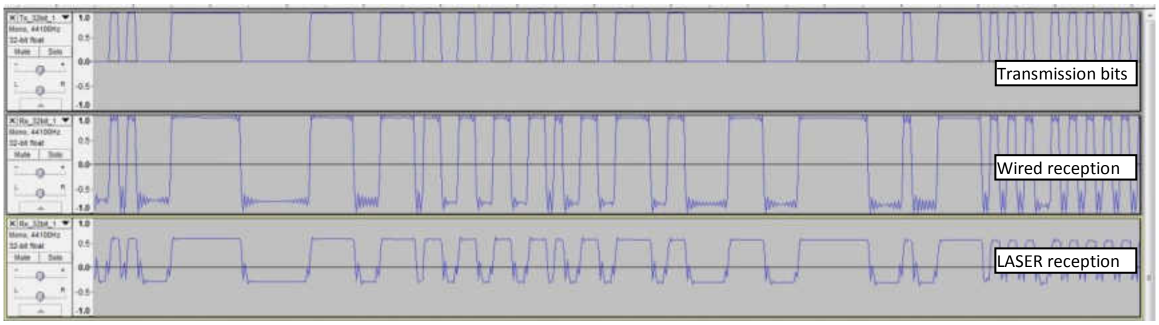

Figure: 5.6 (a): 32 bit mapping, 7 errors in every 32 bit, 4 kHz transmission

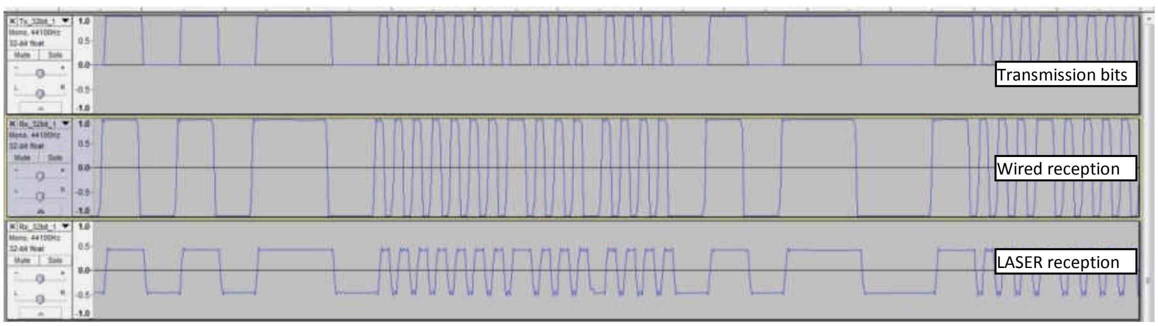

Figure: 5.6 (b): 32 bit mapping, 8 errors in every 32 bit, 4 kHz transmission

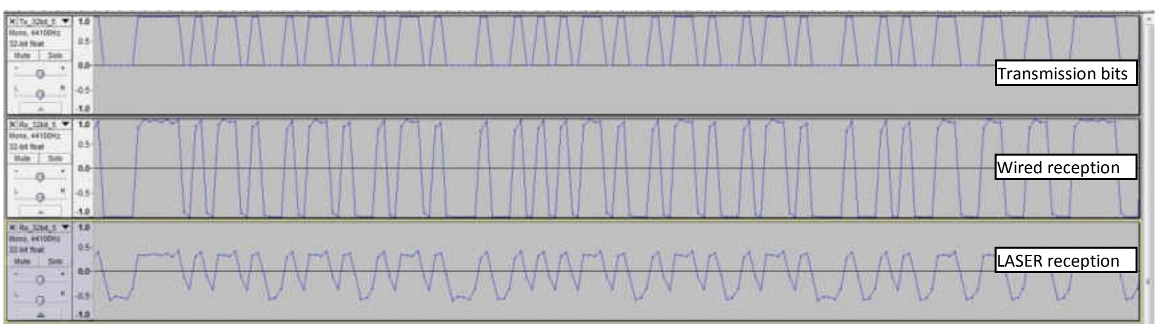

Figure: 5.7 (a): 32 bit mapping, 7 errors in every 32 bit, 8 kHz transmission

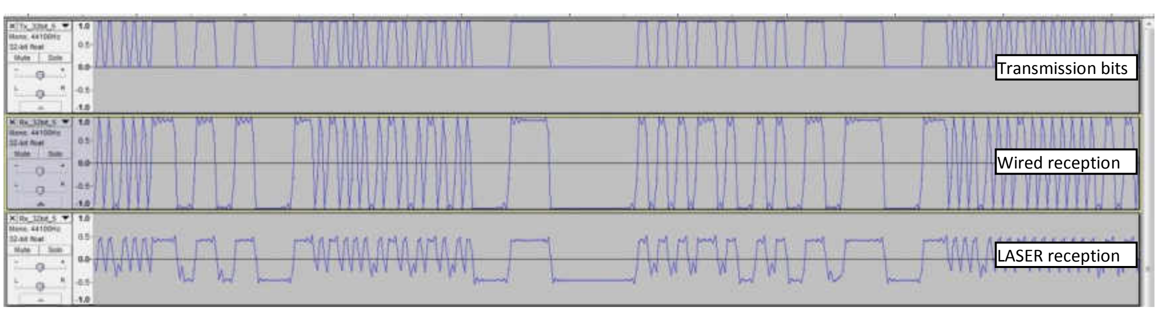

Figure: 5.7 (b): 32 bit mapping, 8 errors in every 32 bit, 8 kHz transmission

5.3.15 Visual pattern of the 64 bit mapped transmission and reception

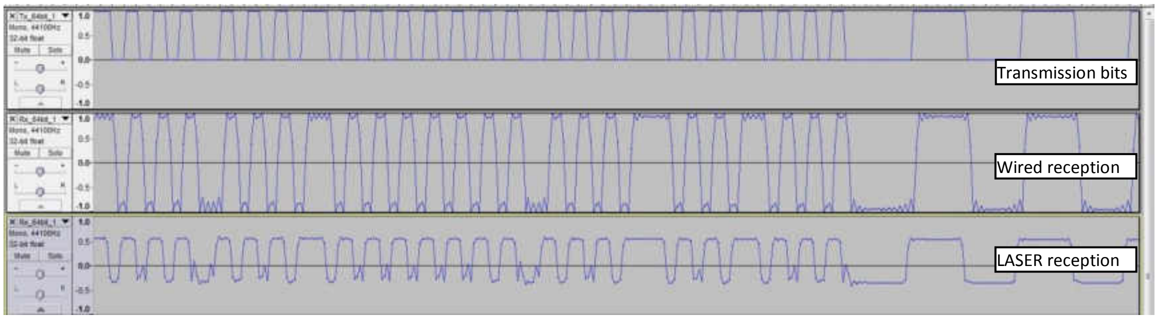

Figure: 5.8 (a): 64 bit mapping, 15 errors in every 64 bit, 4 kHz transmission

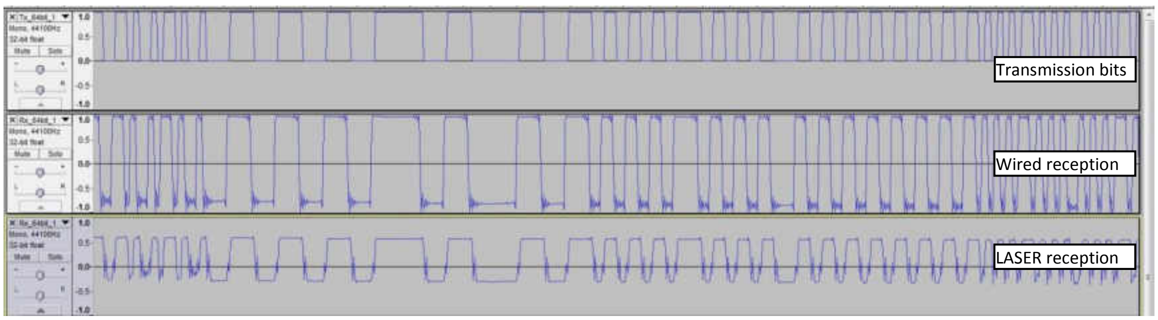

Figure: 5.8 (b): 64 bit mapping, 16 errors in every 64 bit, 4 kHz transmission

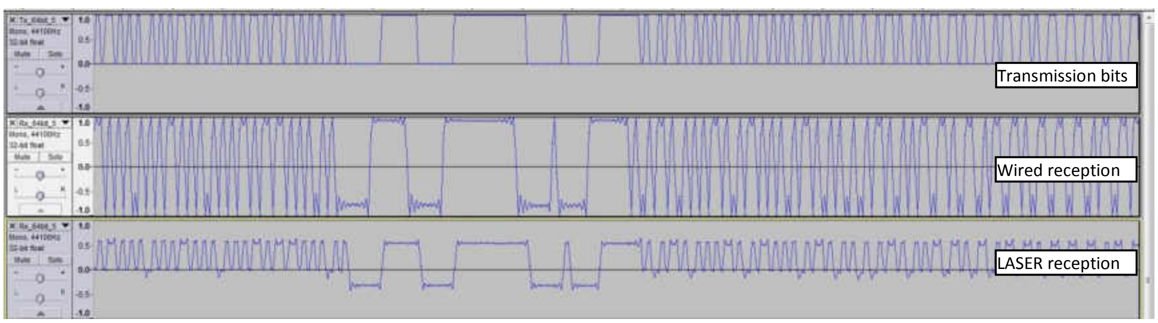

Figure: 5.9 (a): 64 bit mapping, 15 errors in every 64 bit, 8 kHz transmission

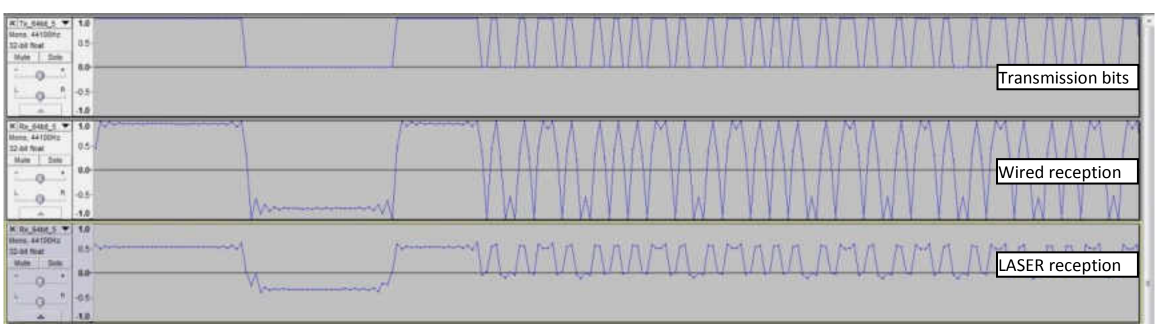

Figure: 5.9 (b): 64 bit mapping, 16 errors in every 64 bit, 8 kHz transmission

5.3.16 Summary of LASER reception results: The following tables show the performance of error correction over various different combinations for **LASER reception**.

