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Design of RoF-VLC based WDM Communication System based on Pre-DCF Technique

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ABSTRACT Radio over Fiber with Visible Light Communication system (RoF-VLC) is a promising technology that integrates the benefits of optical fiber communication and wireless transmission. This abstract presents a novel approach to enhance the RoF system by integrating VLC with millimeter-wave (mmWave) technology, leveraging the advantages of both systems. The proposed system utilizes mmWave signals over a single optical fiber link through a Wavelength Division Multiplexing (WDM) technology to enable the simultaneous transmission of multiple VLC system. However, challenges arise when extending the reach of VLC systems over long distances due to optical fiber dispersion. This paper explores the application of pre-Dispersion Compensation Fiber (pre-DCF) techniques to address dispersion issues in RoF-VLC systems. The study begins with an overview of RoF and VLC technologies, highlighting their respective strengths. RoF enables the seamless transmission of wireless signals over optical fibers, while VLC harnesses the visible light spectrum for data communication. The integration of these technologies holds potential for enhanced coverage and reliability. Dispersion, a critical concern in optical fiber communication, can degrade the quality of transmitted signals. Pre-DCF techniques are introduced as a proactive solution to mitigate dispersion effects before they compromise signal integrity. By combining these technologies, the proposed system achieves high-speed data transmission and increased network capacity. WDM technology plays a crucial role in the proposed system by enabling the simultaneous transmission of VLC and mm Wave signals over a single optical fiber. The RoF-VLC system based on WDM technology is built and simulated using OptiSystem software, with four WDM channels at 450 nm, 450.8 nm, 451.6 nm, and 452.4 nm as an optical source of VLC system and a photodetector as a receiver. Each channel with a 40 GHz radio signal is transmitted over a 40 km of fiber link and a 3 m of VLC channel. This proposed design of RoF-VLC system based on WDM has been analyzed based on the effect of propagation distance (km), modulation format, data rate, and input power. The performance analysis show that this system is achieved by using the values of BER at $2.6355e^{-009}$ for channel 1, $7.54389e^{-010}$ for channel 2, $5.39904e^{-010}$ for channel 3, and $2.45532e^{-010}$ for channel 4.

KEYWORDS Radio over fiber, VLC system, mm-Waves, WDM technology, Pre-DCF

I. INTRODUCTION

In recent years there is growing research in visible light communications (VLC), which is an important branch of optical wireless communications. The other major reason for the use of visible light communications [1], is because it uses frequency range between 400 THz to 800 THz of unlicensed secure and radio free media for wireless communications which are 1000 times more than that of radio communications [2],[3]. This process of transferring the data through optical communications is relatively less complicated and also less costly compared to that of the RF communications. The Radio Frequency (RF) band (3 kHz to 300 GHz) has previously been the most popular band for wireless communications within the electromagnetic (EM) spectrum. However, the demand for wireless traffic is increasing rapidly, the RF range has gotten clogged. This limitation will not be addressed by existing approaches for capacity increase, better spatial reuse, or inter-cell interference coordination. To continuously enhance the capacity, a new communications medium and an alternative technology are needed. In this sense, VLC using the visible light band emerging as an alternative to conventional RF communication techniques and may be used to supplement present RF systems, particularly in indoor settings. When compared to RF, VLC has certain features that allow it to provide secure, affordable, and speedy communications [4].

The growing large-bandwidth demand applications and users have recently driven the indoor access networks to deliver various dates through wired and wireless networks in a single and integrated communication platform [5]. Radio over fiber (RoF) technology combines wireless communication flexibility with high bandwidth and low optical fiber communication loss effectively. It can provide ubiquitous wireless access for indoor wireless networks and has received much attention in recent years [6],[4]. A hybrid RoF-VLC communication system is considered a candidate technique for future access networks for optical single mode fiber based large bandwidth transmission and RF based mm-Wave and visible light wireless communication [7],[6].

The introduction of Wavelength Division Multiplexing (WDM) has revolutionized the field of telecommunications by enabling the transmission of numerous high-speed data channels over a single fiber. It has played a crucial role in meeting the increasing demand for higher data rates and increased capacity in communication networks. Multiple signals can be simultaneously transmitted over a transmission medium, whether an optical fiber or optical wireless, by assigning each signal to a specific wavelength of light. This allows for efficient utilization of the available bandwidth and significantly increases the capacity of the system. While WDM has been effectively used in many communication systems, VLC is still a subject of little research, and there is still room for advancement.

In terms of radio over fiber and VLC systems based on WDM technology, no research has been done to yet. In comparison to earlier research, the designed RoF-VLC system provided higher data rates with a high capacity network. However, as and when the number of users expands, the combination of wireless and optical fiber connection generates non-linear effects such as signal noise, spurious frequencies, poor signal quality, and longer delay occur [8]. Therefore, in this paper suggested development of RoF-VLC system based on WDM using pre-DCF techniques to mitigate the non-linear effects.

II. Theoretical background, methods and experimental setup

A. Theoretical background

RoF is a technology that involves the transmission of radio signals over optical fiber networks [9][10]. In traditional RoF systems, the radio signals are modulated onto an optical carrier using techniques like intensity modulation or direct modulation [11]. The modulated optical signal is then transmitted over the fiber, where it can be easily distributed over long distances with low loss and minimal interference [12].

VLC is a wireless communication technology that utilizes visible light for data transmission [13]. It utilizes the concept of intensity modulation and direct detection, where the light intensity is modulated to carry the data [14]. VLC systems typically operate in the visible light spectrum, leveraging light-emitting diodes (LEDs) as the transmitting devices and photodiodes or image sensors as the receivers.

WDM is a multiplexing technique that enables multiple optical signals to be transmitted simultaneously over a single VLC system. It assigns different wavelengths (colors) to each signal, allowing them to coexist and be separated at the receiver end [15]. WDM technology provides high capacity and scalability to optical fiber networks by exploiting the wide spectral bandwidth available in VLC system [16].

The RoF-VLC hybrid system combines RoF and VLC technologies to achieve high-speed wireless communication using visible light. In this system, the radio signals are converted into optical signals using RoF techniques and then transmitted over the fiber using WDM technology. At the receiver end, the optical signals are demultiplexed using WDM, and the individual signals are converted back to radio signals for further processing.

By integrating RoF and VLC, the RoF-VLC system benefits from the advantages of both technologies [7]. RoF enables long-distance transmission and provides immunity to electromagnetic interference, while VLC offers high data rates and secure communication in localized areas. WDM technology allows multiple RoF-VLC channels to be transmitted over a single VLC system, increasing the overall system capacity. Overall, the theoretical background of RoF-VLC based on WDM technology involves the integration of RoF and VLC techniques with the use of WDM multiplexing to achieve efficient, high-speed wireless communication using visible light.

