Physical Layer Aspects of Li-Fi Technology

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***Abstract*— With the increasing popularity of wirelessly connected devices, the wireless data traffic is growing exponentially. As a result, the network spectral efficiency saturates despite new standards and great technological advancements. Li-Fi (Light-Fidelity) is using visible light instead of radio waves for communication. Light Fidelity (Li-Fi), first introduced by Harald Haas, uses Light Emitting Diode (LED) for visible light spectrum for high-speed data communication, shows very promising results. The concept of combining the functions of illumination and communication offers the potential for tremendous cost savings and carbon footprint reductions. The term Li-Fi refers to visible light communication (VLC) technology that uses light as medium to deliver high-speed communication in a manner similar to Wi-Fi and complies with the IEEE standard IEEE 802.15.7. The IEEE 802.15.7 is a high-speed, bidirectional and fully networked wireless communication technology based standard similar to Wi-Fi's IEEE 802.11.**

This paper focuses on the physical layer aspects of the Li-Fi technology which includes the physical layer configurations and the modulation techniques.

***Index Terms*— Visible Light Communication(VLC), MATLAB, Simulink , Physical Layer, Modulation schemes**

I. Introduction

As per the increasing demand for wireless data communication, the available radio spectrum below 10 GHz (cm-wave communication) has become insufficient. The wireless communication industry has responded to this challenge by considering the radio spectrum above 10 GHz (mm-wave communication). Light-Fidelity (Li-Fi) is a continuation of the trend to move to higher frequencies in the electromagnetic spectrum. Specifically, Li-Fi could be classified as nm-wave communication. Li-Fi is a visible light communication technology, having a various range of frequencies and wavelengths from the infrared through visible light as a medium of transmission rather than the traditional radio waves. [1]

Li-Fi or Light Fidelity is a technology that uses light emitting diodes to transmit data wirelessly. The functioning of new Li-Fi technology is just simple. That is a light source at one end like a LED and a photo detector (Light Sensor) on the other end. The LED is connected to the internet through the modem and the receiver decodes the information, which is then displayed on the device. When a constant current is applied to an LED light bulb a constant stream of photons are emitted from the bulb which is observed as visible light. If the current is varied slowly the output intensity of the light dims up and down. Because LED bulbs are semi-conductor devices, the current, and hence the optical output, can be modulated at extremely high speeds which can be detected by a photo-detector device and converted back to electrical current. [2] Modulation techniques developed for intensity modulation and direct detection (IM/DD) optical wireless communication (OWC) systems are suitable for Li-Fi communications systems.[3]

II. Physical Layer Configurations

In the seven-layer OSI model of computer networking, the physical layer or layer 1 is the first and lowest layer. This layer may be implemented by a PHY. PHY is an abbreviation for the physical layer of the OSI model and refers to the circuitry required to implement physical layer functions. A PHY connects a link layer device (often called MAC as an abbreviation for medium access control) to a physical medium such as an optical fiber or copper cable.

The physical layer consists of the networking hardware transmission technologies of a network. It is a fundamental layer underlying the logical data structures of the higher level functions in a network. Due to the plethora of available hardware technologies with widely varying characteristics, this is perhaps the most complex layer in the OSI architecture.[4]

The physical layer defines the means of transmitting raw bits rather than logical data packets over a physical link connecting network nodes. The bit stream may be grouped into code words or symbols and converted to a physical signal that is transmitted over a hardware transmission medium. The physical layer provides an electrical, mechanical, and procedural interface to the transmission medium. The physical layer deals with bit-level transmission between different devices and supports electrical or mechanical interfaces connecting to the physical medium for synchronized communication.

The shapes and properties of the electrical connectors, the frequencies to broadcast on, the modulation scheme to use and similar low-level parameters, are specified in this layer.

Following are the functions of Li-Fi Physical layer:

- Provide services to upper layers.
- Used to provide error correction at the receiver using FEC (Forward Error Correction) techniques such as Convolutional encoding and RS encoding (Reed Solomon).
- Used to activate and deactivate VLC transceiver.
- Helps in synchronization at the receiver using preamble incorporated in the frame structure.
- Inserts header (PHR) at the transmit end. This is decoded at the receive end to determine the length field of the PSDU(Physical-layer Service Data Unit).
- It is used for channel selection as per requirement.
- RLL (Run Length Limited) encoding helps in correcting DC balance, clock recovery and flicker management.