Table: 5.2 Results of error correction for 8 bit data mapping

8 bit data mapping	Number of error bits introduced at transmission	Error check validation
1kHz transmission	0	Pass
	1	Pass
	2 or more	Failed
2 kHz transmission	0	Pass
	1	Pass
	2 or more	Failed
4 kHz transmission	0	Pass
	1	Pass
	2 or more	Failed
8kHz transmission	0	Failed
	1	Failed
	2 or more	Failed
16kHz transmission	0	Failed
	1	Failed
	2 or more	Failed

Table: 5.3 Results of error correction for 16 bit data mapping

16 bit data mapping	Number of error bits introduced at transmission	Error check validation
1kHz transmission	0	Pass
	3 and less	Pass
	4 or more	Failed
2kHz transmission	0	Pass
	3 and less	Pass
	4 or more	Failed
4kHz transmission	0	Pass
	3 and less	Pass
	4 or more	Failed
8kHz transmission	0	Failed
	3 and less	Failed
	4 or more	Failed
16kHz transmission	0	Failed
	3 and less	Failed
	4 or more	Failed

Table: 5.4 Results of error correction for 32 bit data mapping

32 bit data mapping	Number of error bits introduced at transmission	Error check validation
1kHz transmission	0	Pass
	7 and less	Pass
	8 or more	Failed
2kHz transmission	0	Pass
	7 and less	Pass
	8 or more	Failed
4kHz transmission	0	Pass
	7 and less	Pass
	8 or more	Failed
8kHz transmission	0	Failed
	7 and less	Failed
	8 or more	Failed
16kHz transmission	0	Failed
	7 and less	Failed
	8 or more	Failed

Table: 5.5 Results of error correction for 64 bit data mapping

64 bit data mapping	Number of error bits introduced at transmission	Error check validation
1kHz transmission	0	Pass
	15 and less	Pass
	16 or more	Failed
2kHz transmission	0	Pass
	15 and less	Pass
	16 or more	Failed
4kHz transmission	0	Pass
	15 and less	Pass
	16 or more	Failed
8kHz transmission	0	Failed
	15 and less	Failed
	16 or more	Failed
16kHz transmission	0	Failed
	15 and less	Failed
	16 or more	Failed

5.3.17 Summary of wired reception results: The following tables show the performance of error correction over many different combinations for **Wired Reception**.

Table: 5.6 Results of error correction for 8 bit data mapping

8 bit data mapping	**Number of error bits introduced at transmission**	**Error check validation**
1kHz transmission	0	Pass
	1	Pass
	2 or more	Failed
2 kHz transmission	0	Pass
	1	Pass
	2 or more	Failed
4 kHz transmission	0	Pass
	1	Pass
	2 or more	Failed
8kHz transmission	0	Pass
	1	Pass
	2 or more	Failed
16kHz transmission	0	Failed
	1	Failed
	2 or more	Failed

Table: 5.7 Results of error correction for 16 bit data mapping

16 bit data mapping	**Number of error bits introduced at transmission**	**Error check validation**
1kHz transmission	0	Pass
	3 and less	Pass
	4 or more	Failed
2kHz transmission	0	Pass
	3 and less	Pass
	4 or more	Failed
4kHz transmission	0	Pass
	3 and less	Pass
	4 or more	Failed
8kHz transmission	0	Pass
	3 and less	Pass
	4 or more	Failed
16kHz transmission	0	Failed
	3 and less	Failed
	4 or more	Failed

Table: 5.8 Results of error correction for 32 bit data mapping

32 bit data mapping	Number of error bits introduced at transmission	Error check validation
1kHz transmission	0	Pass
	7 and less	Pass
	8 or more	Failed
2kHz transmission	0	Pass
	7 and less	Pass
	8 or more	Failed
4kHz transmission	0	Pass
	7 and less	Pass
	8 or more	Failed
8kHz transmission	0	Pass
	7 and less	Pass
	8 or more	Failed
16kHz transmission	0	Failed
	7 and less	Failed
	8 or more	Failed

Table: 5.9 Results of error correction for 64 bit data mapping

64 bit data mapping	Number of error bits introduced at transmission	Error check validation
1kHz transmission	0	Pass
	15 and less	Pass
	16 or more	Failed
2kHz transmission	0	Pass
	15 and less	Pass
	16 or more	Failed
4kHz transmission	0	Pass
	15 and less	Pass
	16 or more	Failed
8kHz transmission	0	Pass
	15 and less	Pass
	16 or more	Failed
16kHz transmission	0	Failed
	15 and less	Failed
	16 or more	Failed

From Table 5.2 to Table 5.9 above it is shown that the performance of the Orthogonal On-Off keying for error correction is well acquired by the LASER and wired transmission. However wired transmission shows better performance in higher frequency than the LASER. This helps to understand the required hardware support for driving the laser and detection of a high frequency signal. In case of higher frequency the recording of the received signal may not be as optimized as well as the low frequency modulation. This is quite visible from the pattern of the received signals. Filtration and noise cancelation circuits may also come in effect inside the hardware which also may cause poor reception at higher frequency. That is why the program was able to correct the errors in laser reception at around 4 kHz and less but as the frequency went higher, the reception went poor. Weak reception and noise in the channel attenuated the signal below the selected threshold at points and program failed to detect the bits properly. However wired transmission showed better performances in this regard and showed expected error correction results around 8kHz transmission. But above that it failed as well. The visual patterns show the comparison between bits received by LASER and wired transmission and the difference between lower and higher frequency. To study the higher frequency response beyond this range, some hardware modification and equipment recommendation are also discussed in the following chapter.

5.4 Bit Error Rate and performance analysis

In data transmission, number of error bits are counted as the number of bits altered in the channel. This change in the bits can be a result of the noise, interference, defects, distortions or other unwanted parameters. The calculation of Bit Error Rate (BER) refers to the ratio of number of error bits to the number of bits transferred during a certain time period. The study of bit error rate analysis helps to analyze the performance of error control coding in a certain channel.

The expected value of bit error rate is referred as bit error probability Pe. Thus the BER gives an approximate estimation of error occurrence. As mentioned earlier, there are numbers of factors in the channel that can cause errors. Calculation of BER and Coding Gain will complement the study.

Coding gain: For uncoded data, if there is an error it cannot be corrected. On the other hand coded data transmission comes into play to provide error correction. Coding gain is obtained by comparing the BER with coding to the BER without coding. Measurement of coding gain helps to understand the performances between different codes as well as uncoded data.

For the bit error rate calculation a channel model is introduced to simulate the random noise in the transmission. Additive White Gaussian Noise (AWGN) is a channel model and it is used to mimic the random processes in nature. Additive- refers that it is added to any noise intrinsical to the system. White refers to that it considers uniform noise power distribution. And it is Gaussian because the normal distribution in the time domain yields an average value of zero.

Now, for the uncoded data, the bit error rate expression is [**2**] [**27**].

$$Pe(U/AWGN) = \frac{1}{2} erfc\left(\sqrt{E_b/N_0}\right) \qquad (5.2)$$

And, for the coded data, the bit error rate expression is [**2**] [**27**].

$$Pe(Blk/AWGN) = \sum_{i=t+1}^{n} \binom{n}{i} Pe(U/AWGN)^i \left(1 - Pe(U/AWGN)^{n-i}\right)$$

(5.3)

Here AWGN stands for Additive White Gaussian Noise. If we plot the results for orthogonally mapped data using the equations above, we find the following.

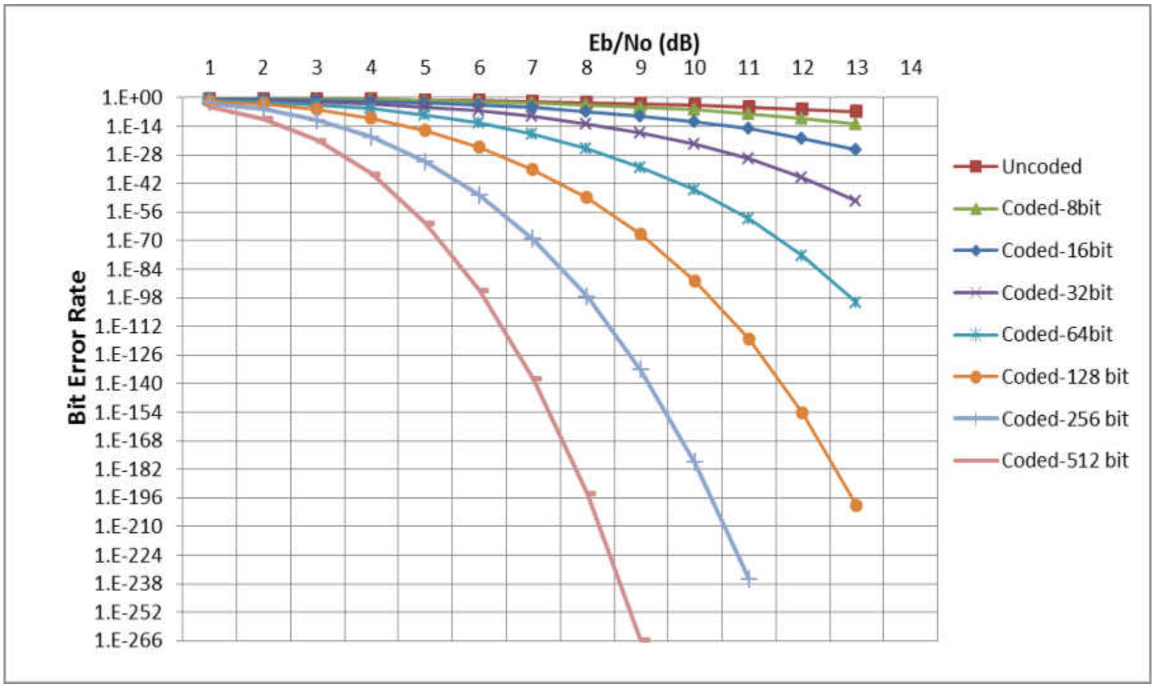

Figure: 5.10 BER performances for 8/16/32/64/128/256/512 bit bi-orthogonal codes- wide scale view

