Design and Implementation of Visible Light Communication Using Error Correcting Turbo Codes

Hafiz Waqas Moazzam*, Usman Ayub, Asad Shahzad, Mussab Shahid

Abstract— Visible light communication is a short range optical wireless communication technology that is used for the illumination and data communication simultaneously. It is one of the most promising technologies for the indoor wireless communication as it opens the broad spectrum for applications. The spectrum (430 – 790 THz) used by the VLC system does not overlap with other wireless technologies such as radio spectrum, and thus interference with other wireless signal is minimal. In this paper, hardware prototype is designed and implemented for VLC system. The transceiver is designed for VLC offers a data communication at a distance of 5 m. The novelty of the design lies in the application of turbo codes to improve the reliability of data communication. Simulation results are presented to represent the bit error rate (BER) analysis. Hardware implementation results are also presented which verify the transmitted data being received accurately at a distance of 5 m for indoor communication using visible light.

Index Terms— Source and Channel Coding, Modulation, Turbo-encoder, Turbo-decoder, VLC Hardware, Channel Modeling, Bit Error Rate (BER).

1 INTRODUCTION

IN the present era the VLC has significantly important role in wireless indoor communication systems. Now the potential of dual function of light emitting diodes (LED) has become a popular research topic due to the advantages of large bandwidth in terahertz, license free operation, and an inexpensive front end. LED lighting has low power consumption, minimal heat generation, high tolerance to humidity, and long life expectancy [1]. It is believed that the LEDs will replace the conventional illumination lights such as fluorescent lamps, incandescent bulbs since they have high switching characteristic of LEDs, light intensity can be modulated with data signal [1],[2].

The internet-of-things (IoT) is a prominent use case example expected to outperformance traditional wireless sensors network. With the congestion of the radio spectrum utilization by WPAN, WLAN and other cellular standards, VLC has emerged as a potential broadband transmission technology promoting a complete Light Fidelity (Li-Fi) [3]. An Internet of Things (IoT) for indoor lighting system that consists of multiple luminaires with an IP address such as sensors and controllers are considered to perform Device-to-Device communication. The sensors provide sensing information for controlling artificial lighting system and additionally serve as a data source for other building systems and services [4],[5],[6].

VLC generally is a short range wireless communication system, if we increase distance between the transceiver ultimate the performance compromises. These performance limits of communication system are determined by the channel in which it operates [7],[8],[9]. Error detection and correction signify two digital communication techniques that are responsible for transmitting digital data over unpredictable communication channels reliably. Numerous communication channels encounter channel noise which may lead to errors during transmission from the information source to a sink. An error detection technique helps the system in detecting such errors, while error correction technique allows reconstruction of the original transmitted data. With the advancement of technology and need for high data rate communication, error control coding became an integral part of a modern digital communication systems [10],[11].

There is always trade-off between energy efficiency and bandwidth efficiency. The code can usually correct more errors if more redundant bits are added in the code word. If more errors can be corrected, the communication system can, operate with a low transmit power and transmit at a higher data rate. These are the properties which makes the code energy efficient. On the other side low-code rate have large redundancy and hence consumes more bandwidth. Decoding complexity grows exponentially according to the length of the code, and low rate codes sets high computational requirements to the conventional decoders [12],[13],[15].

The general idea for achieving error correction is to add some redundancy in digital signal, which receivers can use to check consistency of the transmitted signal, and to recover the original transmitted data. Error-detection and correction techniques can be either systematic or non-systematic. In a systematic scheme, the data will be transmitted along with the parity bits side by side while in non-systematic code, the original message is transformed into an encoded message that has at least as many bits as the original message [14].

In this paper an inexpensive hardware prototype is designed for the VLC system using the turbo codes having the code rate 1/3. Design of turbo encoder and decoder algorithms is discussed in detail in section 741. Simulation result in terms of bit error rate (BER) of the VLC channel using AWNG and hardware description is also described in rest of the paper.

2 VLC COMMUNICATION SYSTEM

The main purpose of any communication system is to provide error free data transmission. In a communication system, information can be transmitted by analog or digital. In the purposed VLC system digital communication system is used. The basic digital communication system is shown in (Figure 1).