B. Block diagram of RoF-VLC system

The block diagram of the transceiver is shown in Figure 3.3. As in the diagram, there are 3 parts involved which is transmitter as RoF-Tx, medium as RoF-Rx/VLC-Tx and receiver as VLC-Rx. The first stage, the Pseudo-Random Bit Sequence (PRBS) generator data which get encoded by NRZ and RZ encoder before mixed together with RF carrier at mm Wave frequency of 40 GHz. The resulting electrical signal is optically modulated by external modulation process using Mach Zehnder Modulator (MZM). The optical light source will be injected into the MZM and carried the electrical signal at wavelength of 1550 nm. The light signals are then multiplexed in the wavelength domain and transmitted over the fiber optics channel. The optical signal after MZM will travel along the fiber at attenuation of 0.2 dB and in the range of 40 km. The fiber loss and attenuation loss will reduce the optical signal level after gone through certain distance. The signal can be boost up if using the amplifiers. However, in this design, amplifiers not be included in the system as the output of optical signal after 40 km can be retrieved back at RoF-Rx (Base station). At the RoF-Rx/VLC-Tx, the PIN photodiode will detect the optical signal and converted to electrical. This conversion process is performed at the photodiode, which generates an electrical signal proportional to the received optical power. In this part also, the mmWave signal will be transmitted again into the VLC medium at distance of 3 m by modulating with optical carrier at wavelength of 450 nm. At the receiver of VLC-Rx, the PIN transforms the optical signal which travel in the Visible Light medium to electrical signal. It then passed through a filter that reflect the broad noise the signal is passed through the 3 Regenerator to regenerate back the data.

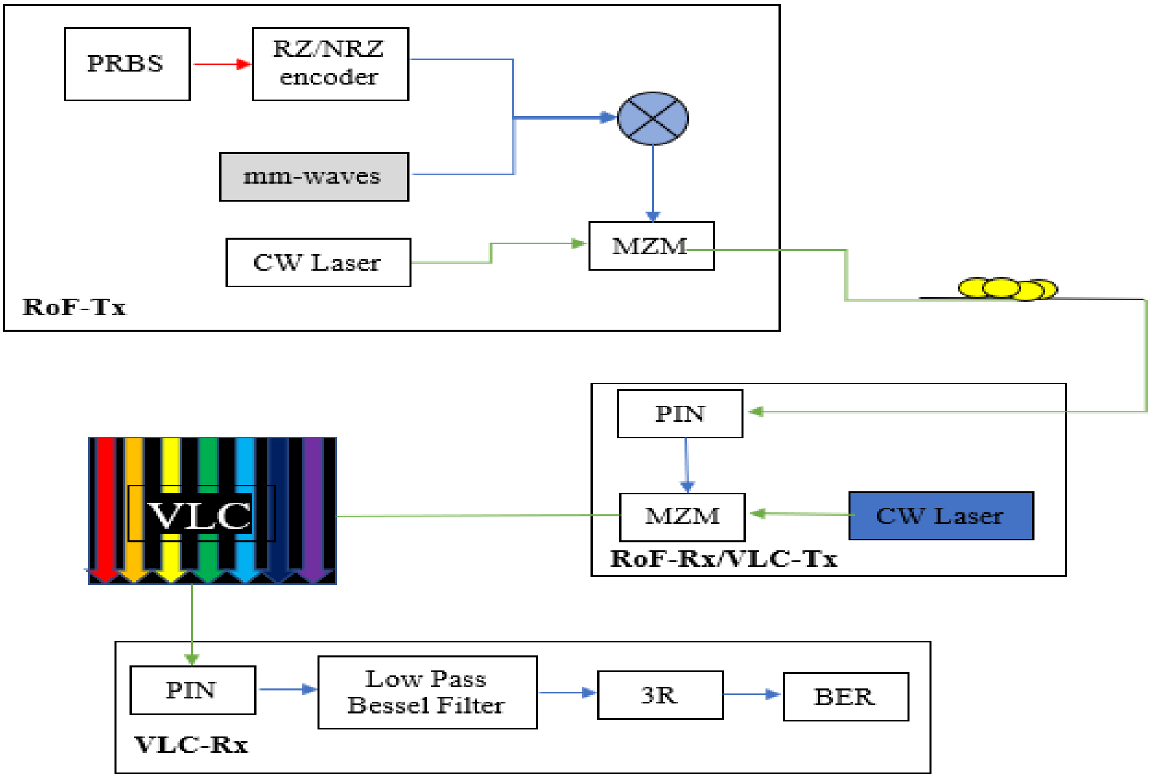


Figure 1: Block diagram of radio over a fiber with a VLC system

C. Block Diagram of Pre-DCF technique

The compensating dispersion that Pre-DCF introduces when an optical signal travels through it before entering the main transmission fiber as shown in Figure 2. As a result, the optical signal entering the transmission fiber is more regulated and less diffused. Pre-DCF enables network administrators to better control chromatic dispersion and uphold superior signal quality throughout the entire optical communication system. This is crucial in long-distance and high-speed communication systems where signal integrity might be compromised by dispersion.

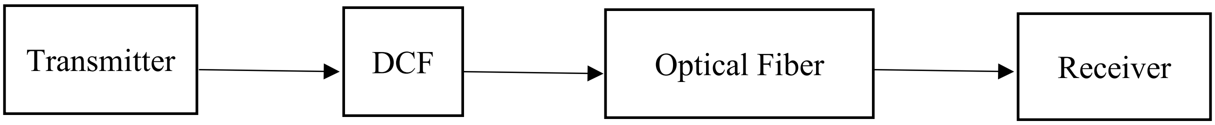


Figure 2: Block diagram of Pre-DCF [17]

D. Parameter for system design

All the selected parameters will be introduced and all the specifications will be shown. The table below shows the model's full specification and system designs based on NRZ encoding techniques. There were 4 channels with 0.8 nm channels spacing as input for VLC system which is 450 nm, 450.8 nm, 451.6 nm, and 452.4 nm with each carrying 9 Gbps of data rate. The range used for fiber is 40 km and for VLC is 3 m. Here PIN photodetector is used with 0.9 A/W of responsivity and 10 nA of dark current.