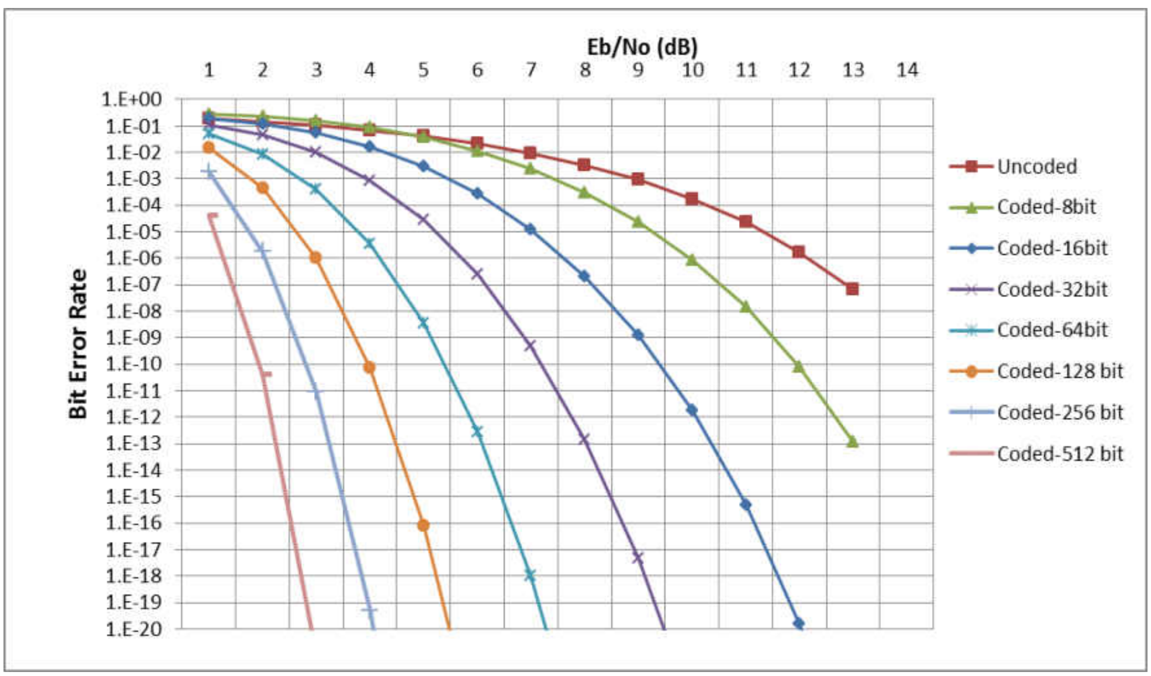

Figure: 5.11 BER performances for 8/16/32/64/128/256/512 bit bi-orthogonal code- zoomed view.

The Eb/No value gives the signal to noise ratio (SNR) in the medium and the vertical axis shows the probability of error occurrence with respect to the SNR. From the Figures 5.9 and 5.10 above it is quite visible that for higher length of code the probability of error goes significantly lower. Also the uncoded data shows most poor performance in this regard that evidently supports the need of coded data. There has been use of conventional block coding for error correction. The bit error rate analysis for regular block codes is shown in the Figure 5.11

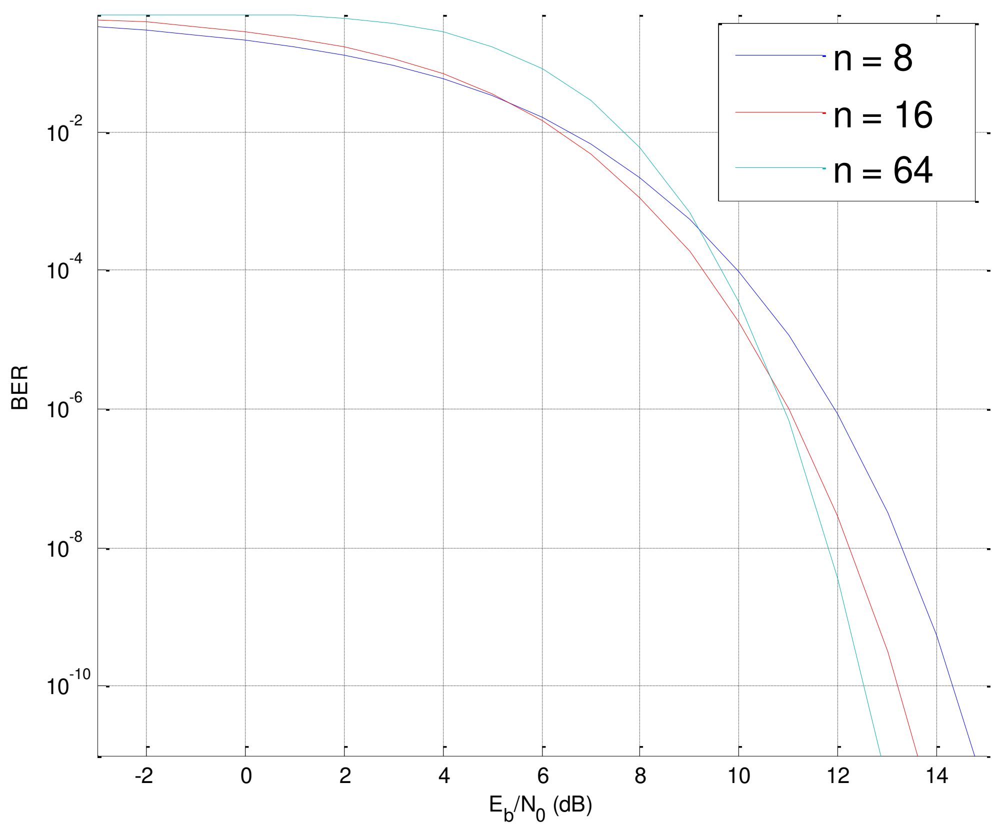

Figure: 5.12 BER Performance for regular block Codes.

If we compare the performance analysis of regular block coding and the bi-orthogonal coding scheme, it is proven that the proposed error correction technique offers much higher error control capability than the conventional ones. Also longer code length offers higher coding gain which allows choosing the suitable block size for coding in a certain channel.

Code rate performance of Orthogonal and Bi-orthogonal coding: Orthogonal coding has been used in Code Divisional Multiple Access (CDMA) communication as an error control coding. But using a set of bi-orthogonal matrix for error control is a new idea for laser communication. As mentioned earlier, every block of orthogonal codes has a set of antipodal codes and antipodal codes are orthogonal amongst themselves as well. These two sets of blocks combined, forms the bi orthogonal code matrix and the following analysis shows the difference in the code rate of orthogonal and bi-orthogonal coding. For orthogonal codes, the coding rate r is given by

$$r = \frac{n}{2^n} \qquad (5.4)$$

For bi-orthogonal codes, the coding rate r is given by

$$r' = \frac{n+1}{2^n} \qquad (5.5)$$

Combining the two Equations (5.4) and (5.5) above, we can calculate the percentage of increment in coding rate. That shows

$$percent\ increase = \frac{r'-r}{r} \times 100 \qquad (5.6)$$

It is obvious that using bi-orthogonal code will give the option to encode twice the number of data combinations. For an example, if n = 3, length of orthogonal code length has to be 8, whereas length of bi-orthogonal code will only be 4. For n = 4, orthogonal and bi-orthogonal code lengths are 16 and 8 respectively. So, the increment in code rate remains same for the same value of n. The Table 5.10 shows more examples of it.

But the change in bi orthogonal code rate with respect to the increment of bit number and consequently larger code length is more of an interesting phenomenon.

Table: 5.10 Change in code rate calculation

Number of bits ‘n’	Orthogonal code length	Bi-orthogonal code length	Orthogonal code rate	Bi-orthogonal code rate	Increase in code rate	Bi-orthogonal code rate increment compared to orthogonal coding
3	8	4	0.3750	0.7500	50.00%	33.333%
4	16	8	0.2500	0.5000	50.00%	25.000%
5	32	16	0.1563	0.3125	50.00%	20.000%
6	64	32	0.0938	0.1875	50.00%	16.667%
7	128	64	0.0547	0.1094	50.00%	14.286%
8	256	128	0.0313	0.0625	50.00%	12.500%
9	512	256	0.0176	0.0352	50.00%	11.111%
10	1024	512	0.0098	0.0195	50.00%	10.000%
11	2048	1024	0.0054	0.0107	50.00%	9.091%
12	4096	2048	0.0029	0.0059	50.00%	8.333%
13	8192	4096	0.0016	0.0032	50.00%	7.692%
14	16384	8192	0.0009	0.0017	50.00%	7.143%
15	32768	16384	0.0005	0.0009	50.00%	6.667%

Due to different values of n, different code length is required. Different code lengths exert different code rates. Above from the Table 5.10, we can see how the code rate changes between orthogonal and bi-orthogonal coding while value of n is varied.

From the numbers, we can see that the decrement in the percentage of code rate follows a nonlinear pattern. Higher code rate is always desired for more efficient data transmission while using error control coding. And we can see for all the cases, bi-orthogonal code rate is higher than the orthogonal coding which is an advantage over the existing scheme. For higher values of n- which also indicates longer bi orthogonal code, the change in code rate decreases gradually. The change is plotted in the Figure 5.12 below. The plot shows the code rate performance of bi orthogonal mapping for different code lengths.