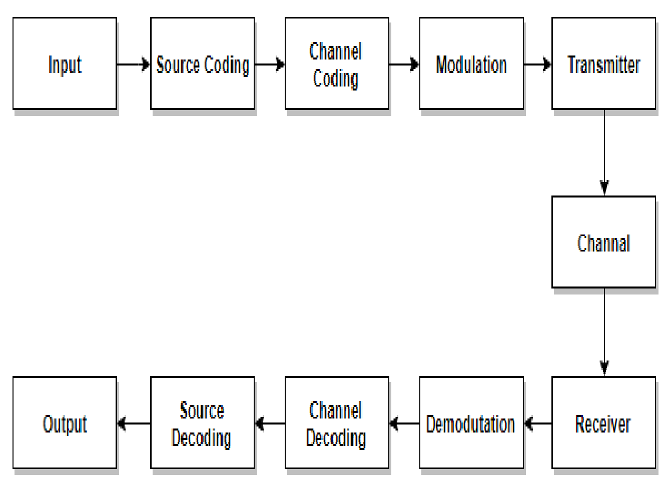

Fig. 1. Block diagram for communication system

2.1 Source Coding and Decoding

Suppose a word 'visible' is to be transmitted. Before the transmission of the word to channel, it is first converted into stream of bits '0' and '1'. This process of conversion is called source coding [15]. There are many commonly used source coding techniques. If ASCII code is used each alphabet is represented by 7-bit or 8-bit. The alphabets 'v', 'i', 's', 'i', 'b', 'l', 'e' can be encoded to 8-bit as '01110110', '01101001', '01110011', '01101001', '01100010', '01101100', '01100101'. Similarly during channel decoding, the resulting stream of bits is divided into group of 8-bits. Later on, each group of 8-bits will be converted into the alphabets.

2.2 Channel Coding and Decoding

Error control coding is a technique to detect and possibly correct the errors by introducing redundancy in data bits. In general, the channel encoder will divide the input message bits into blocks of 'k' message bits and replaces each 'k' message bits block with an n-bit code word by introducing n-k redundant bits to each message block [16],[17],[18]. During the channel decoding every channel code has its own decoding algorithms. Turbo algorithms for channel encoding and decoding are discussed in section 3.

2.3 Modulation and Demodulation Scheme

Modulation is a process of adding a message signal to an electrical or optical signal carrier. Among several techniques, there are two modulation schemes which are widely used in digital communication, on-off keying (OOK) and pulse-position modulation (PPM) [19]. In Visible light communication systems, simple and low-cost optical carrier modulation and demodulation are usually achieved by intensity modulation with direct detection (IM/DD). The desired digital signal is modulated onto the instantaneous power of the optical carrier, and the detector generates a current proportional to the received instantaneous power that is, only the intensity of the optical wave is detected. This is because light of LED is non-coherent therefore the information can be reliably encoded only in the form of signal intensity. The amplitude and phase of the light signal cannot be modulated or detected with LEDs and PDs respectively. It limits the conventional modulation schemes that can be adopted from the field of radio frequency (RF) communications [1],[20]. OOK is the simplest form of amplitude-shift keying, it is also easy to use in terms of hardware implementation and integration. In this method binary '1' is represented with high voltage level and binary '0' is represented as low voltage level. In our system on-off keying (OOK) is used where, binary '1' is represented by 5v and binary '0' with 0v. Similarly, In the case of demodulation 5v signal is mapped to binary '1' and 0v signal is mapped to binary '0'.

2.4 VLC Channel

After the modulation of signal, signal is transmitted through transmitter in channel. The nature of channel is unpredictable. In case of visible light communication, generally there are three types of channel, one is the Line of Sight (LOS), second is Non-line of Sight (N-LOS), and third one is Diffuse Non-line of Sight (D-LOS) [19]. In this paper LOS channel is used for VLC systems.

3 Error Correction Turbo Codes

In theory, error free transmission is possible if the data rate does not exceed the channel capacity. So, a theoretical upper limit on the data transmission rate is defined as avoiding any errors in the transmission. This limit is known as channel capacity or Shannon capacity [21]. Although Shannon had developed his theory in 1940s, several decades later the code designs were not able to come close to the theoretical limit. Even in the beginning of the 1990s, the difference between the theoretical bound and practical implementations was still at best about 3dB. The original concept of turbo coding was introduced by Berrou, Glavieux, and Thitimajshima in a paper [22] presented at IEEE forum, and it was further elaborated in [23]. Two papers by Benedetto and Montorsi, provided the first time theoretical analysis for the performance of turbo codes [24],[25]. These codes combine the concepts of iterative decoding, soft-in soft-out decoding, Recursive Systematic Convolutional (RSC) encoding, and non-uniform random interleaving [26]. Turbo codes are high performance error correction codes and first practical codes. In fact, for essentially any code rate and information block lengths greater than about 10^4 bits, turbo codes with iterative decoding can achieve

BERs as low as 10^{-5} at SNRs within 1 dB of the Shannon limits, it is the value of E_b/N_o for which the code rate equals channel capacity.