Table 1: Design specification table

Specification	Parameter	Value
Simulation window	Data rate	9 Gbps
	Time window	5.67e-008 s
	Sample rate	576000000000 Hz
	No of channel	4
	Channel spacing	0.8 nm
PIN photodetector	Responsivity	0.9 A/W
	Dark current	10 nA
Sine Generator	Frequency	40 GHz
Fiber	Wavelength	1550 nm
	Range	40 Km
VLC Channel	Range	3 m
	Attenuation	0.2 dB/Km
Modulation Type	NRZ	

Table 2 Value of CW laser used

	Channel 1	Channel 2	Channel 3	Channel 4
VLC	450 nm	450.8 nm	451.6 nm	452.4 nm

III. Simulation Design

The Radio over fiber with VLC system based on WDM for mm-wave was designed by OptiSystem software, which is shown in Figure 3 and with its parameters of table 1 and table 2. This design has four transmitter and receiver channels, with each carrying 9 Gbps of data rate placed on the RF signal. At the RoF transmitter (Tx) side, consists of a message signal generated through a sequence generator (in Gbps), a Pseudo-Random Bit Sequence generator (PRBS). The PRBS signal is passed through the electrical pulse generator, via NRZ which converts the bit sequence in the form of 0 and 1 into an electrical pulse. A sine generator of 40 GHz with 0 degrees of phase for RF signal is used in an electrical multiplier to mix the data. This mixed data and CW laser with a wavelength of 1550 nm as an input source are modulated using a MZM. Using MZM, this signal is subsequently transformed into an optical signal. Then, MZM is connected with DCF of 5 km and the signal will pass through a single fiber mode with a length of 35 km and attenuation is 0.2 dB per km. The signal is pumped into an optical fiber. At receiver side, a suitable photodetector is then used to transform the received optical signal into an electrical signal before being coupled with VLC transmitter. PIN photodetector is the type of photodetector used here. The signal from PIN goes through MZM that acts as a mixer to connected with CW laser at 450 nm. This technique was repeated for 4 channels as input for transmitter CW laser wavelengths have been employed by

WDM which was 450 nm, 450.8 nm, 451.6 nm, and 452.4 nm to transport 9 Gbps of information (9 Gbps × 4λ). The modulation electric signal could transmit through the VLC channel by employing optical waves when optically modulated by MZM. Here distance between VLC transmitter and receiver is 3 m and attenuation are 0.2 dB per km. The WDM DEMUX is used to demultiplexing the signal. Then, the signal will be sent to optical attenuator to reduce the power level of an optical signal. Next, the data is converted back into electrical form by the photo detector. The electrical signal is then sent to the low pass Bessel filter which having cut off frequency of 0.75 × bit rate Hz is used to remove the other undesired frequency components of the transmitted signal. The electrical signal is re-timed, reshaped, and re-amplified using the 3R regenerator. A BER analyzer is used to evaluate the performance of a received electrical transmission.

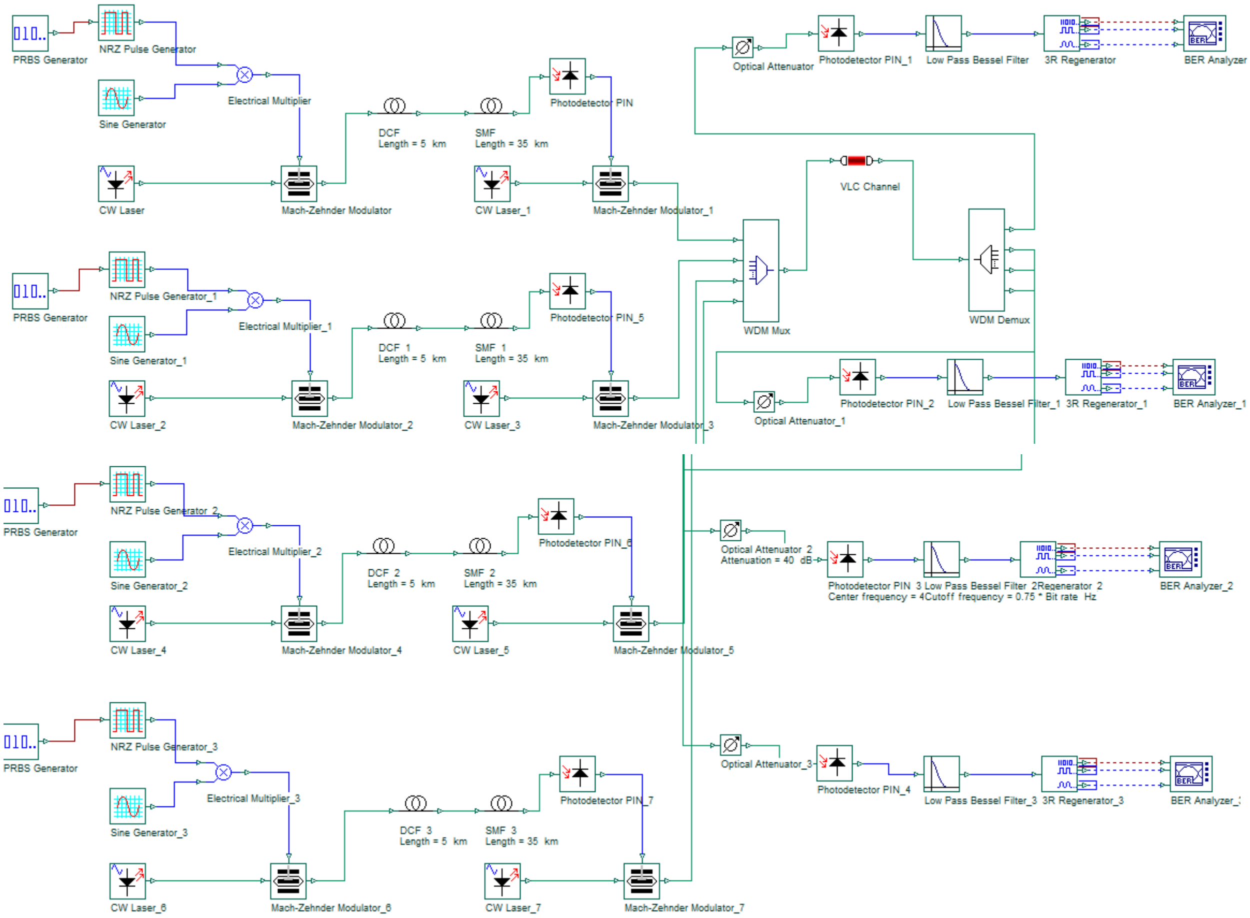


Figure 3: Radio over fiber-VLC system based on WDM using Pre-DCF Technique in optisystem

IV. Results and discussion

A. Simulation Design

Figure 4 shows the output of an oscilloscope visualizer which is connected to NRZ pulse generator. The NRZ Pulse Generator electrical signal is shown by the oscilloscope visualizer as part of its operation. This system made use of an oscilloscope visualizer with four channels. Due to almost similar performance for each channel, the following results are taken from channel 1.