A. *Li-Fi Physical Layer frame structure*

Preamble	PHY header	HCS	Optional fields	PSDU
SHR	PHR			PHY payload

Fig 1 Li-Fi Frame structure

Multiple octets are transmitted least significant octet first and in each octet least significant bit first.

1. Preamble

It is used by the transceiver to perform optical clock synchronization.

Preamble = { FLP (64 to 16384 bits), TDP(15 bits each),~TDP, TDP, ~TDP }

FLP (Fast Locking Pattern) consists of alternate one and zeros. Four TDPs (Topology Dependent Patterns) distinguish PHY modes used. Every alternate TDP pattern is inverted to achieve DC balance in the Li-Fi Physical layer.

2. PHY HEADER

It is transmitted along with OOK modulation type. It carry burst mode, channel number, MCS ID (defines PHY type (PHY-I,II or III) and data rate), PSDU length etc.

3. HCS

It is 16 bit in size. It is used to protect PHY header in LiFi Physical layer. There are optional fields in the frame used in PHY-I mode at clock rate of 200 KHz.

4. PSDU Field

This field has variable length. It carries data of PHY frame.

There are different Li-Fi physical layers based on different data rate and application of use such as indoor or outdoor and they are known as :

- PHY-1
- PHY-2
- PHY-3

B. *PHY-I*

- It is designed for outdoor, low data rate applications.
- It provides data rates in the range 12 – 267 k-bit/s.

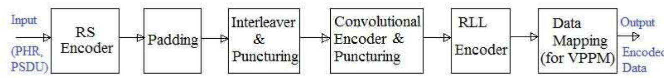

Fig 2 LiFi physical layer TX (version: PHY-I) [4]

1. RS Encoder

Convolutional codes (CC) and Reed Solomon (RS) codes are used by the PHY-I for forward error correction because of its design for outdoor use. In coding theory, the Reed–Solomon code belongs to the class of non-binary cyclic error-correcting codes. It is able to detect and correct multiple symbol errors. By adding t check symbols to the data, a Reed–Solomon code can detect any combination of up to t erroneous symbols, or correct up to $\lfloor t/2 \rfloor$ symbols. A Reed-Solomon code is specified as RS(n,k) with s-bit symbols. This means that the encoder takes k data symbols of s bits each and adds parity symbols to make an n symbol code-word. There are n-k parity symbols of s bits each. A Reed-Solomon decoder can correct up to t symbols that contain errors in a code-word, where 2t = n-k.

2. Inter-leavers

One of the most popular ways to correct burst errors is to take a code that works well on random errors and interleave the bursts to “spread out” the errors so that they appear random to the decoder. There are two types of inter-leavers commonly in use today, block inter-leavers and convolutional inter-leavers. Block inter-leavers are used in li-fi physical layers.

3. Convolutional Encoders

In telecommunication, a convolutional code is a type of error-correcting code that generates parity symbols via the sliding application of a Boolean polynomial function to a data stream. The sliding application represents the 'convolution' of the encoder over the data, which gives rise to the term 'convolutional coding.' The sliding nature of the convolutional codes facilitates trellis decoding using a time-invariant trellis. Time invariant trellis decoding allows convolutional codes to be maximum-likelihood soft-decision decoded with reasonable complexity.

4. RLL encoder

Run-length limited or RLL coding is a line coding technique that is used to send arbitrary data over a communications channel with bandwidth limits. RLL codes are defined by four main parameters: m, n, d, k. The first two, m/n, refer to the rate of the code, while the remaining two specify the minimal d and maximal k number of zeroes between consecutive ones. This is used in both telecommunication and storage systems that move a medium past a fixed recording head.

5. Data Mapping

For data mapping various modulation techniques are used (eg. OOK or VPPM are used for modulation). The details of various modulation techniques are discussed further in this paper.

The following table summarises the paramters of PHY-I

Modulation	RLL Code	Optical Clock rate	FEC(RS outer code)	FEC(CC inner code)	data rate
OOK	Manchester	200 KHz	(15,7)	1/4	11.67 Kbps
			(15,11)	1/3	24.44 Kbps
			(15,11)	2/3	48.89 Kbps
			(15,11)	None	73.3 Kbps
			None	None	100Kbps
VPPM	4B6B	400 KHz	(15,2)	None	35.56 Kbps
			(15,4)	None	71.11 kbps
			(15,7)	None	124.4 Kbps
			None	None	266.6 Kbps

Table 1 PHY-I Operating Modes (Modulation, Code rates) [4]

C. PHY-II

• This is designed for indoor operation with moderate data rates in the range 1.25 – 96 Mbit/s.