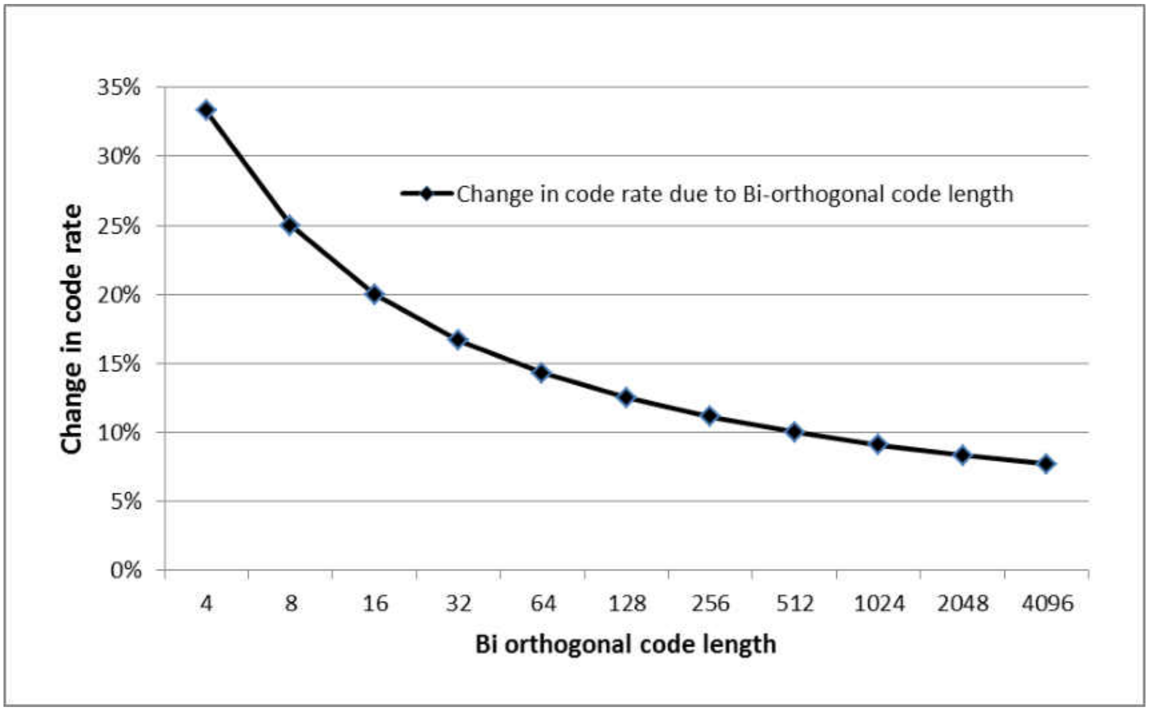

Figure: 5.13 Change in code rate for different code lengths of bi-orthogonal mapping

From the Figure 5.12 we can see that if the code length becomes 512 or longer, the difference between orthogonal and bi orthogonal code rate becomes smaller and smaller. This describes the difference between them in longer codes and helps to choose the length of the code accordingly.

Point of diminishing return: Another parameter to choose the correct length of coding depends on the performance or error correction in different code lengths. The error correction capability increases with the length of the code but this increment is not linear either. To see the changes in error correction performance the following Table 5.11 is populated using the Equation 5.1 for n = 2 to 15.

Table 5.11 Percentage of error correction with respect to code length

Number of bits 'n'	Code length	Number of errors corrected	Percentage of error corrected
2	4	0	0.000%
3	8	1	12.500%
4	16	3	18.750%
5	32	7	21.875%
6	64	15	23.438%
7	128	31	24.219%
8	256	63	24.609%
9	512	127	24.805%
10	1024	255	24.902%
11	2048	511	24.951%
12	4096	1023	24.976%
13	8192	2047	24.988%
14	16384	4095	24.994%
15	32768	8191	24.997%

The error correction for different code lengths is plotted below in the Figure 5.13

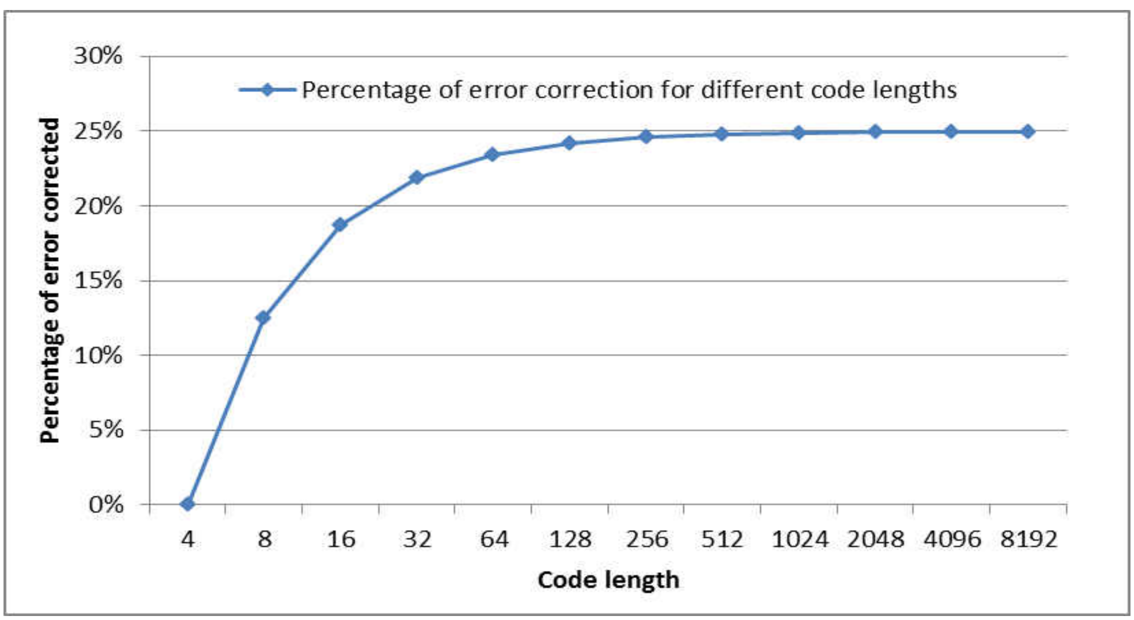

Figure: 5.14 Percentage of error correction with respect to code length

From the Figure 5.13, we can see the error correction capability almost saturates after 256 bit code length. Longer code than 256 bit offers error correction towards 25% but at the cost of a much higher bit rate. To find out more efficient error correction in terms of code length we can check the length varying from 8 to 128 bit. This part of the plot shows error correction ranging from 12.5% to 24.22%. Looking at the pattern of the plot we can tell the most efficient error control coding considering the code length can be expected from 16, 32 or 64 bit coding. Depending on the channel characteristics and application, a suitable mapping option can be obtained from the above mentioned analysis.

Considering the bit error rate performance, coding gain, code rate and option for bandwidth optimization, the Orthogonal On-Off Keying shows very high potential in laser communication and promising error control performance in practice. In addition, this coding scheme can also be applied to other modulation technique.

CHAPTER 6

FUTURE WORK AND CONCLUSION

LASER communication is an alternative solution over RF communication for long-haul connectivity and security. And Orthogonal On-Off Keying can be a complementary error control coding scheme to that approach. The higher error correction capability, self-synchronization property, lower implementation cost, easy maintenance and other characteristics make it a promising alternative in the future of communication systems. However, there are many challenges on the way before it can be applied and be available for mass use. This requires further research and development and leaves a lot of room for future works.

In this thesis, the direct modulation of laser using orthogonal codes has been investigated. The sub carrier modulation and other modulation techniques can be applied and may provide even greater bandwidth efficiency. Analog modulations like amplitude modulation (AM), frequency modulation (FM) or pulse modulation (PM) and digital modulations like Frequency Shift Keying (FSK), Phase Shift Keying (PSK) or Pulse Position Modulation (PPM) can be lucrative topics of research.

In the current experiment the upper limit of the frequency to check the response was limited. To extend this to higher frequencies and study the response some hardware modification will help. Use of a Data Acquisition System like Signatec or Pico

Technology product for data acquisition may help to capture higher frequency receiving signal. Switching to high speed LASER product and PIN diode for detection will increase the bandwidth. Also, the Universal Serial Bus (USB) port instead of the audio interface can be used here and in that case the port itself can detect high speed signals. As for an example if a USB 3.0 is used, it can respond up to 5 gigabits per second and will give acceptance of a lot higher frequency range. USB 2.0 interface is fairly low compared to that and has the limit of going up to 480 megabits per second but that can be used too for experiments in that range [**28**]. The program will need to include configuration of USB port in this regard to perform the tasks.

For detection of LASER the bright ambient light in day time can be a challenge for good reception. There needs to be a reliable means of receiver for detection in all conditions. Differential receiver can be a potential solution which needs further research and development.

Successful communication using laser depends largely on proper alignment of the beam towards the photodetector. Manual adjustment may not be a well suited option for long distance coverage and development to an automated alignment system is demanding. A retro reflector alignment system can be considered for future development in this regard.

The prospect of laser based communication system is very high and with secured high speed data transfer ability, it has already proved its potential. Any line of sight communication ranging from air to air, ground to ground, air to ground, space to ground, deep space communication or even for underwater communication, this is a promising solution. With proper development and implementation of error controlling capacity like orthogonal coding and combining with different modulation techniques it can provide higher speed data access to mass user.

APPENDICES

Appendix A

Appendix A contains the steps of the experiment.

Preparation of the transmitter

- Connect a stereo jack to the audio output port of the transmitter computer
- Connect the left or right channel output to the amplifier input
- Connect the amplifier output to the laser control input
- All the grounds to be connected
- Open MATLAB® in the computer
- Run the file final_t8/16/32/64 for 8/16/32 or 64 bit mapping respectively
- Use the parameters "inputdata" for input file, "f" for frequency, "err" for number of errors to be introduced and "eml" to define the window of bits to choose 'err' from
- Running the file will create a wav file named Tx.wav in the same folder
- Playing the wav file will send the bits out to the laser to drive

Preparation of the receiver

- Connect photodiode to the left channel of 'Line in' audio port of the receiver computer
- Select the 'Line in' as the recording option in Audacity and start recording

Experiment

- Play the Tx.wav file. It will modulate the laser and the response will be recorded by Audacity software in the receiver computer. Save the recorded file in wav format.
- Run final_r8/16/32/64 (same as transmitted one) to check the received file.