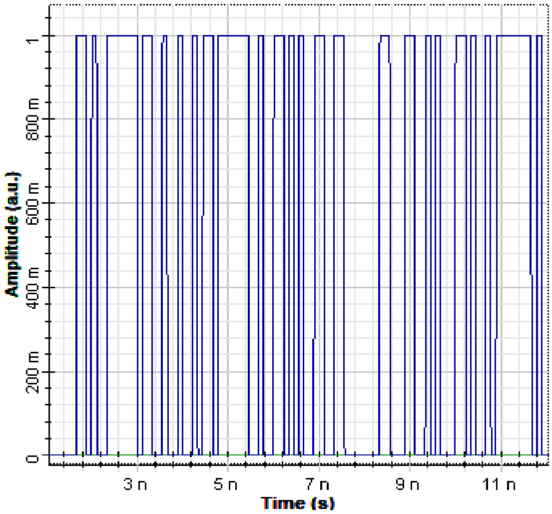


Figure 4: The output of an oscilloscope visualiser which is connected to NRZ pulse generator

Figure 5 shows the output of the sine generator, which is the mm-wave carrier with data. The generated mm-wave carrier is at frequency of 40 GHz. Results show that the generated mm-wave carriers have power at approximately equals −27 dBm. Figure 6 represents the bit sequence of the electrical multiplier which combines the RF signals at 40 GHz of mm-wave with the code sequences.

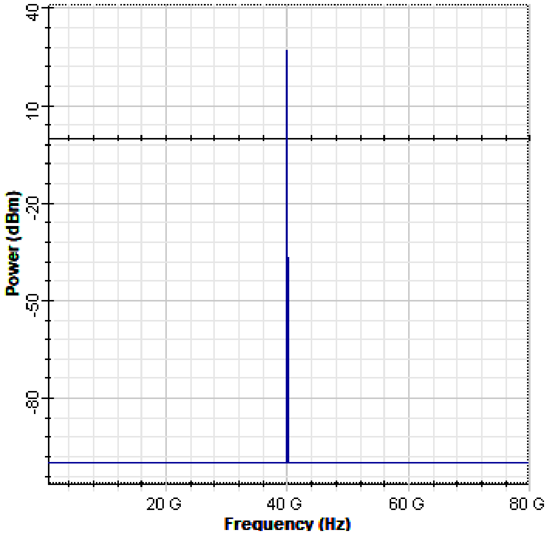


Figure 5: The RF spectrum at the sine generator output showing the 40 GHz of mm-wave modulated data.

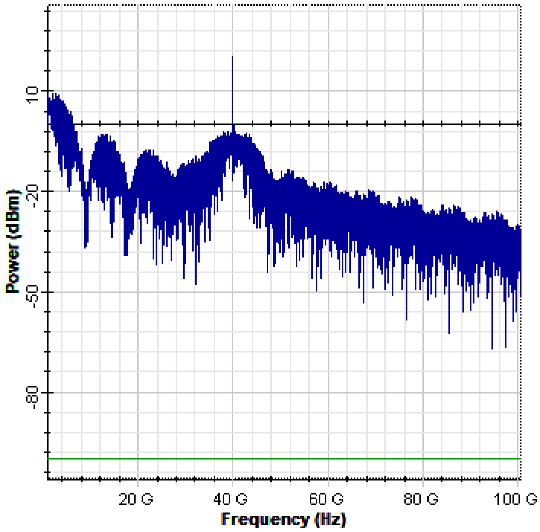
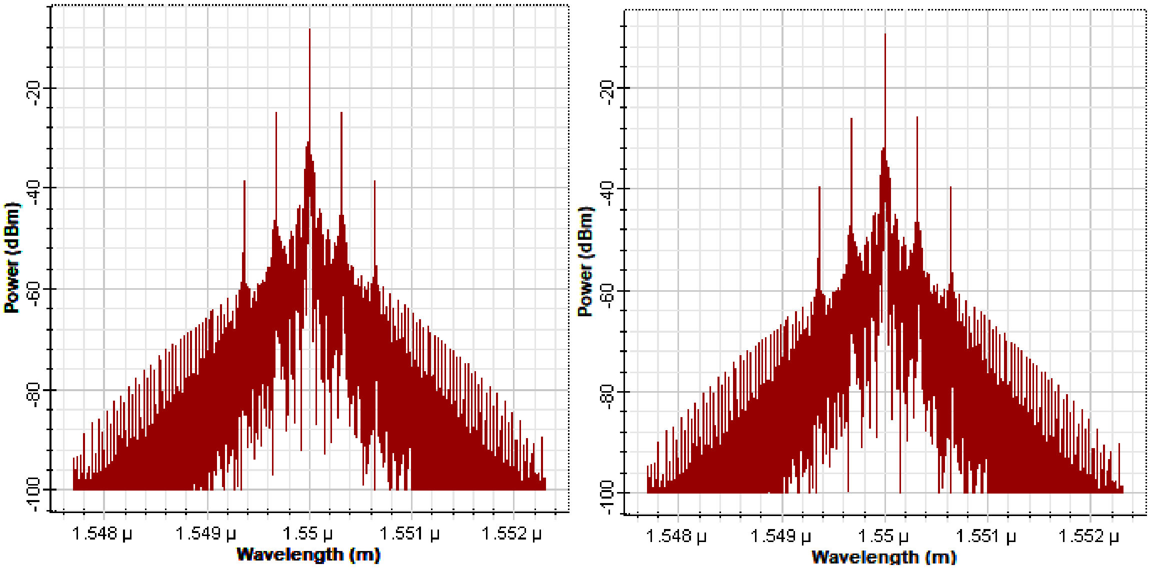
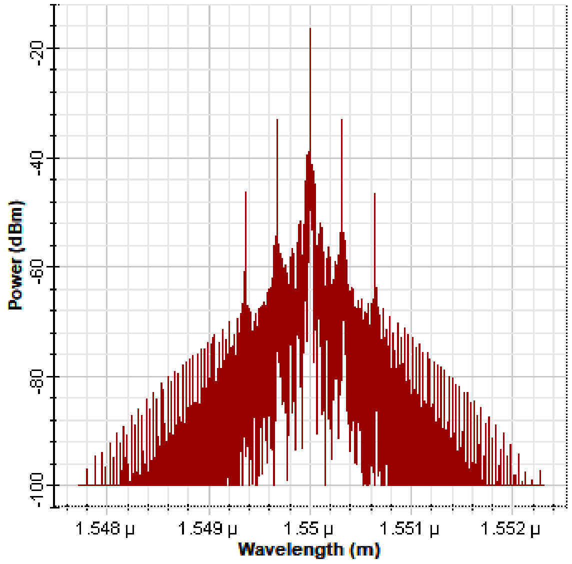