The encoder of turbo codes consist of two or more concatenated recursive convolutional encoders, serial or parallel manner along with an interleaver. The constituent codes can be either block codes or convolutional codes [27]. Currently, most of the work on turbo codes has essentially focused on convolutional turbo codes (CTC) and block turbo codes (BTC) have been partially neglected.

3.1 Turbo Encoder

In our work, turbo encoder is designed by implemented two parallel recursive convolutional encoders [28] along with a row column interleaver. In a row column interleaver data is written row wise and read column wise, in this manner interleaver provides a little randomness in the data bits [29]. This encoder encodes data bit by bit depending upon the states of flip flop of the systematic convolutional encoder. In turbo code encoder, both the RSC encoders are of short constraint length in order to avoid excessive decoding complexity. Typically, an RSC encoder having a rate of r = 1/2 is termed as component encoder. The two component encoders are separated by an interleaver. The output of the turbo encoder consists of the systematic output data and the parity outputs from two constituent RSC encoders. Thus the overall code rate becomes r = 1/3. Figure 2 shows the turbo code encoder.

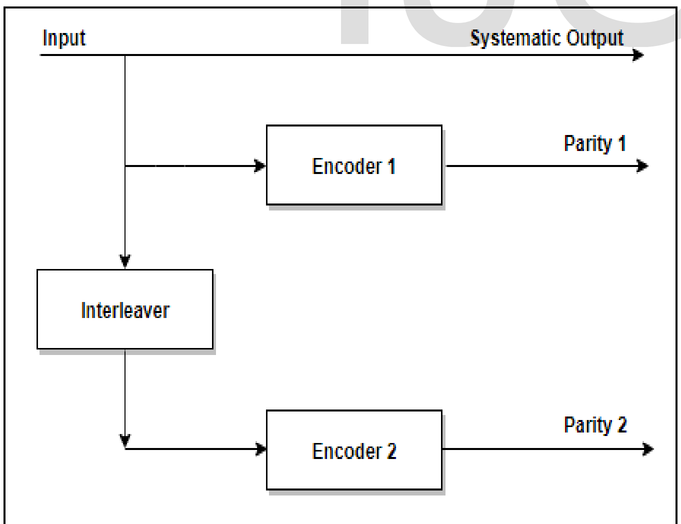

Fig. 2. Block diagram for turbo encoder

3.1.1 Generator Sequence

Generator sequence provides the parity bits in the code word. For a turbo encoder the generator sequence is a kind of feedback nature. Figure 3 shows the recursive systematic convolutional (RSC) encoder [28] for purposed system. The generator sequence used for encoding algorithm which is defined in (1). In this sequence, 1 represents the systematic output and the transfer function generates the parity bits as shown Table 1.

$$G(D) = [1, \frac{1+D^2}{1+D+D^2}] \tag{1}$$

TABLE 1
PARITY BITS GENERATED BY TRANSFER FUNCTION

Input	Present State	Next State	Parity Generated
0	00	00	0
1		10	1
0	01	10	0
1		00	1
0	10	11	1
1		01	0
0	11	01	1
1		11	0

Each convolutional encoder based on a recursive systematic convolutional code having the 4 states. The operation of the encoder is summarized by the trellis diagram shown in Figure 4, which shows the bit pairs output for each possible transition between successive states.