Appendix B

Appendix A contains the MATLAB® code for 8bit data mapping of a binary input file with the choice of number of errors to introduce and bit rate. This also converts the mapped data into a file.

```
function out_t = final_t8(inputdata,f,err,eml)

i=1;
j=1;

for i=1:4:length(inputdata)

    if (inputdata(i:i+3) == [0 0 0 0])
        out(j:j+7) = [0 0 0 0 0 0 0 0];

    elseif(inputdata(i:i+3) == [0 0 0 1])
        out(j:j+7) = [0 1 0 1 0 1 0 1];

    elseif(inputdata(i:i+3) == [0 0 1 0])
      out(j:j+7) = [0 0 1 1 0 0 1 1];

    elseif(inputdata(i:i+3) == [0 0 1 1])
      out(j:j+7) = [0 1 1 0 0 1 1 0];

    elseif(inputdata(i:i+3) == [0 1 0 0])
      out(j:j+7) = [0 0 0 0 1 1 1 1];

    elseif(inputdata(i:i+3) == [0 1 0 1])
      out(j:j+7) = [0 1 0 1 1 0 1 0];

    elseif(inputdata(i:i+3) == [0 1 1 0])
      out(j:j+7) = [0 0 1 1 1 1 0 0];

    elseif(inputdata(i:i+3) == [0 1 1 1])
      out(j:j+7) = [0 1 1 0 1 0 0 1];

    elseif(inputdata(i:i+3) == [1 0 0 0])
      out(j:j+7) = [1 1 1 1 1 1 1 1];

    elseif(inputdata(i:i+3) == [1 0 0 1])
      out(j:j+7) = [1 0 1 0 1 0 1 0];

    elseif(inputdata(i:i+3) == [1 0 1 0])
     out(j:j+7) = [1 1 0 0 1 1 0 0];

    elseif(inputdata(i:i+3) == [1 0 1 1])
      out(j:j+7) = [1 0 0 1 1 0 0 1];
```

```
    elseif(inputdata(i:i+3) == [1 1 0 0])
      out(j:j+7) = [1 1 1 1 0 0 0 0];

    elseif(inputdata(i:i+3) == [1 1 0 1])
      out(j:j+7) = [1 0 1 0 0 1 0 1];

    elseif(inputdata(i:i+3) == [1 1 1 0])
      out(j:j+7) = [1 1 0 0 0 0 1 1];

    else
      out(j:j+7) = [1 0 0 1 0 1 1 0];
    end

    j=j+8;

end

out1=out;
out = error_calc(out1,err,eml);

e = [0 0 0 1 0 1 0 1 0 1 0 1 0 0 0 0];
s = [1 1 1 0 1 0 1 0 1 0 1 0 1 1 1 1];
out = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 s out e e e e];

i=1;
t=0;
j=1;
for i=1:1:length(out)
    for t=(0+2/f):2/f:1
        out_t(j)=out(i)*1;
            j=j+1;
    end

end
out_t = out_t*1;
wavwrite(out_t,44100,16,'Tx');

end
```

Appendix C

Appendix B contains the MATLAB® code for 16 bit data mapping of a binary input file with the choice of number of errors to introduce and bit rate. This also converts the mapped data into a file.

```
function out_t = final_t16(inputdata,f,err,eml)

i=1;
j=1;

for i=1:5:length(inputdata)

    if (inputdata(i:i+4) == [0 0 0 0 0])
        out(j:j+15) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0];

    elseif(inputdata(i:i+4) == [0 0 0 0 1])
        out(j:j+15) = [0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1];

    elseif(inputdata(i:i+4) == [0 0 0 1 0])
      out(j:j+15) = [0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1];

    elseif(inputdata(i:i+4) == [0 0 0 1 1])
      out(j:j+15) = [0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0];

    elseif(inputdata(i:i+4) == [0 0 1 0 0])
      out(j:j+15) = [0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1];

    elseif(inputdata(i:i+4) == [0 0 1 0 1])
      out(j:j+15) = [0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0];

    elseif(inputdata(i:i+4) == [0 0 1 1 0])
      out(j:j+15) = [0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0];

    elseif(inputdata(i:i+4) == [0 0 1 1 1])
      out(j:j+15) = [0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1];



    elseif(inputdata(i:i+4) == [0 1 0 0 0])
      out(j:j+15) = [0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1];

    elseif(inputdata(i:i+4) == [0 1 0 0 1])
      out(j:j+15) = [0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0];

    elseif(inputdata(i:i+4) == [0 1 0 1 0])
     out(j:j+15) = [0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0];
```

```
elseif(inputdata(i:i+4) == [0 1 0 1 1])
  out(j:j+15) = [0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1];

elseif(inputdata(i:i+4) == [0 1 1 0 0])
  out(j:j+15) = [0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0];

elseif(inputdata(i:i+4) == [0 1 1 0 1])
  out(j:j+15) = [0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1];

elseif(inputdata(i:i+4) == [0 1 1 1 0])
  out(j:j+15) = [0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1];

elseif(inputdata(i:i+4) == [0 1 1 1 1])
  out(j:j+15) = [0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0];



elseif (inputdata(i:i+4) == [1 0 0 0 0])
    out(j:j+15) = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1];

elseif(inputdata(i:i+4) == [1 0 0 0 1])
    out(j:j+15) = [1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0];

elseif(inputdata(i:i+4) == [1 0 0 1 0])
  out(j:j+15) = [1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0];

elseif(inputdata(i:i+4) == [1 0 0 1 1])
  out(j:j+15) = [1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1];

elseif(inputdata(i:i+4) == [1 0 1 0 0])
  out(j:j+15) = [1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0];

elseif(inputdata(i:i+4) == [1 0 1 0 1])
  out(j:j+15) = [1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1];

elseif(inputdata(i:i+4) == [1 0 1 1 0])
  out(j:j+15) = [1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1];

elseif(inputdata(i:i+4) == [1 0 1 1 1])
  out(j:j+15) = [1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0];



elseif(inputdata(i:i+4) == [1 1 0 0 0])
  out(j:j+15) = [1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0];

elseif(inputdata(i:i+4) == [1 1 0 0 1])
  out(j:j+15) = [1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1];

elseif(inputdata(i:i+4) == [1 1 0 1 0])
 out(j:j+15) = [1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1];
```

```
    elseif(inputdata(i:i+4) == [1 1 0 1 1])
      out(j:j+15) = [1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0];

    elseif(inputdata(i:i+4) == [1 1 1 0 0])
      out(j:j+15) = [1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1];

    elseif(inputdata(i:i+4) == [1 1 1 0 1])
      out(j:j+15) = [1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0];

    elseif(inputdata(i:i+4) == [1 1 1 1 0])
      out(j:j+15) = [1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0];

   elseif(inputdata(i:i+4) == [1 1 1 1 1])
      out(j:j+15) = [1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1];
    else

    end

    j=j+16;

end

out1=out;
out = error_calc(out1,err,eml);

e = [0 0 0 1 0 1 0 1 0 1 0 1 0 0 0 0];
s = [1 1 1 0 1 0 1 0 1 0 1 0 1 1 1 1];
out = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 s out e e e e];

i=1;
t=0;
j=1;
for i=1:1:length(out)
    for t=(0+2/f):2/f:1
        out_t(j)=out(i)*1;
            j=j+1;
    end

end
out_t = out_t*1;
wavwrite(out_t,44100,16,'Tx');

end
```