• Reed Solomon codes can be used for forward error correction, and OOK or VPPM are used for modulation.

• Note that to achieve 96 Mbit/s an optical clock rate of 120 MHz is required which most off the shelf optical devices will not support. At the more realistic clock rate of 15 MHz a data rate of 9.6 Mbit/s can be achieved.

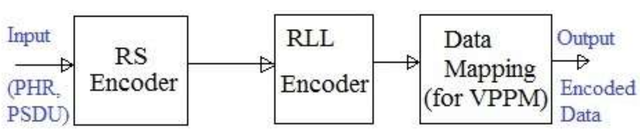

Fig 3 Li-Fi physical layer TX (version: PHY-II) [4]

The following table summarizes the parameters of PHY-II:

Modulation	RLL Code	Optical Clock rate	FEC	data rate
VPPM	4B6B	3.75 MHz	RS(64,32)	1.25 Mbps
			RS(160,128)	2 Mbps
		7.5 MHz	RS(64,32)	2.5 Mbps
			RS(160,128)	4 Mbps
			None	5 Mbps
OOK	8B10B	15MHz	RS(64,32)	6 Mbps
			RS(160,128)	9.6 Mbps
		30 MHz	RS(64,32)	12 Mbps
			RS(160,128)	19.2 Mbps
		60 MHz	RS(64,32)	24 Mbps
			RS(160,128)	38.4 Mbps
		120 MHz	RS(64,32)	48 Mbps
			RS(160,128)	76.8 Mbps
			None	96 Mbps

Table 2 PHY-II (Modulations, Code rates) [4]

D. PHY-III

• This is designed for applications where RGB sources and detectors are available.

• It provides data rates in the range 12 – 96 Mbit/s.

• Again Reed Solomon codes can be used for forward error correction and this time CSK with 4, 8 or 16 color constellations are used.

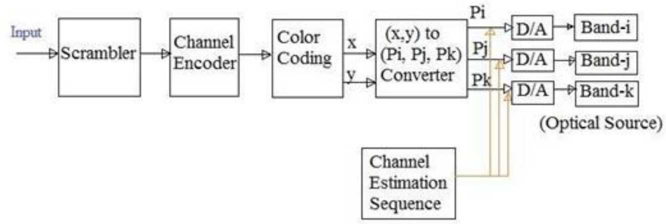

Fig 4 Li-Fi physical layer TX (version: PHY-III) [4]

The following table summarizes the modulations , code rates of PHY-III:

Modulation	Clock rate	FEC	Data rate
4-CSK	12MHz	RS(64,32)	12 Mbps
8-CSK	12MHz	RS(64,32)	18 Mbps
4-CSK	24MHz	RS(64,32)	24 Mbps
8-CSK	24MHz	RS(64,32)	36 Mbps
16-CSK	24MHz	RS(64,32)	48 Mbps
8-CSK	24MHz	NONE	72 Mbps
16-CSK	24MHz	NONE	96 Mbps

Table 3 PHY-III (parameters) [4]

III. MODULATION TECHNIQUES

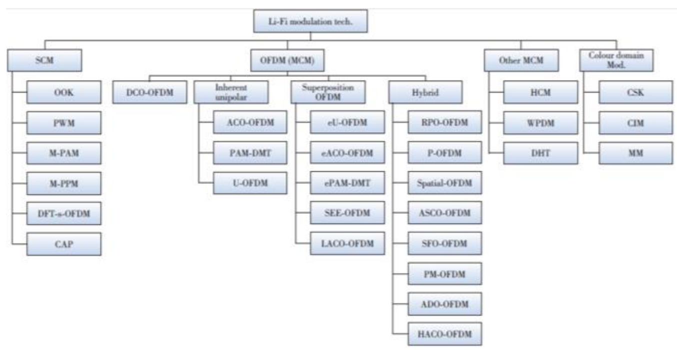

Fig 5 Li-Fi Modulation Schemes [3]