Figure 6: The RF spectrum at the Electrical multiplier output of the upper sideband showing the 40 GHz of mm-wave signal mix with 9 Gbps of NRZ

Figure 7 (a) illustrate the RoF transmitter modulated data on the CW laser at a wavelength of 1550 nm using Mach-Zehnder Modulator (MZM). Continuous-wave (CW) laser beams each having a power level of 0 dBm are fed to four transmitters, outputs of which are modulated by MZM using a PRBS with NRZ format and RF signal using sine generator which combined using an electrical multiplier. The power at frequency carrier is about -8.36 dBm. The signal spectrum for 1550 nm at fiber after traveling through 5 km of DCF is shown in Figure 7 (b). The generated power at frequency carrier is about -9.36 dBm. Output of the SMF which is set at 35 km and the result can be seen in the wavelength dBm unit in Figure 7 (c). The power at frequency carrier is about -16.36 dBm



(a) (b)



(c)

Figure 7: Optical spectrum (a) after MZM, (b) after travelling through 5 Km of DCF (c) after travelling through 35 Km of SMF

Figure 8 shows the output of the optical receiver of RoF, which is the mm-wave carrier with data. The loss of the signal was determined in the received signal and then once more changed into an electrical signal by means of the photodetector. When these RF signals are mixed with optical fiber in radio over fiber, the intermodulation distortion (IMD) effect can occur. This mixing can result in the generation of new frequencies, including spurious frequencies, which were not present in the original signals.

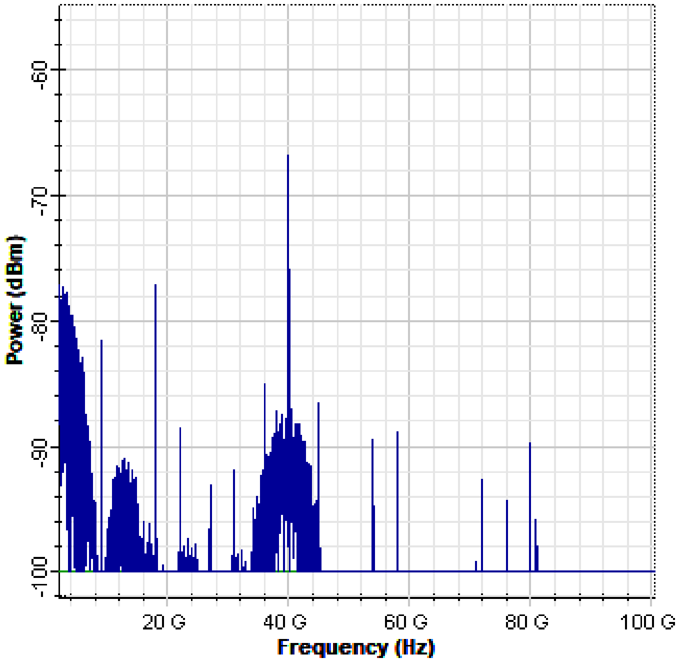
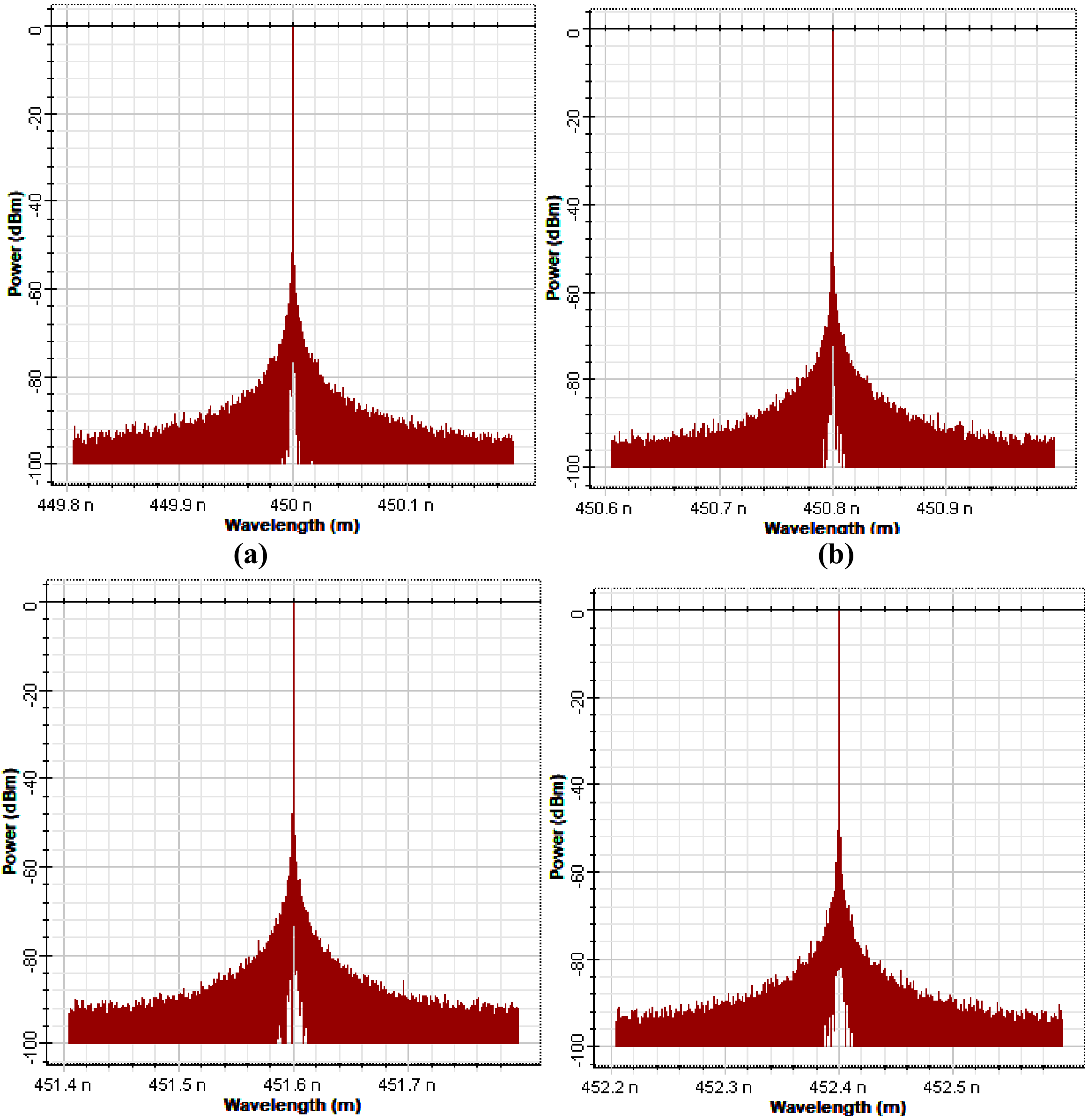