Appendix D

Appendix C contains the MATLAB® code for 32 bit data mapping of a binary input file with the choice of number of errors to introduce and bit rate. This also converts the mapped data into a file.

```
function out_t = final_t32(inputdata,f,err,eml)

i=1;
j=1;

for i=1:6:length(inputdata)

    if (inputdata(i:i+5) == [0 0 0 0 0 0])
        out(j:j+31) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0];

    elseif(inputdata(i:i+5) == [0 0 0 0 0 1])
        out(j:j+31) = [0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1];

    elseif(inputdata(i:i+5) == [0 0 0 0 1 0])
      out(j:j+31) = [0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1];

    elseif(inputdata(i:i+5) == [0 0 0 0 1 1])
      out(j:j+31) = [0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0];

    elseif(inputdata(i:i+5) == [0 0 0 1 0 0])
      out(j:j+31) = [0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1];

    elseif(inputdata(i:i+5) == [0 0 0 1 0 1])
      out(j:j+31) = [0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0];

    elseif(inputdata(i:i+5) == [0 0 0 1 1 0])
      out(j:j+31) = [0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0];

    elseif(inputdata(i:i+5) == [0 0 0 1 1 1])
      out(j:j+31) = [0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1];



    elseif(inputdata(i:i+5) == [0 0 1 0 0 0])
      out(j:j+31) = [0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1];

    elseif(inputdata(i:i+5) == [0 0 1 0 0 1])
      out(j:j+31) = [0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0];

    elseif(inputdata(i:i+5) == [0 0 1 0 1 0])
     out(j:j+31) = [0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0];

    elseif(inputdata(i:i+5) == [0 0 1 0 1 1])
      out(j:j+31) = [0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1];

    elseif(inputdata(i:i+5) == [0 0 1 1 0 0])
      out(j:j+31) = [0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0];

    elseif(inputdata(i:i+5) == [0 0 1 1 0 1])
      out(j:j+31) = [0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1];

    elseif(inputdata(i:i+5) == [0 0 1 1 1 0])
      out(j:j+31) = [0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1];

    elseif(inputdata(i:i+5) == [0 0 1 1 1 1])
      out(j:j+31) = [0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0];
```

```
elseif (inputdata(i:i+5) == [0 1 0 0 0 0])
    out(j:j+31) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1];

elseif(inputdata(i:i+5) == [0 1 0 0 0 1])
    out(j:j+31) = [0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0];

elseif(inputdata(i:i+5) == [0 1 0 0 1 0])
  out(j:j+31) = [0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0];

elseif(inputdata(i:i+5) == [0 1 0 0 1 1])
  out(j:j+31) = [0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1];

elseif(inputdata(i:i+5) == [0 1 0 1 0 0])
  out(j:j+31) = [0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0];

elseif(inputdata(i:i+5) == [0 1 0 1 0 1])
  out(j:j+31) = [0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1];

elseif(inputdata(i:i+5) == [0 1 0 1 1 0])
  out(j:j+31) = [0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1];

elseif(inputdata(i:i+5) == [0 1 0 1 1 1])
  out(j:j+31) = [0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0];


elseif(inputdata(i:i+5) == [0 1 1 0 0 0])
  out(j:j+31) = [0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0];

elseif(inputdata(i:i+5) == [0 1 1 0 0 1])
  out(j:j+31) = [0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1];

elseif(inputdata(i:i+5) == [0 1 1 0 1 0])
 out(j:j+31) = [0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1];

elseif(inputdata(i:i+5) == [0 1 1 0 1 1])
  out(j:j+31) = [0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0];

elseif(inputdata(i:i+5) == [0 1 1 1 0 0])
  out(j:j+31) = [0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1];

elseif(inputdata(i:i+5) == [0 1 1 1 0 1])
  out(j:j+31) = [0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0];

elseif(inputdata(i:i+5) == [0 1 1 1 1 0])
  out(j:j+31) = [0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0];

elseif(inputdata(i:i+5) == [0 1 1 1 1 1])
  out(j:j+31) = [0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1];


elseif (inputdata(i:i+5) == [1 0 0 0 0 0])
    out(j:j+31) = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1];

elseif(inputdata(i:i+5) == [1 0 0 0 0 1])
    out(j:j+31) = [1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0];

elseif(inputdata(i:i+5) == [1 0 0 0 1 0])
  out(j:j+31) = [1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0];

elseif(inputdata(i:i+5) == [1 0 0 0 1 1])
  out(j:j+31) = [1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1];

elseif(inputdata(i:i+5) == [1 0 0 1 0 0])
  out(j:j+31) = [1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0];
```

```
elseif(inputdata(i:i+5) == [1 0 0 1 0 1])
  out(j:j+31) = [1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1];

elseif(inputdata(i:i+5) == [1 0 0 1 1 0])
  out(j:j+31) = [1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1];

elseif(inputdata(i:i+5) == [1 0 0 1 1 1])
  out(j:j+31) = [1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0];



elseif(inputdata(i:i+5) == [1 0 1 0 0 0])
  out(j:j+31) = [1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0];

elseif(inputdata(i:i+5) == [1 0 1 0 0 1])
  out(j:j+31) = [1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1];

elseif(inputdata(i:i+5) == [1 0 1 0 1 0])
 out(j:j+31) = [1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1];

elseif(inputdata(i:i+5) == [1 0 1 0 1 1])
  out(j:j+31) = [1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0];

elseif(inputdata(i:i+5) == [1 0 1 1 0 0])
  out(j:j+31) = [1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1];

elseif(inputdata(i:i+5) == [1 0 1 1 0 1])
  out(j:j+31) = [1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0];

elseif(inputdata(i:i+5) == [1 0 1 1 1 0])
  out(j:j+31) = [1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0];

elseif(inputdata(i:i+5) == [1 0 1 1 1 1])
  out(j:j+31) = [1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1];



elseif (inputdata(i:i+5) == [1 1 0 0 0 0])
    out(j:j+31) = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0];

elseif(inputdata(i:i+5) == [1 1 0 0 0 1])
    out(j:j+31) = [1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1];

elseif(inputdata(i:i+5) == [1 1 0 0 1 0])
  out(j:j+31) = [1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1];

elseif(inputdata(i:i+5) == [1 1 0 0 1 1])
  out(j:j+31) = [1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0];

elseif(inputdata(i:i+5) == [1 1 0 1 0 0])
  out(j:j+31) = [1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1];

elseif(inputdata(i:i+5) == [1 1 0 1 0 1])
  out(j:j+31) = [1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0];

elseif(inputdata(i:i+5) == [1 1 0 1 1 0])
  out(j:j+31) = [1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0];

elseif(inputdata(i:i+5) == [1 1 0 1 1 1])
  out(j:j+31) = [1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1];



elseif(inputdata(i:i+5) == [1 1 1 0 0 0])
  out(j:j+31) = [1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1];

elseif(inputdata(i:i+5) == [1 1 1 0 0 1])
  out(j:j+31) = [1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0];

elseif(inputdata(i:i+5) == [1 1 1 0 1 0])
```

```
     out(j:j+31) = [1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0];

    elseif(inputdata(i:i+5) == [1 1 1 0 1 1])
      out(j:j+31) = [1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1];

    elseif(inputdata(i:i+5) == [1 1 1 1 0 0])
      out(j:j+31) = [1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0];

    elseif(inputdata(i:i+5) == [1 1 1 1 0 1])
      out(j:j+31) = [1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1];

    elseif(inputdata(i:i+5) == [1 1 1 1 1 0])
      out(j:j+31) = [1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1];

   elseif(inputdata(i:i+5) == [1 1 1 1 1 1])
      out(j:j+31) = [1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0];
    else

    end

    j=j+32;

end

out1=out;
out = error_calc(out1,err,eml);

e = [0 0 0 1 0 1 0 1 0 1 0 1 0 0 0 0];
s = [1 1 1 0 1 0 1 0 1 0 1 0 1 1 1 1];
out = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 s out e e e e];

i=1;
t=0;
j=1;
for i=1:1:length(out)
    for t=(0+2/f):2/f:1
        out_t(j)=out(i)*1;
            j=j+1;
    end

end
out_t = out_t*1;
wavwrite(out_t,44100,16,'Tx');

end
```

Appendix E

Appendix D contains the MATLAB® code for error correction and data recovery of 8 bit orthogonally mapped data.

```
function [out_r,c] = final_r8(data,f)

fs = 44100;
i=1;
j=1;
total_err = 0;
remainder=rem(length(data),(f/2));
th = .3;%(max(data)+min(data))/2;
out_r = 0;
for i=1:f/2:(length(data) - remainder)

    if ((data(i))>th)
       out_t(j) = 1;
       j=j+1;
   else
       out_t(j) = 0;
       j=j+1;
    end

end

i=1;
for i=1:1:length(out_t)
    if (out_t(i:i+15) == [1 1 1 0 1 0 1 0 1 0 1 0 1 1 1 1])
        start=i+16;
        break;
    end
end

for i=1:1:length(out_t)
    if (out_t(i:i+15) == [0 0 0 1 0 1 0 1 0 1 0 1 0 0 0 0])
        finish=i-1;
        break;
    end
end

i=1;
j=1;

for j=start:8:finish

        a(1) = sum(xor(out_t(j:j+7),[0 0 0 0 0 0 0 0]));
        a(2) = sum(xor(out_t(j:j+7),[0 1 0 1 0 1 0 1]));
        a(3) = sum(xor(out_t(j:j+7),[0 0 1 1 0 0 1 1]));
        a(4) = sum(xor(out_t(j:j+7),[0 1 1 0 0 1 1 0]));
```

```
        a(5) = sum(xor(out_t(j:j+7),[0 0 0 0 1 1 1 1]));
        a(6) = sum(xor(out_t(j:j+7),[0 1 0 1 1 0 1 0]));
        a(7) = sum(xor(out_t(j:j+7),[0 0 1 1 1 1 0 0]));
        a(8) = sum(xor(out_t(j:j+7),[0 1 1 0 1 0 0 1]));
        a(9) = sum(xor(out_t(j:j+7),[1 1 1 1 1 1 1 1]));
        a(10) = sum(xor(out_t(j:j+7),[1 0 1 0 1 0 1 0]));
        a(11) = sum(xor(out_t(j:j+7),[1 1 0 0 1 1 0 0]));
        a(12) = sum(xor(out_t(j:j+7),[1 0 0 1 1 0 0 1]));
        a(13) = sum(xor(out_t(j:j+7),[1 1 1 1 0 0 0 0]));
        a(14) = sum(xor(out_t(j:j+7),[1 0 1 0 0 1 0 1]));
        a(15) = sum(xor(out_t(j:j+7),[1 1 0 0 0 0 1 1]));
        a(16) = sum(xor(out_t(j:j+7),[1 0 0 1 0 1 1 0]));

        c = min(a);
        t=0;
        for k=1:1:16
            if(c==a(k))
                t=t+1;
            end
        end
        if(t>=2)
            fprintf('Error not corrected because of more than one match
in map table. ');
            break
        end

        if (c<4)
            if (c ~= 0)
                total_err=total_err+c;
            end

        if (c == a(1))
            out_r(i:i+3) = [0 0 0 0];
        elseif(c == a(2))
            out_r(i:i+3) = [0 0 0 1];
        elseif(c == a(3))
            out_r(i:i+3) = [0 0 1 0];
        elseif(c == a(4))
            out_r(i:i+3) = [0 0 1 1];
        elseif(c == a(5))
            out_r(i:i+3) = [0 1 0 0];
        elseif(c == a(6))
            out_r(i:i+3) = [0 1 0 1];
        elseif(c == a(7))
            out_r(i:i+3) = [0 1 1 0];
        elseif(c == a(8))
            out_r(i:i+3) = [0 1 1 1];
        elseif(c == a(9))
            out_r(i:i+3) = [1 0 0 0];
        elseif(c == a(10))
            out_r(i:i+3) = [1 0 0 1];
        elseif(c == a(11))
            out_r(i:i+3) = [1 0 1 0];
        elseif(c == a(12))
            out_r(i:i+3) = [1 0 1 1];
        elseif(c == a(13))
```

```
            out_r(i:i+3) = [1 1 0 0];
        elseif(c == a(14))
            out_r(i:i+3) = [1 1 0 1];
        elseif(c == a(15))
            out_r(i:i+3) = [1 1 1 0];
        elseif(c == a(16))
            out_r(i:i+3) = [1 1 1 1];
        else

        end
        else
            fprintf('Irrecoverable number of errors occured. Number of
mismatch = %f',c);
    end

    i=i+4;
end


end
```