Since LI-FI uses visible light for sending data, it is necessary to modulate the data into a signal which can be transmitted. These signals consist of light pulses. modulation techniques should support dimmable illumination so that communication would be still available when the illumination is not required. Li-Fi uses off-the-shelf light emitting diodes (LEDs) and photodiodes (PDs) as channel front-end devices. signals. Single carrier modulation (SCM) techniques are straight forward to implement in Li-Fi. Modulation techniques, such as on-off keying (OOK), pulse position modulation (PPM), and M-ary pulse amplitude modulation (M-PAM), can be easily implemented. However, due to the dispersive nature of optical wireless channels, such schemes require complex equalizers at the receiver. Therefore, the performance of these schemes degrades as their Spectral Efficiency (SE) increases. On the other hand, multiple carrier modulation (MCM) techniques, such as the orthogonal frequency division multiplexing (OFDM), have been shown to be potential candidates for optical wireless channels since they only require single tap equalizer at the receiver. Adaptive bit and power loading can maximize the achievable data rates of

OFDM based Li-Fi systems by adapting the system loading to the channel frequency response.

A. Single Carrier Modulations

Widely used single-carrier modulation (SCM) schemes for Li-Fi include on-off keying (OOK), pulse position modulation (PPM) and pulse amplitude modulation (PAM), which have been studied in wireless infrared (IR) communication systems.

1. On-Off keying (OOK)

On-off keying (OOK) denotes the simplest form of amplitude-shift keying (ASK) modulation that represents digital data at the presence or absence of a carrier wave. In its simplest form, the presence of a carrier for a specific duration represents a binary one, while its absence for the same duration represents a binary zero. OOK is more spectrally efficient than frequency-shift keying, but more sensitive to noise when using a regenerative receiver or a poorly implemented super-heterodyne receiver. For a given data rate, the bandwidth of a BPSK (Binary Phase Shift keying) signal and the bandwidth of OOK signal are equal. In addition to RF carrier waves, OOK is also used in optical communication systems.

2. Variable Pulse Position Modulation (VPPM)

PPM encodes the data using the position of the pulse within a set time period. The duration of the period containing the pulse must be long enough to allow different positions to be identified. VPPM is similar to PPM but it allows the pulse width to be controlled to support light dimming.

3. Pulse Amplitude Modulation (M-PAM)

By encoding the information in the amplitude of the pulse, the spectral efficiency of the single-carrier OWC can be increased. If we unite M-PPM and M-PAM in a hybrid system (M-PAPM), we can increase the spectral efficiency further.

4. Pulse Width Modulation (PWM)

Pulse-width modulation (PWM), or pulse-duration modulation (PDM), is a modulation technique used to encode a message into a pulsing signal. The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there is practically no current, and when it is on and power is being transferred to the load, there is almost no voltage drop across the switch.

B. Multiple Carrier Modulations

For high-speed optical wireless communication, efforts are drawn to multi-carrier modulation (MCM). Compared with SCM, MCM is more bandwidth-efficient but less energy-efficient. One and perhaps the most common realization of MCM in Li-Fi networks is orthogonal frequency division multiplexing (OFDM), where parallel data streams are transmitted simultaneously through a collection of orthogonal subcarriers and complex equalizer circuitry can be omitted. [3] Each sub-channel can be considered as a flat fading channel.

1. ACO-OFDM (Asymmetrically clipped optical OFDM)

A real unipolar OFDM waveform can be achieved by exploiting the Fourier transformation properties on the frequency domain input OFDM frames. The principle of ACO-OFDM is to skip the even subcarriers of an OFDM frame, by only loading the odd subcarriers with useful information. This creates asymmetry in the time domain OFDM signal, without the need of any DC biasing. Clipping of the negative values is distortion-less since all of the distortion will only affect the even indexed subcarriers. However, skipping half of the subcarriers reduces the SE of ACO-OFDM to half of that in DCO-OFDM. A penalty of 3 dB should be applied to the signal-to-noise ratio (SNR) of ACO-OFDM when compared with bipolar OFDM, since half of the signal power is lost due to clipping. Hermitian symmetry is also used to guarantee a real valued ACO-OFDM output. At the receiver, after a fast Fourier transformation (FFT) is applied on the incoming frame, only odd subcarriers are considered. [3]