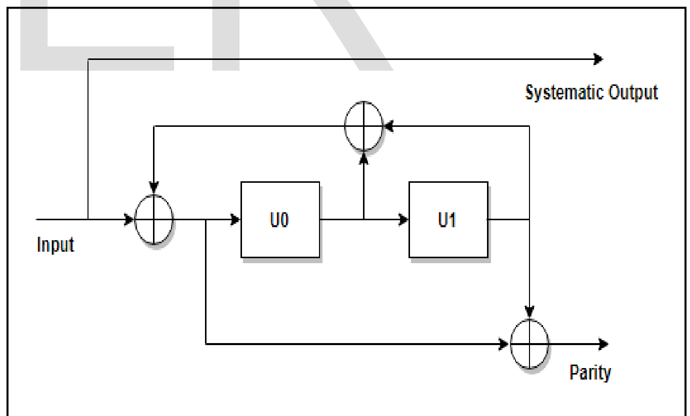

Fig. 3. Block diagram for RSC encoder

3.2 Turbo Decoder

The structure of turbo decoder is shown in Fig. 5. The decoding side of a turbo code consists of two decoders which coordinate in order to improve the estimation of the original information bits. These decoders follow the maximum a-posteriori probability (MAP) algorithm [30],[33] and soft decision information acquired from the noisy parity bits. Initially, decoder 1 starts without initializing information. In successive iteration, one of the decoder is initialized by the soft decision information of the other decoder. The decoder information is cycled around the loop until the soft decisions converge on a stable set of value. The latter soft decision is then sliced to recover the original binary sequence.

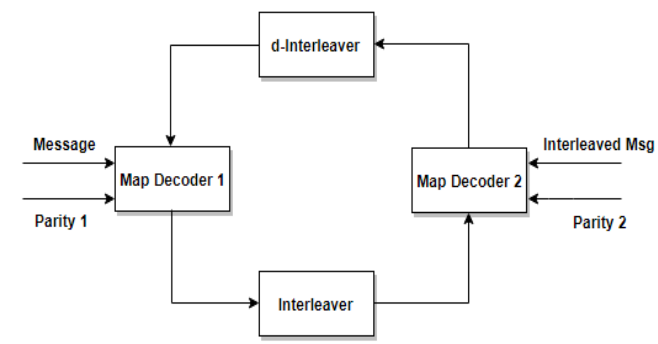

Fig. 5. Block diagram for turbo decoder

3.2.1 MAP Decoding

The MAP decoding is based on a-posterior probabilities (APP) [31],[33] for each information bit followed by choosing the data bit value corresponding to MAP probability for that data bit. In this paper, there are two decoders used for outputs from both encoders shown in Fig. 5. Both decoders provide estimation of the same set of data bits, but in different order due to the presence of interleaver. Information is iterated number of times to enhance the performance. During each iteration, the estimates are re-evaluated by the decoder using the information from other decoder. It allows the decoder to calculate the likelihood [32], also helps that what information bit was transmitted during each iteration. In the final stages, the hard decisions will be made to assigning the values 1 or 0 to each bit.

The APPs are used to calculate the likelihood ratio. The logarithmic form of the likelihood is the log of likelihood ratio denoted by LLR. The mathematic expressions are represented in (2) and (3).

$$\Lambda(\hat{a}_k) = \frac{\sum m\, \lambda_k^{1,m}}{\sum m\, \lambda_k^{0,m}} \tag{2}$$

$$L(\hat{a}_k) = \log[\Lambda(\hat{a}_k)] \tag{3}$$

$\Lambda(\hat{a}_k)$ is the likelihood ratio and $L(\hat{a}_k)$ is the LLR. The term $\lambda_k^{i,m}$ is described as joint probability which is equal to,

$$\lambda_k^{i,m} = P(a_k = i, s_k = m | R_1^N) \tag{4}$$

where, $a_k = i$ is the encoded data bit, $s_k = m$ is the state and R_1^N is the received sequence, observed at time interval k = 1 to N. The decoder makes the decision by comparing the $L(\hat{a}_k)$ to the zero threshold i.e. $\hat{a}_k = 1$ if $L(\hat{a}_k) > 0$ else $\hat{a}_k = 0$ if $L(\hat{a}_k) <$ 0.

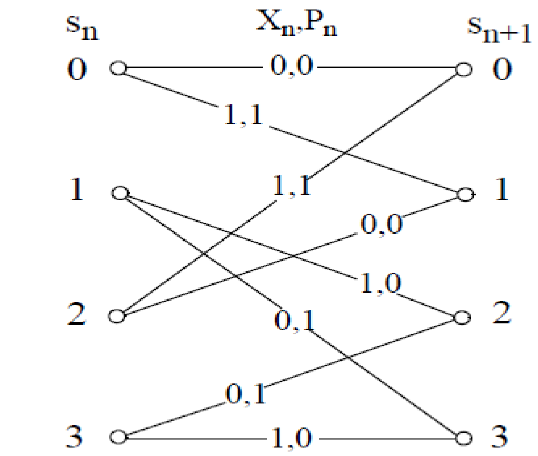

Fig. 4. Block diagram for RSC encoder

4 VLC Communication System

Following are the discrete phases which we have experienced incrementally to realize our product in the given time, which includes considering a VLC channel study, its simulation and utilization in hardware. We simulated a LOS VLC system and evaluated its BER performance and finally, we performed hardware implementation.