Figure 8: RF spectrum for the RoF signals after photodetector PIN showing the 40 GHz of mm-wave signal

The optical spectrum was measured at different wavelengths in nm from a VLC transmitter in Figure 9 (a) 450 nm, (b) 450.8 nm, (c) 451.6 nm and (d) 452.4 nm. In this architecture, four signals are transmitted with different wavelengths. Each wavelength values are 450 nm, 450.8 nm, 451.6 nm, and 452.4.



(a) (b)

(c) (d)

Figure 9: The optical spectrum with CW laser is set at (a) 450 nm, (b) 450.8 nm, (c) 451.6 nm and (d) 452.4 nm

Four signals are then combined by the WDM multiplexer and launched through the VLC link. Optical spectrums of WDM multiplexer signal transmitted 4 channels with 0.8 nm channel spacing and 9 Gbps data rate over Visible Light Communication link is simulated and analyzed. Figure 10 shows the optical spectrum after being multiplexed by the WDM multiplexer and travelling through VLC medium. The transmission wavelength spectrums of four WDM channels travelling through the VLC link for wavelength 450 nm, 450.8 nm, 451.6 nm and 452.4 nm with the power which is about 71.89 dBm, 72.65 dBm, 72.40 dBm, and 72.77 dBm, respectively. By sampling method 4 channels, $\lambda1$ = 450 nm, $\lambda2$ = 450.8 nm, $\lambda3$ =451.6 nm and $\lambda4$ = 452.4 nm are selected for observation of WDM-Visible Light Communication system. Then, the signal is demultiplexed by WDM demultiplexer. Optical spectrums of the signals at the exit of WDM DeMux at the receiver side of the hybrid WDM is shown in Figure 11.

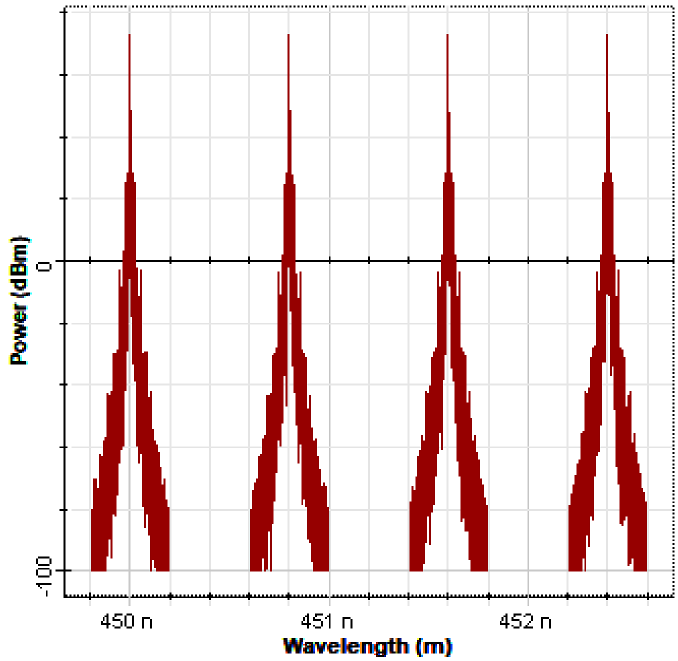
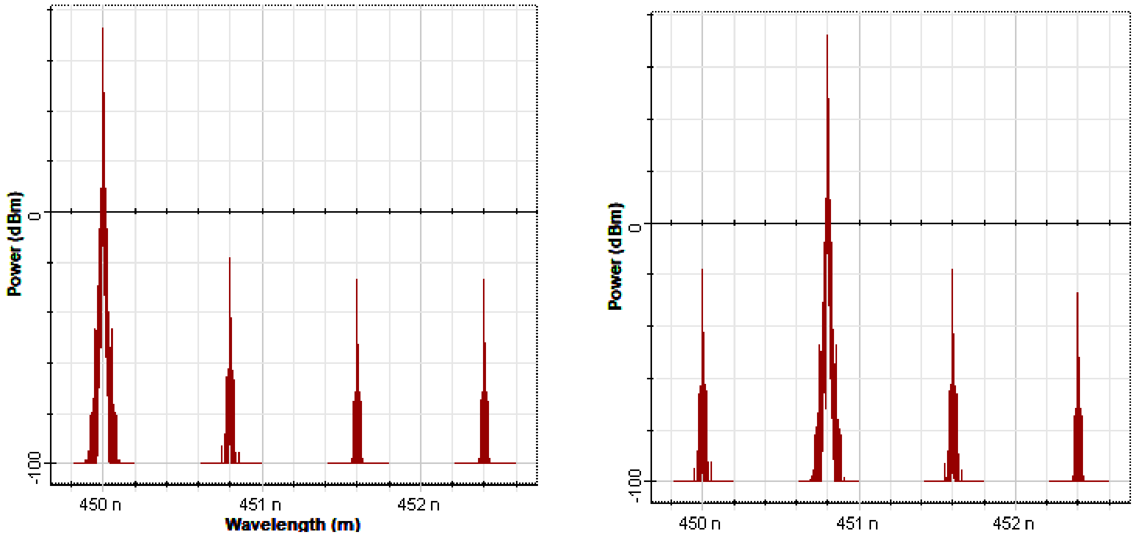
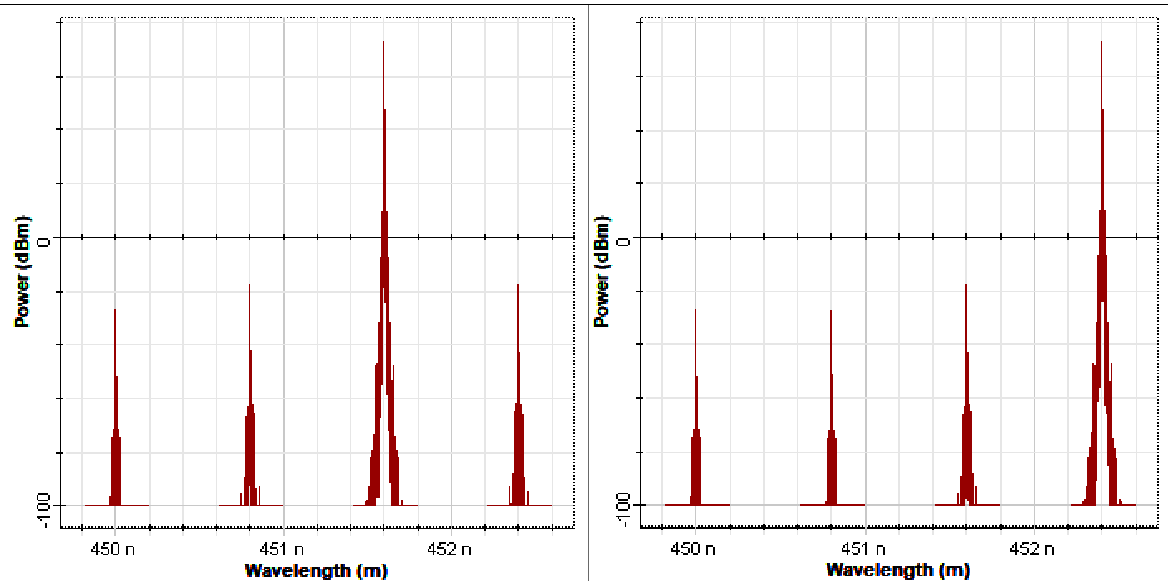