2. PAM-DMT (PAM Discrete Multi-tone)

A real unipolar optical OFDM is realized in PAM-DMT by exploiting the Fourier properties of imaginary signals. The real component of the subcarriers is not used in PAM-DMT, which restricts the modulation scheme used to M-PAM. By only loading M-PAM modulated symbols on the imaginary components of the subcarriers, an anti-symmetry in the time domain waveform of PAM-DMT would be achieved. This would facilitate the distortion-less zero level clipping of PAM DMT waveform, as all of the distortion would only affect the real component of the subcarriers. Hermitian symmetry is also used to guarantee a real valued PAM-DMT output. PAM-DMT is more attractive than ACO-OFDM when bit loading techniques are considered, as the PAM-DMT performance can be optimally adapted to the frequency response of the channel since all of the subcarriers are used. The SE of PAM-DMT is similar to that of DCO-OFDM. PAM-DMT has a 3 dB fixed penalty when compared with bipolar OFDM at an appropriate constellation size, as half of the power is also lost due to clipping. At the receiver, the imaginary part of the subcarriers is only considered, while the real part is ignored. [3]

3. U-OFDM/Flip-OFDM (Unipolar OFDM)

The concept and performance of U-OFDM and Flip-OFDM is identical. In this paper, the term U-OFDM is used, however, all discussion and analysis is applicable to both schemes. Hermitian symmetry is applied on the incoming frame of M-QAM symbols. The bipolar OFDM time-domain frame obtained afterwards is expanded into two time domain frames in U-OFDM with similar sizes to the original OFDM frame. The first frame is identical to the original frame, while the second is a flipped replica of the original frame. A unipolar

OFDM waveform can be achieved by zero-level clipping without the need of any DC biasing. At the receiver, each second frame would be subtracted from the first frame of the same pair, in order to reconstruct the original bipolar OFDM frame. This would double the noise at the receiver, which leads to a 3 dB penalty when compared with bipolar OFDM at equivalent constellation sizes. The SE of U‑OFDM is half of the SE of DCO‑OFDM since two U‑OFDM frames are required to convey the same information conveyed in a single DCO-OFDM frame. The single tap equalizer can be used for U‑OFDM, providing that the ISI effects on the first frame are identical to the ISI effects on the second frame. [3]

4. eU-OFDM (enchanced-UOFDM)

Superposition OFDM based modulation techniques rely on the fact that the SE of U‑OFDM/Flip-OFDM, ACO‑OFDM, and PAM‑DMT can be doubled by proper superimposing of multiple layers of OFDM waveforms. Superposition modulation was first introduced for OFDM ‑ based OWC and has led to enhanced U‑OFDM (eU-OFDM). The eU-OFDM compensates for the spectral efficiency loss of U‑OFDM by superimposing multiple U‑OFDM streams so that the inter-stream-interference is null. The generation method of the first depth in eU-OFDM is exactly similar to that in U‑OFDM. Subsequent depths can be generated by U‑OFDM modulators before each unipolar OFDM frame is repeated 2d‑1 times and scaled by 1/2d‑1, where d is the depth number. At the receiver, the information conveyed in the first depth is demodulated and then re-modulated to be subtracted from the overall received signal. Then repeated frames which are equivalent at higher depths are recombined and the demodulation procedure continues the same as for the stream at the first depth. [3]

5. e-PAM-DMT (enhanced PAM-DMT)

.The enhanced pulse-amplitude-modulated discrete multi-tone (ePAM‑DMT) demonstrates that superposition modulation can also be utilized when the anti-symmetry of PAM‑DMT waveforms is used. Analogous to eU-OFDM and eACO-OFDM, unique time-domain structures are also present in PAM‑DMT. If the interference over a single PAM‑DMT frame possesses a Hermitian symmetry in the time-domain, its frequency profile falls on the real component of the subcarriers. Hence, the interference is completely orthogonal to the useful information which is encoded in imaginary symbols of the PAM-DMT frames. [3]

C. Li-Fi Specific Modulations (Domain)

Li-Fi transmitters are generally designed not only for wire-less communication but also for illumination, which can be realized either by using blue LEDs with yellow phosphorus or by mixing through colored LEDs. Luminaries equipped with multicolored LEDs can provide further possibilities for signal modulation and detection in Li-Fi systems.[3]