4.1 LOS Optical Channel

To provide a theoretical analysis and simulation results of the proposed VLC system, a light positioning system (LPS) channel model is established. In visible light communication, the influence of the directed light is large and significantly depends on the performance of the system [34], so only the line of sight (LOS) link is assumed in this paper. The LPS channel model in a LOS environment is shown in Fig. 6. Due to the similar characteristic between visible light and infrared, the channel model of wireless infrared communication [35],[19] can be used for LPS. The channel direct current (DC) gain can be given as,

$$H_{LOS} = \begin{cases} \frac{A'}{d^2} R_0(\emptyset)\cos(\psi) T_s(\psi) G(\psi), & 0 \le \psi \le \psi_c \\ 0 & \psi > \psi_c \end{cases} \tag{5}$$

(1)

Here, $$R_0(\emptyset) = \frac{m+1}{2\pi} \cdot \cos^m(\emptyset) \tag{6}$$

where, m is the order of lambertian radiation, which is relative to the semi-angle at half illuminance of an LED denoted as $\phi_{1/2}$. Smaller the semi-angle higher the gain in normal direc-

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tion of optical source to detector. m can be given as m = -ln 2 / ln(cos $\phi_{1/2}$). R_0 is the lambertian radiation of the LED shown in (6). A' is the effective physical area of a detector, d is the distance between a LED and a detector, $\emptyset$ is the angle of irradiance, and ψ is the angle of incidence. ψ_c denotes the field of view (FOV) of a receiver. $T_s(\psi)$ is the gain of an optical filter. $G(\psi)$ is the gain of an optical concentrator, which is given as in (7).

$$G(\psi) = \begin{cases} \frac{m^2}{\sin^2(\psi_c)}, & 0 \le \psi \le \psi_c \\ 0 & \psi > \psi_c \end{cases} \tag{7}$$

In view of the influence of noise, the received signals can be expressed as follows:

$$P_r = R \cdot P_t \cdot H_{LOS} + N \tag{8}$$

where P_r is the received signal power, R is the detector responsivity, and N is the noise. P_t is the transmitted optical power of LED. In our work, the simulation analysis is presented by keeping the upper limit of ψ and $\emptyset$ is equal to 90˚.

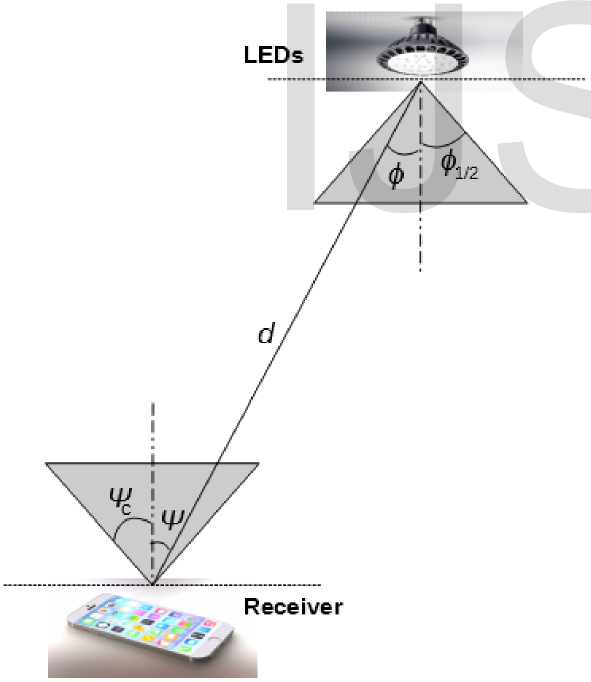

Fig. 6. Channel modeling for LOS environment

4.2 Simulation

After modelling the LOS channel, AWGN noise is added to cater optical noise which includes short noise and thermal noise. The block diagram of VLC communication system is shown in Fig. 7. In order to perform the simulation one million message bits are transmitted. Each bit is encoded by using

TABLE 2
SIMULATION PARAMETERS

Parameters	Values
Channel	Optical
Noise (N)	AWNG
Modulation	BPSK
Channel Coding	PCCC (Turbo)
Interleaver	Row-Column Interleaver
FOV (Ψ_c)	65 degree
Semi-angle of half power ($\emptyset$½)	55 degree
PD Responsivity (R)	0.65 A/W
Distance b/w Tx-Rx (d)	5 m
Active Area of Each PD (A')	7.5 mm^2

turbo codes. BPSK modulation is used to modulate the coded signal [36]. In BPSK, the positive pulse is mapped to 1 while 0 is mapped to -1. The transmitted signal is passed through LOS channel and AWGN noise is added to the signal. The parameter which are being used in LOS channel modeling using the (5) are given in Table 2.