Appendix F

Appendix E contains the MATLAB® code for error correction and data recovery of 16 bit orthogonally mapped data.

```
function [out_r,c,j] = final_r16(data,f)

fs = 44100;
i=1;
j=1;
total_err = 0;
remainder=rem(length(data),(f/2));
th = 0.5;%(max(data)+min(data))/2;
out_r = 0;

for i=(round(f/(2*2))):f/2:(length(data) - remainder)

    if ((data(i))>th)
       out_t(j) = 1;
       j=j+1;
   else
       out_t(j) = 0;
       j=j+1;
    end

end




for i=1:1:length(out_t)
    if (out_t(i:i+15) == [1 1 1 0 1 0 1 0 1 0 1 0 1 1 1 1])
        start=i+16;
        break;
    end
end

for i=1:1:length(out_t)
    if (out_t(i:i+15) == [0 0 0 1 0 1 0 1 0 1 0 1 0 0 0 0])
        finish=i-1;
        break;
    end
end

i=1;
j=1;

for j=start:16:finish
```

```
        a(1) = sum(xor(out_t(j:j+15),[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0]));
        a(2) = sum(xor(out_t(j:j+15),[0 1 0 1 0 1 0 1 0 1 0 1 0 1 0
1]));
        a(3) = sum(xor(out_t(j:j+15),[0 0 1 1 0 0 1 1 0 0 1 1 0 0 1
1]));
        a(4) = sum(xor(out_t(j:j+15),[0 1 1 0 0 1 1 0 0 1 1 0 0 1 1
0]));
        a(5) = sum(xor(out_t(j:j+15),[0 0 0 0 1 1 1 1 0 0 0 0 1 1 1
1]));
        a(6) = sum(xor(out_t(j:j+15),[0 1 0 1 1 0 1 0 0 1 0 1 1 0 1
0]));
        a(7) = sum(xor(out_t(j:j+15),[0 0 1 1 1 1 0 0 0 0 1 1 1 1 0
0]));
        a(8) = sum(xor(out_t(j:j+15),[0 1 1 0 1 0 0 1 0 1 1 0 1 0 0
1]));

        a(9) = sum(xor(out_t(j:j+15),[0 0 0 0 0 0 0 0 1 1 1 1 1 1 1
1]));
        a(10) = sum(xor(out_t(j:j+15),[0 1 0 1 0 1 0 1 1 0 1 0 1 0 1
0]));
        a(11) = sum(xor(out_t(j:j+15),[0 0 1 1 0 0 1 1 1 1 0 0 1 1 0
0]));
        a(12) = sum(xor(out_t(j:j+15),[0 1 1 0 0 1 1 0 1 0 0 1 1 0 0
1]));
        a(13) = sum(xor(out_t(j:j+15),[0 0 0 0 1 1 1 1 1 1 1 1 0 0 0
0]));
        a(14) = sum(xor(out_t(j:j+15),[0 1 0 1 1 0 1 0 1 0 1 0 0 1 0
1]));
        a(15) = sum(xor(out_t(j:j+15),[0 0 1 1 1 1 0 0 1 1 0 0 0 0 1
1]));
        a(16) = sum(xor(out_t(j:j+15),[0 1 1 0 1 0 0 1 1 0 0 1 0 1 1
0]));

        a(17) = sum(xor(out_t(j:j+15),[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1]));
        a(18) = sum(xor(out_t(j:j+15),[1 0 1 0 1 0 1 0 1 0 1 0 1 0 1
0]));
        a(19) = sum(xor(out_t(j:j+15),[1 1 0 0 1 1 0 0 1 1 0 0 1 1 0
0]));
        a(20) = sum(xor(out_t(j:j+15),[1 0 0 1 1 0 0 1 1 0 0 1 1 0 0
1]));
        a(21) = sum(xor(out_t(j:j+15),[1 1 1 1 0 0 0 0 1 1 1 1 0 0 0
0]));
        a(22) = sum(xor(out_t(j:j+15),[1 0 1 0 0 1 0 1 1 0 1 0 0 1 0
1]));
        a(23) = sum(xor(out_t(j:j+15),[1 1 0 0 0 0 1 1 1 1 0 0 0 0 1
1]));
        a(24) = sum(xor(out_t(j:j+15),[1 0 0 1 0 1 1 0 1 0 0 1 0 1 1
0]));

        a(25) = sum(xor(out_t(j:j+15),[1 1 1 1 1 1 1 1 0 0 0 0 0 0 0
0]));
        a(26) = sum(xor(out_t(j:j+15),[1 0 1 0 1 0 1 0 0 1 0 1 0 1 0
1]));
```

```
        a(27) = sum(xor(out_t(j:j+15),[1 1 0 0 1 1 0 0 0 0 1 1 0 0 1
1]));
        a(28) = sum(xor(out_t(j:j+15),[1 0 0 1 1 0 0 1 0 1 1 0 0 1 1
0]));
        a(29) = sum(xor(out_t(j:j+15),[1 1 1 1 0 0 0 0 0 0 0 0 1 1 1
1]));
        a(30) = sum(xor(out_t(j:j+15),[1 0 1 0 0 1 0 1 0 1 0 1 1 0 1
0]));
        a(31) = sum(xor(out_t(j:j+15),[1 1 0 0 0 0 1 1 0 0 1 1 1 1 0
0]));
        a(32) = sum(xor(out_t(j:j+15),[1 0 0 1 0 1 1 0 0 1 1 0 1 0 0
1]));

        c = min(a);
        t=0;
        for k=1:1:32
            if(c==a(k))
                t=t+1;
            end
        end
        if(t>=4)
            fprintf('Error not corrected because of more than one match
in map table. ');
            break
        end

        if (c<4)
            if (c ~= 0)
                total_err=total_err+c;
            end

        if (c == a(1))
            out_r(i:i+4) = [0 0 0 0 0];
        elseif(c == a(2))
            out_r(i:i+4) = [0 0 0 0 1];
        elseif(c == a(3))
            out_r(i:i+4) = [0 0 0 1 0];
        elseif(c == a(4))
            out_r(i:i+4) = [0 0 0 1 1];
        elseif(c == a(5))
            out_r(i:i+4) = [0 0 1 0 0];
        elseif(c == a(6))
            out_r(i:i+4) = [0 0 1 0 1];
        elseif(c == a(7))
            out_r(i:i+4) = [0 0 1 1 0];
        elseif(c == a(8))
            out_r(i:i+4) = [0 0 1 1 1];
        elseif(c == a(9))
            out_r(i:i+4) = [0 1 0 0 0];
        elseif(c == a(10))
            out_r(i:i+4) = [0 1 0 0 1];
        elseif(c == a(11))
            out_r(i:i+4) = [0 1 0 1 0];
        elseif(c == a(12))
            out_r(i:i+4) = [0 1 0 1 1];
        elseif(c == a(13))
```

```
            out_r(i:i+4) = [0 1 1 0 0];
        elseif(c == a(14))
            out_r(i:i+4) = [0 1 1 0 1];
        elseif(c == a(15))
            out_r(i:i+4) = [0 1 1 1 0];
        elseif(c == a(16))
            out_r(i:i+4) = [0 1 1 1 1];

        elseif (c == a(17))
            out_r(i:i+4) = [1 0 0 0 0];
        elseif(c == a(18))
            out_r(i:i+4) = [1 0 0 0 1];
        elseif(c == a(19))
            out_r(i:i+4) = [1 0 0 1 0];
        elseif(c == a(20))
            out_r(i:i+4) = [1 0 0 1 1];
        elseif(c == a(21))
            out_r(i:i+4) = [1 0 1 0 0];
        elseif(c == a(22))
            out_r(i:i+4) = [1 0 1 0 1];
        elseif(c == a(23))
            out_r(i:i+4) = [1 0 1 1 0];
        elseif(c == a(24))
            out_r(i:i+4) = [1 0 1 1 1];
        elseif(c == a(25))
            out_r(i:i+4) = [1 1 0 0 0];
        elseif(c == a(26))
            out_r(i:i+4) = [1 1 0 0 1];
        elseif(c == a(27))
            out_r(i:i+4) = [1 1 0 1 0];
        elseif(c == a(28))
            out_r(i:i+4) = [1 1 0 1 1];
        elseif(c == a(29))
            out_r(i:i+4) = [1 1 1 0 0];
        elseif(c == a(30))
            out_r(i:i+4) = [1 1 1 0 1];
        elseif(c == a(31))
            out_r(i:i+4) = [1 1 1 1 0];
        elseif(c == a(32))
            out_r(i:i+4) = [1 1 1 1 1];

        end
        else
            fprintf('Irrecoverable number of errors occured. Number of
mismatch = %f',c);
    end

    i=i+5;
end


end
```