1. Color Shift Keying (CSK)

This is used if the illumination system uses RGB-type LEDs. By combining different colors of light, the output data can be carried by the color itself and hence the intensity of the output can be near constant. Mixing of RGB primary sources produces different colors which are coded as information bits. [3] The CSK modulation requires complex design at the transmitter and receiver end of optical system. This is the only disadvantage of CSK modulation. In spite, of this, the CSK modulation has advantages due to which it has become very popular. co-ordinates are used to represent information and the same is represented in the form of binary codes for simplicity in programming. As information is represented by of light, amplitude is kept constant and hence total average power of light sources will be kept constant. CSK helps achieve variable high bit rate due to higher order modulation support such as 4-CSK, 8-CSK and 16-CSK. [4]

2. Color Intensity Modulation (CIM)

Color intensity modulation (CIM) was proposed to improve the communication capacity without any loss to the illumination properties (dimming and target color-matching).The instantaneous intensity of the RGB LED was modulated in CIM while only maintaining a constant perceived color. Therefore, CIM can be considered as a relaxed version of CSK since a constant perceived power is additionally required in CSK [3].

3. Metameric modulation (MM)

Metameric modulation (MM) constrains the CSK to have a constant instantaneous perceived ambient light with the aid of an external green LED. An improved control of the RGB output color was achieved in MM by improving the color rendering and reducing the color flickering [3].

IV. SIMULATION OF SOME SCM TECHNIQUES

A. On-Off Keying Method

For the simulation of these schemes we have used the tool of Simulink of MATLAB.
The blocks were taken from Simulink and Simscape toolboxes.

In order to see the simulation of Simscape blocks in Simulink we need to use two special blocks known as :

- *Solver Configuration* : The Solver Configuration block is a necessary block for all Simscape models. Unlike other Simscape blocks such as motors or springs, it does not represent a physical part in the overall system. Instead, it is used to specify simulation options for your physical system, such as the type of solver to use, initialization options, and the sample time for the simulation.

- *PS-S and S-PS Block* : The PS-Simulink Converter block converts a physical signal into a Simulink output signal. We use this block to connect outputs of a Physical Network diagram to Simulink scopes or other Simulink blocks. The Output signal unit parameter lets you specify the desired units for the output signal. These units must be commensurate with the units of the input physical signal coming into the block.

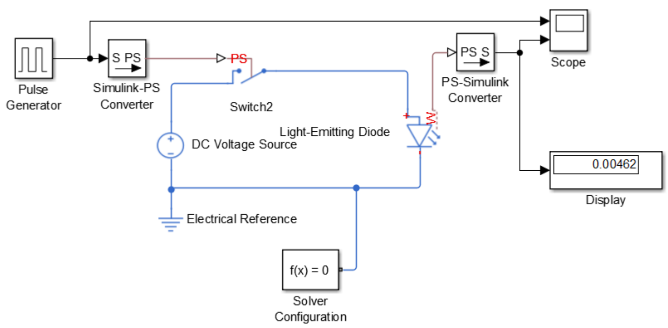

Fig 6 Simulation Circuit (OOK)

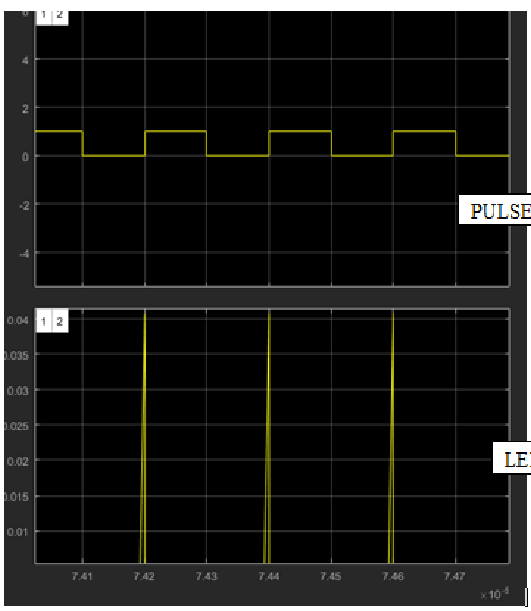

Fig 7 Simulation Output (OOK)

As we can see for every rising edge we get a spike response from the LED.
This indicates the working of ON-OFF keying where the data is modulated by continuous switching On and Off of the LED.