At receiver side, hard decision is made before decoding the turbo codes. The received signal is decoded by using BCJR algorithm [33],[37]. In BCJR, several soft decisions are taken which are dependent on the number of iterations, before taking a final hard decision [30].

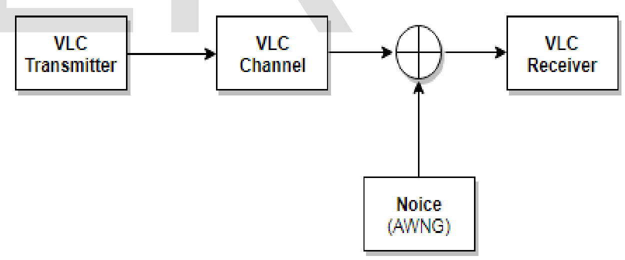

Fig. 7. Block diagram for VLC communication system

4.3 Applying Channel Coding

To demonstrate the performance of turbo codes on VLC's LOS channel the simulation is performed in MATLAB. The performance metric includes the BER performance. Figure 8 shows the performance analysis of the VLC communication system with and without using turbo codes, the graph of BER is plotted against E_b/N_o. At the transmitter side one million bits are passed through the simulated channel to evaluate the performance of turbo codes. It has been demonstrated that a coding gain of 8.5 dB in E_b/N_o is achieved after applying turbo codes. The BER curves in Fig. 3.2 which show that 10^{-5} BER is achieved when the system does not employ turbo codes and the value of E_b/N_0 is approximate 12.6 dB at that case, while at the same BER, 4.0 dB value of E_b/N_o is achieved by employing the turbo codes [38]. Thus, the results clearly demonstrate that without increasing the transmitted power at transmit antenna we can achieve the same BER of 10^{-5} by using turbo codes.

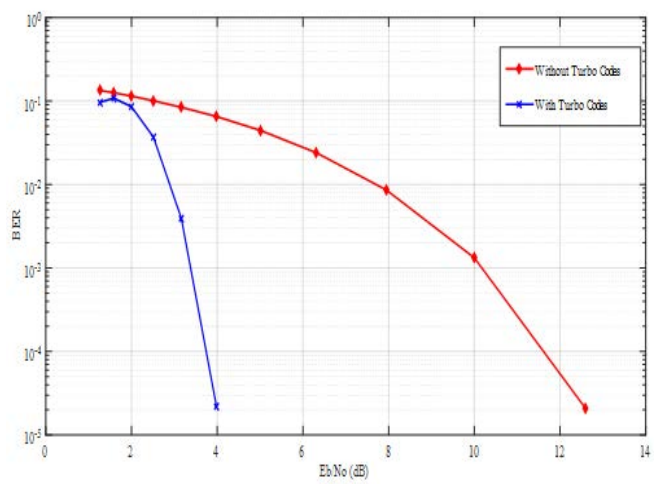

Fig. 8. Simulation results in term of performance analysis of BER

5 HARDWARE DESIGN

Figure 9 shows the overall functional block diagram of the proposed VLC system prototype. The transmitter side consists of a signal source (computer), an external power source, microprocessor (encoder), LED driver circuit and array of LEDs. In the same fashion, the receiver side consists of an array of photodiodes, amplifier circuit, microprocessor (decoder) and a computer to display the received signal. Both transmitter and the receiver need power to operate. At the transmitter side, the microprocessor is connected directly to the computer's USB port [39],[40]. An output of 5V from a computer is used to operate a microprocessor. The microprocessor is then output either a 5V or 0V on its pin. The output of the microprocessor is then sent to the analog circuit to drive the LEDs. The microprocessor at the receiver side is powered on in the same manner as on the transmitter side. A 5v from the decoder is fed into the amplifier in order to amplify the photodiode's output.