Appendix G

Appendix F contains the MATLAB® code for error correction and data recovery of 32 bit orthogonally mapped data.

```
function [out_r,c,j] = final_r32(data,f)

fs = 44100;
i=1;
j=1;
total_err = 0;
remainder=rem(length(data),(f/2));
th = (max(data)+min(data))/2;
out_r = 0;

for i=1:f/2:(length(data) - remainder)

    if ((data(i))>th)
       out_t(j) = 1;
       j=j+1;
   else
       out_t(j) = 0;
       j=j+1;
    end

end



for i=1:1:length(out_t)
    if (out_t(i:i+15) == [1 1 1 0 1 0 1 0 1 0 1 0 1 1 1 1])
        start=i+16;
        break;
    end
end

for i=1:1:length(out_t)
    if (out_t(i:i+15) == [0 0 0 1 0 1 0 1 0 1 0 1 0 0 0 0])
        finish=i-1;
        break;
    end
end

i=1;
j=1;

for j=start:32:finish

        a(1) = sum(xor(out_t(j:j+31),[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]));
        a(2) = sum(xor(out_t(j:j+31),[0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1]));
        a(3) = sum(xor(out_t(j:j+31),[0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1]));
        a(4) = sum(xor(out_t(j:j+31),[0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0]));
        a(5) = sum(xor(out_t(j:j+31),[0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1]));
        a(6) = sum(xor(out_t(j:j+31),[0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0]));
        a(7) = sum(xor(out_t(j:j+31),[0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0]));
        a(8) = sum(xor(out_t(j:j+31),[0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1]));

        a(9) = sum(xor(out_t(j:j+31),[0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1  0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1]));
        a(10) = sum(xor(out_t(j:j+31),[0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0]));
        a(11) = sum(xor(out_t(j:j+31),[0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0]));
        a(12) = sum(xor(out_t(j:j+31),[0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1]));
        a(13) = sum(xor(out_t(j:j+31),[0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0]));
        a(14) = sum(xor(out_t(j:j+31),[0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1]));
        a(15) = sum(xor(out_t(j:j+31),[0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1]));
        a(16) = sum(xor(out_t(j:j+31),[0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0]));

        a(17) = sum(xor(out_t(j:j+31),[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1]));
        a(18) = sum(xor(out_t(j:j+31),[0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0]));
        a(19) = sum(xor(out_t(j:j+31),[0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0]));
        a(20) = sum(xor(out_t(j:j+31),[0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1]));
        a(21) = sum(xor(out_t(j:j+31),[0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0]));
        a(22) = sum(xor(out_t(j:j+31),[0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1]));
        a(23) = sum(xor(out_t(j:j+31),[0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1]));
        a(24) = sum(xor(out_t(j:j+31),[0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0]));

        a(25) = sum(xor(out_t(j:j+31),[0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0]));
        a(26) = sum(xor(out_t(j:j+31),[0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1]));
        a(27) = sum(xor(out_t(j:j+31),[0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1]));
```

```
a(28) = sum(xor(out_t(j:j+31),[0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0]));
a(29) = sum(xor(out_t(j:j+31),[0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1]));
a(30) = sum(xor(out_t(j:j+31),[0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0]));
a(31) = sum(xor(out_t(j:j+31),[0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0]));
a(32) = sum(xor(out_t(j:j+31),[0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1]));

a(33) = sum(xor(out_t(j:j+31),[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1]));
a(34) = sum(xor(out_t(j:j+31),[1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0]));
a(35) = sum(xor(out_t(j:j+31),[1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0]));
a(36) = sum(xor(out_t(j:j+31),[1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1]));
a(37) = sum(xor(out_t(j:j+31),[1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0]));
a(38) = sum(xor(out_t(j:j+31),[1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1]));
a(39) = sum(xor(out_t(j:j+31),[1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1]));
a(40) = sum(xor(out_t(j:j+31),[1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0]));

a(41) = sum(xor(out_t(j:j+31),[1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0]));
a(42) = sum(xor(out_t(j:j+31),[1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1]));
a(43) = sum(xor(out_t(j:j+31),[1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1]));
a(44) = sum(xor(out_t(j:j+31),[1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0]));
a(45) = sum(xor(out_t(j:j+31),[1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1]));
a(46) = sum(xor(out_t(j:j+31),[1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0]));
a(47) = sum(xor(out_t(j:j+31),[1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0]));
a(48) = sum(xor(out_t(j:j+31),[1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1]));

a(49) = sum(xor(out_t(j:j+31),[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]));
a(50) = sum(xor(out_t(j:j+31),[1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1]));
a(51) = sum(xor(out_t(j:j+31),[1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1]));
a(52) = sum(xor(out_t(j:j+31),[1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0]));
a(53) = sum(xor(out_t(j:j+31),[1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1]));
a(54) = sum(xor(out_t(j:j+31),[1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0]));
a(55) = sum(xor(out_t(j:j+31),[1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0]));
a(56) = sum(xor(out_t(j:j+31),[1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1]));

a(57) = sum(xor(out_t(j:j+31),[1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1]));
a(58) = sum(xor(out_t(j:j+31),[1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 1 0 1 0 1 0 1 0]));
a(59) = sum(xor(out_t(j:j+31),[1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 1 1 0 0 1 1 0 0]));
a(60) = sum(xor(out_t(j:j+31),[1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 1 0 0 1 1 0 0 1]));
a(61) = sum(xor(out_t(j:j+31),[1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1 1 1 1 1 0 0 0 0]));
a(62) = sum(xor(out_t(j:j+31),[1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 0 1 0 1 1 0 1 0 1 0 1 0 0 1 0 1]));
a(63) = sum(xor(out_t(j:j+31),[1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 0 0 1 1 1 1 0 0 1 1 0 0 0 0 1 1]));
a(64) = sum(xor(out_t(j:j+31),[1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 0]));

c = min(a);
t=0;
for k=1:1:64
    if(c==a(k))
        t=t+1;
    end
end
if(t>=4)
    fprintf('Error not corrected because of more than one match in map table. ');
    break
end

if (c<8)
    if (c ~= 0)
        total_err=total_err+c;
    end

if (c == a(1))
    out_r(i:i+5) = [0 0 0 0 0 0];
elseif(c == a(2))
    out_r(i:i+5) = [0 0 0 0 0 1];
elseif(c == a(3))
    out_r(i:i+5) = [0 0 0 0 1 0];
elseif(c == a(4))
    out_r(i:i+5) = [0 0 0 0 1 1];
elseif(c == a(5))
    out_r(i:i+5) = [0 0 0 1 0 0];
elseif(c == a(6))
    out_r(i:i+5) = [0 0 0 1 0 1];
elseif(c == a(7))
    out_r(i:i+5) = [0 0 0 1 1 0];
elseif(c == a(8))
    out_r(i:i+5) = [0 0 0 1 1 1];
elseif(c == a(9))
    out_r(i:i+5) = [0 0 1 0 0 0];
elseif(c == a(10))
    out_r(i:i+5) = [0 0 1 0 0 1];
elseif(c == a(11))
    out_r(i:i+5) = [0 0 1 0 1 0];
elseif(c == a(12))
    out_r(i:i+5) = [0 0 1 0 1 1];
elseif(c == a(13))
    out_r(i:i+5) = [0 0 1 1 0 0];
elseif(c == a(14))
    out_r(i:i+5) = [0 0 1 1 0 1];
elseif(c == a(15))
```

```
    out_r(i:i+5) = [0 0 1 1 1 0];
elseif(c == a(16))
    out_r(i:i+5) = [0 0 1 1 1 1];

elseif (c == a(17))
    out_r(i:i+5) = [0 1 0 0 0 0];
elseif(c == a(18))
    out_r(i:i+5) = [0 1 0 0 0 1];
elseif(c == a(19))
    out_r(i:i+5) = [0 1 0 0 1 0];
elseif(c == a(20))
    out_r(i:i+5) = [0 1 0 0 1 1];
elseif(c == a(21))
    out_r(i:i+5) = [0 1 0 1 0 0];
elseif(c == a(22))
    out_r(i:i+5) = [0 1 0 1 0 1];
elseif(c == a(23))
    out_r(i:i+5) = [0 1 0 1 1 0];
elseif(c == a(24))
    out_r(i:i+5) = [0 1 0 1 1 1];
elseif(c == a(25))
    out_r(i:i+5) = [0 1 1 0 0 0];
elseif(c == a(26))
    out_r(i:i+5) = [0 1 1 0 0 1];
elseif(c == a(27))
    out_r(i:i+5) = [0 1 1 0 1 0];
elseif(c == a(28))
    out_r(i:i+5) = [0 1 1 0 1 1];
elseif(c == a(29))
    out_r(i:i+5) = [0 1 1 1 0 0];
elseif(c == a(30))
    out_r(i:i+5) = [0 1 1 1 0 1];
elseif(c == a(31))
    out_r(i:i+5) = [0 1 1 1 1 0];
elseif(c == a(32))
    out_r(i:i+5) = [0 1 1 1 1 1];


elseif (c == a(33))
    out_r(i:i+5) = [1 0 0 0 0 0];
elseif(c == a(34))
    out_r(i:i+5) = [1 0 0 0 0 1];
elseif(c == a(35))
    out_r(i:i+5) = [1 0 0 0 1 0];
elseif(c == a(36))
    out_r(i:i+5) = [1 0 0 0 1 1];
elseif(c == a(37))
    out_r(i:i+5) = [1 0 0 1 0 0];
elseif(c == a(38))
    out_r(i:i+5) = [1 0 0 1 0 1];
elseif(c == a(39))
    out_r(i:i+5) = [1 0 0 1 1 0];
elseif(c == a(40))
    out_r(i:i+5) = [1 0 0 1 1 1];
elseif(c == a(41))
    out_r(i:i+5) = [1 0 1 0 0 0];
elseif(c == a(42))
    out_r(i:i+5) = [1 0 1 0 0 1];
elseif(c == a(43))
    out_r(i:i+5) = [1 0 1 0 1 0];
elseif(c == a(44))
    out_r(i:i+5) = [1 0 1 0 1 1];
elseif(c == a(45))
    out_r(i:i+5) = [1 0 1 1 0 0];
elseif(c == a(46))
    out_r(i:i+5) = [1 0 1 1 0 1];
elseif(c == a(47))
    out_r(i:i+5) = [1 0 1 1 1 0];
elseif(c == a(48))
    out_r(i:i+5) = [1 0 1 1 1 1];

elseif (c == a(49))
    out_r(i:i+5) = [1 1 0 0 0 0];
elseif(c == a(50))
    out_r(i:i+5) = [1 1 0 0 0 1];
elseif(c == a(51))
    out_r(i:i+5) = [1 1 0 0 1 0];
elseif(c == a(52))
    out_r(i:i+5) = [1 1 0 0 1 1];
elseif(c == a(53))
    out_r(i:i+5) = [1 1 0 1 0 0];
elseif(c == a(54))
    out_r(i:i+5) = [1 1 0 1 0 1];
elseif(c == a(55))
    out_r(i:i+5) = [1 1 0 1 1 0];
elseif(c == a(56))
    out_r(i:i+5) = [1 1 0 1 1 1];
elseif(c == a(57))
```

```
            out_r(i:i+5) = [1 1 1 0 0 0];
        elseif(c == a(58))
            out_r(i:i+5) = [1 1 1 0 0 1];
        elseif(c == a(59))
            out_r(i:i+5) = [1 1 1 0 1 0];
        elseif(c == a(60))
            out_r(i:i+5) = [1 1 1 0 1 1];
        elseif(c == a(61))
            out_r(i:i+5) = [1 1 1 1 0 0];
        elseif(c == a(62))
            out_r(i:i+5) = [1 1 1 1 0 1];
        elseif(c == a(63))
            out_r(i:i+5) = [1 1 1 1 1 0];
        elseif(c == a(64))
            out_r(i:i+5) = [1 1 1 1 1 1];

        end
        else
            fprintf('Irrecoverable number of errors occured. Number of mismatch = %f',c);
    end

    i=i+6;
end


end
```

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