The following Table shows spike duration of LED for different pulse period:

Pulse Period (seconds)	Spike Duration (seconds)
2e-7 sec	4.278 ns
2e-8 sec	839.38 ps
2e-9 sec	110.95 ps

Table 4 Spike Durations for varying Pulse width

Thus we can attain higher switching speed for higher frequency range.

B. PWM Method

For this Modulation scheme we give a PWM signal as the input to the LED via a switch.
The input signal is then transmitted physically from the LED at the transmitter side to the photodiode at the receiver side.
The photo-diode captures all the intensity of light falling on it and then fluctuates the current proportionally. We can then place a voltage sensor in order to detect the signal and use a scope to display it.

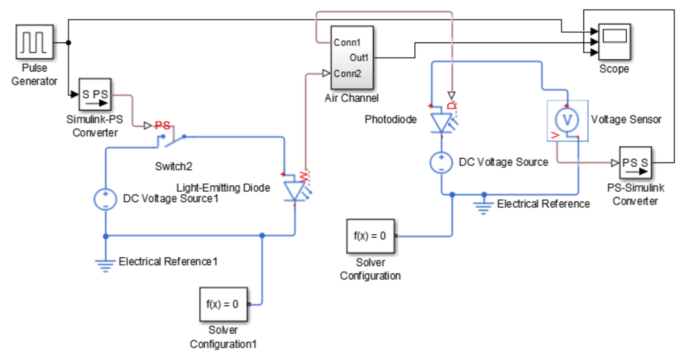

Fig 8 Simulation Circuit (PWM)

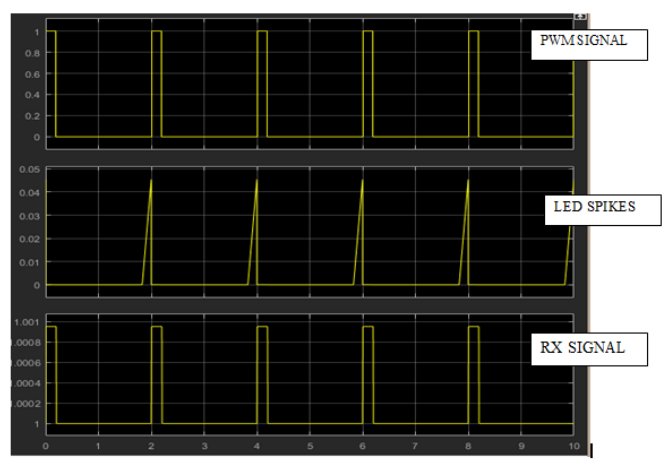

Fig 9 Simulation Output (PWM)

In the above figure, the first graph displays the PWM signal that is given to the LED.
The second graph shows the corresponding spikes generated at each pulse which is captured by the photo-diode as light pulses.
The third graph shows the received signal after getting captured by the photodiode.
As we can see the PWM signal transmitted by the LED is captured as it is by the photodiode on the receiver side.

V. CONCLUSIONS

Li-Fi currently is being explored and researched on a large scale in order to deal with the shortage RF bandwidth and increasing application requirements. Li-Fi solve issues such as the shortage of radio-frequency bandwidth and also allow internet where traditional radio based wireless isn't allowed such as aircraft or hospitals. If this technology can be put into practical use then every bulb can be used something like a Wi-Fi hotspot to transmit wireless data and we will proceed toward the safe, attractive, and beautiful future. The new technology Li-Fi is currently attracting a great deal of interest of researchers because it may offer a great and very efficient alternative to radio-based wireless.

The physical layer configurations PHY-I, PHY-I and PHY-III can provide data ranges 12-267 k-bits/sec, 1.25-96 M-bits/sec and 12-96 M-bits/sec respectively.

There are various modulation schemes being researched for the use in Li-Fi technology

These techniques should satisfy illumination and communication requirements. Single carrier modulation techniques offer a simple solution for frequency flat Li-Fi channels. Low to medium data rates can be achieved using single carrier modulation techniques. Multicarrier modulation techniques offer high data rates solution that can adapt the system performance to the channel frequency response.

The color domain modulation techniques requires complex design at the transmitter and receiver end of optical system. This is the only disadvantage of CSK modulation. In spite of this, the CSK modulation has many advantages due to which it has become very popular.

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