5.1 LOS Optical Channel

Hardware components and their specifications are given in Table 3. To demonstrate the functionality of the microprocessor, a simple code of pulse wave modulation was uploaded. A signal of 61.58 Hz was transmitted on one of the digital input pins of the board. The output was displayed on digital oscilloscope shown in Fig. 10a. To test the functionality of the receiver side, function generator was used to generate a square wave which would drive the LEDs. The receiver was placed at different distances from the transmitter and the resulting outputs

TABLE 3
HARDWARE COMPONENTS

Components / Parameters	Model / Specifications
LED	LXHL-BW02
Photodiode	BPW34 (PIN Diode)
PD Spectral Range	460 nm – 1100 nm
PD Rise and Fall Time	20 nm
Microprocessor	Arduino Maga 2560 (ATmega2560)
Operational Amplifire	LM358N

were observed on the digital oscilloscope. Figure 10b shows the received signal when the receiver is at a distance of 3m from the transmitter. Despite, the noise added to the signal, the two levels of the signal can be easily differentiated. The difference between the two voltage levels ensures that the receiver side would receive the signal accurately. The array of photodiodes gives an output of 14.40 mV. The received signal at a distance of 5m is shown in Fig. 10c.The result demonstrates that the as the distance is increased the signal is further distorted and attenuated but still the two levels can be differentiated.

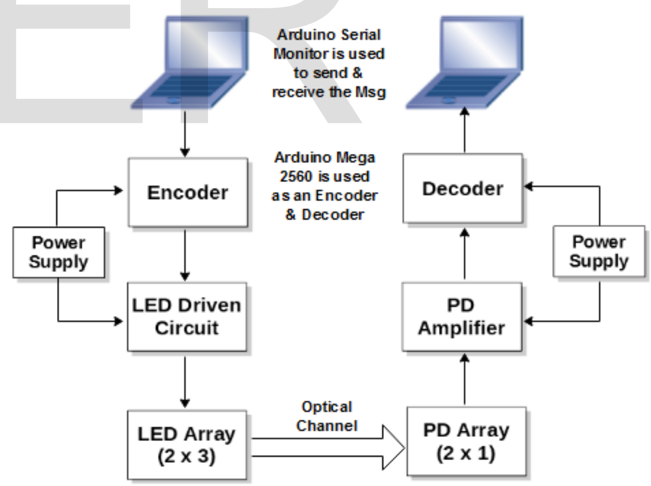

Fig. 9. Block diagram for VLC hardware system

5.2 System Integration and Operation

Arduino microprocessor board is used to interface the software with the prototype hardware system. In order to transmit the data digitally we used alphanumeric form of data which is converted into binary form. PWM is used to transmit digital data on analog circuitry. On the transmitter side ULN2003A is used as a switch, if the input from encoder is low it acts as an open circuit, whereas if the input is high it acts as a short circuit. The encoded sequence is sent through an array of LEDs at the transmitter side. The LEDs stay off when the input from Arduino board is low and stays on when the input is high. The encoded bits are sent through the Arduino board with a delay of 15ms. On the receiver side two photodiodes are used in parallel to convert light signal into current. To make photodiode less sensitive to light, a variable resistor is used. The output voltage from photodiode is very low therefore, the signal is amplified at the receiver side. For this reason LM358N is used as an operational amplifier. LM358N converted current into voltage and amplified the signal strength up to 5V [41]. To avoid the effect of ambient light, a variable resister is used to set a threshold voltage on the negative pin of LM358N. The output of LM358N is fed to one of the digital pin of decoder. After decoding the received signal the decoder also converts the received binary into alphabets which were originally transmitted. Message string is then displayed on a Serial Monitor of Arduino software. Fig. 11 shows the transceiver of VLC system.