Figure 10: Optical spectrum of VLC system



(a) **b)**



(c) **(d)**

Figure 11: Optical spectrum demultiplexed by WDM (a) 450 nm, (b) 450.8 nm, (c) 451.6 nm and (d) 452.4 nm

At the RoF-VLC receiver, the output optical signal is detected by PIN photodetector to convert into electrical signals, as shown in Figure 12. The generated mm-wave carrier is at frequency of 40 GHz with power is -45.93 dBm has been successfully received.

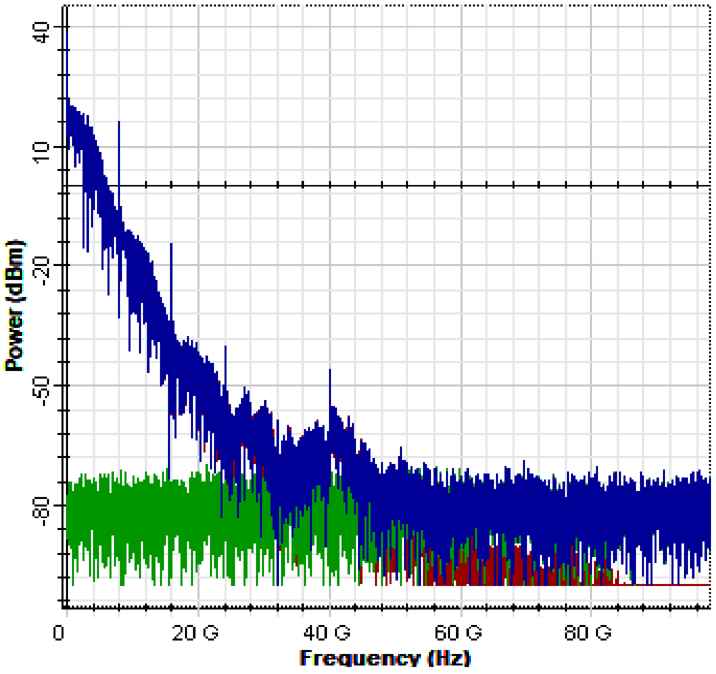


Figure 12: RF spectrum for the RoF-VLC signal after PIN photodetector showing the 40 GHz of Mmwave signal

Figure 13 illustrates the RF spectrum of the low-pass Bessel filter. The low pass filter is employed to reject the other unwanted frequencies signal. As well as both figures show the detected signal that exactly reproduces the transmitted signal, whereas the blue lines indicate the received signal and green lines indicate the noise. Then the low noise signal is passed to the 3R regenerator to reproduce the original signal once more and examined the signal by eye diagram and BER analyzer in the simulation tool.