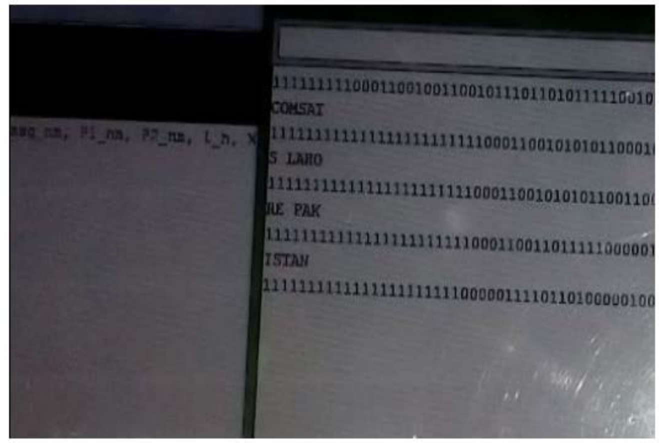

Fig. 12. Output of transmitted string using turbo codes

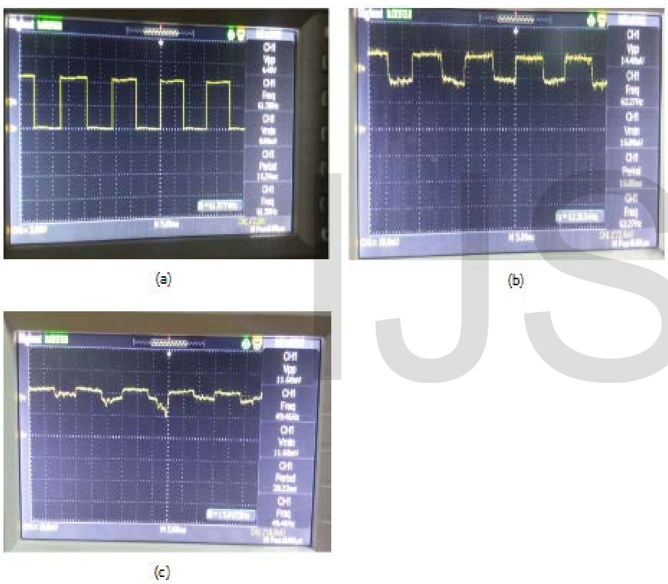

Fig. 10. Component analysis by using the digital oscilloscope

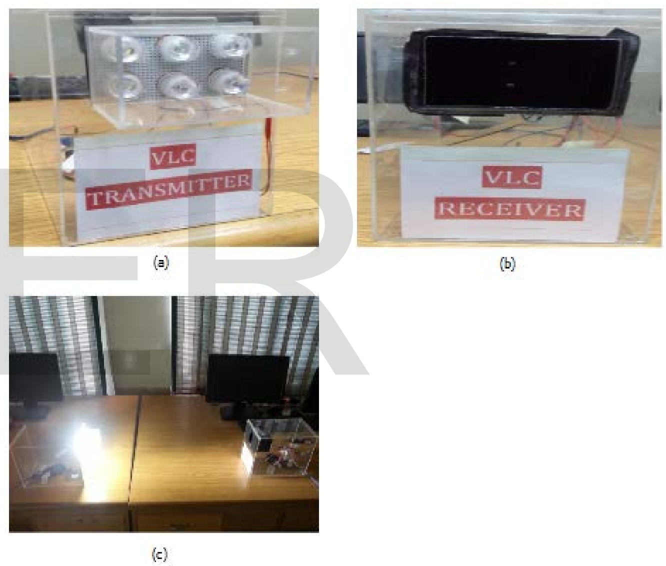

Fig. 11. Prototype of designed VLC hardware system

5.3 Testing of VLC System Prototype with Turbo Codes

Finally, In order to demonstrate the effect of turbo codes output of the designed prototype is shown in Fig. 12. A string “COMSATS LAHORE PAKISTAN” is sent to analyses the output response of the VLC prototype using turbo codes. The good result confirmed that the VLC system prototype with the help of turbo codes can receive data accurately at a distance of 5 meters.

6 Hardware Design

In this paper we focused on the design, simulation and hardware implementation of a VLC system. The proposed communication system deals with indoor data communication by utilizing the LEDs used for illumination and for data transmission. In this work, we focused on improving the reliability of data communication. Therefore, we proposed utilizing error correction codes, such as turbo codes to improve the quality of data communication. To verify the facts, we simulated a VLC communication system in MATLAB and tested its BER performance with and without Turbo codes. There was a remarkable improvement of BER in the VLC system using turbo codes, also supported by references in literature. Finally we were able to implement the proposed VLC system in hardware. It was successfully tested for a distance of five meters.

7 Conclusion

In this paper we focused on the design, simulation and hardware implementation of a VLC system. The proposed communication system deals with indoor data communication by utilizing the LEDs used for illumination and for data transmission. In this work, we focused on improving the reliability of data communication. Therefore, we proposed utilizing error correction codes, such as turbo codes to improve the quality of data communication. To verify the facts, we simulated a VLC communication system in MATLAB and tested its BER performance with and without Turbo codes. There was a remarkable improvement of BER in the VLC system using turbo codes, also supported by references in literature. Finally we were able to implement the proposed VLC system in hardware. It was successfully tested for a distance of five meters.

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