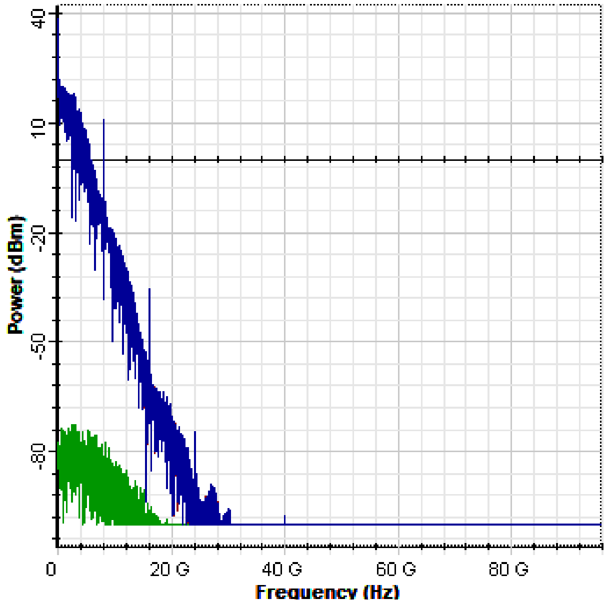
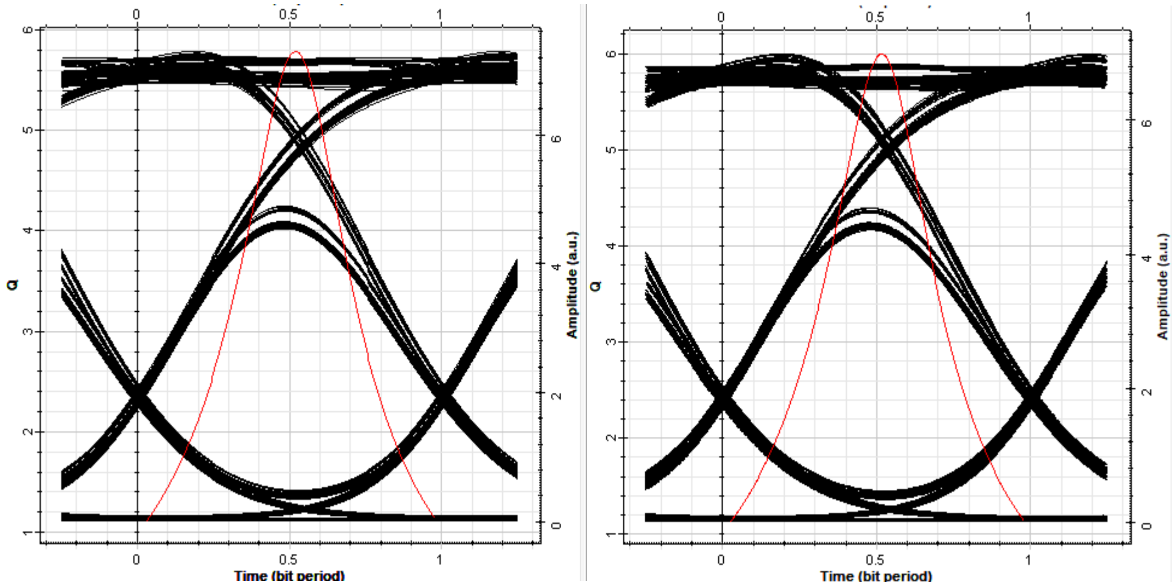
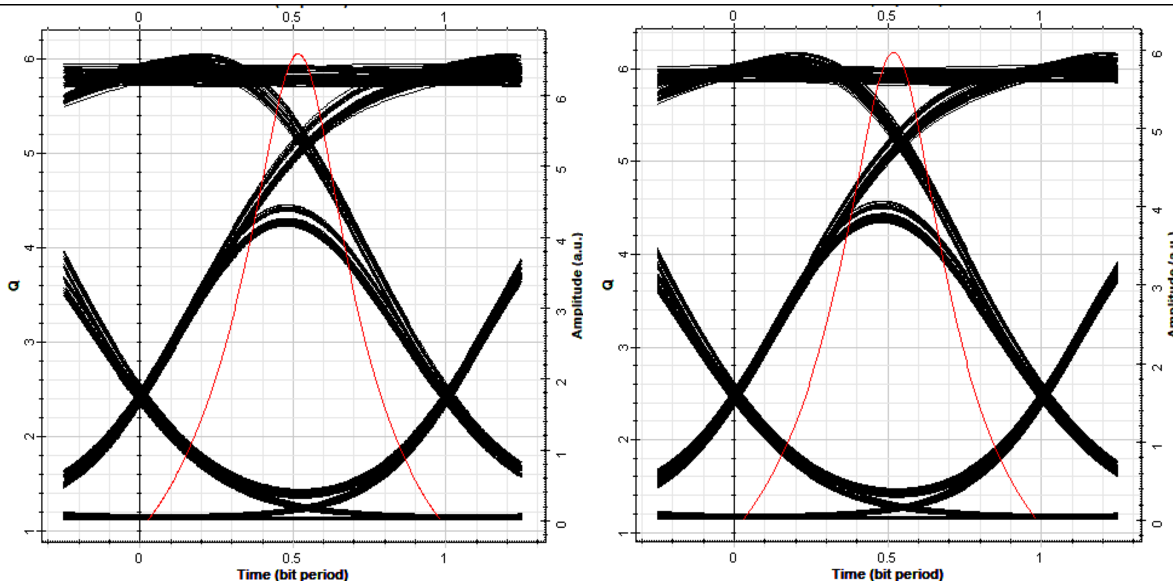


Figure 13: Electrical spectrum for the RoF-VLC signals after Low pass Bessel filter of the showing the 40 GHz of mm-wave signal

The analysis of the receiver performance of radio over fiber-VLC system based on WDM for 0.8 nm channel spacing can be seen in the simulation run of the BER. The results can be seen in Figures 14.



(a) **(b)**



(c) **(d)**

Figure 14: The eye diagram for radio over fiber-VLC system based on WDM. (a) Eye diagram at channel 1, (b) Eye diagram at channel 2, (c) Eye diagram at channel 3, and (d) Eye diagram at channel 4

Wavelength (nm)	Max.Q Factor	Min.BER	Eye Height	Threshold
450 nm	5.98462	$8.18536e^{-010}$	2.99246	1.23654
450.8 nm	5.86657	$1.6657e^{-009}$	2.95892	1.24558
451.6 nm	5.85011	$1.83193e^{-009}$	2.88654	1.21363
452.4 nm	5.89703	$1.39675e^{-009}$	2.9313	1.24664

Table 3 Performance of RoF-VLC system based on WDM

Table 3 shows the eye diagram description of designed Radio over fiber-VLC system based on WDM for mm-Waves for the bit rate of 9 Gbps at 40 Km of fiber length and 3 m of VLC link. The table signifies that the maximum quality factor, minimum bit error rate, eye height and threshold of eye diagram for the planned with different wavelengths using WDM structure. The maximum quality factor at 9 Gbps for the designed Channel 1 using 450 nm for VLC wavelength is 5.98462, minimum bit error rate is $8.18536e^{-010}$, maximum eye opening is 2.99246 and the threshold of eye diagram is 1.23654. The planned Channel 2 with 450.8 nm for VLC wavelength has a maximum quality factor of 5.86657, a minimum bit error rate of $1.6657e^{-009}$, a maximum eye opening of 2.95892, and an eye diagram threshold of 1.24558. For the proposed Channel 3 using 451.6 nm for VLC wavelength, the maximum quality factor is 5.85011, the minimum bit error rate is $1.83193e^{-009}$, the maximum eye opening is 2.88654, and the eye diagram threshold is 1.21363. The maximum quality factor for the designed Channel 4 using 452.4 nm for VLC wavelength is 5.89703, minimum bit error rate is $1.39675e^{-009,}$ maximum eye opening is 2.9313 and the threshold of eye diagram is 1.24664.

V. Conclusion

In conclusion, the integration of Radio over Fiber (RoF) with Visible Light Communication (VLC) system using Wavelength Division Multiplexing (WDM) offers several advantages and opens up new possibilities for wireless communication. The combination of RoF and VLC allows for the seamless transmission of radio signals over fiber-optic networks, leveraging the benefits of both technologies. RoF enables the long-distance and high-capacity transmission of radio signals, while VLC provides wireless communication through visible light, offering high-speed data transfer and secure communication. From this project, it can be concluded that a design for a radio over fiber with VLC system based on WDM technology successfully has been presented with 4 channel of CW Laser with the fiber wavelengths of 1550 nm were used for transmitting 9 Gbps of data per channel and RF signal at 40 GHz over the VLC channel with the wavelengths of 450 nm, 450.8 nm, 451.6 nm, and 452.4 nm at the distances of 3 m with some attenuations. In this study, Optisystem simulation has been applied to evaluate and present the performance results of WDM system radio over VLC link based on BER.

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