Vol. 8, No. 2 | July – Dec 2025

Performance Analysis of Blue Led-Based Visible Light Communication Using One-Dimensional Multidiagonal Codes

Kehkashan Asma Memon[1], Muhammad Anus Shaikh[1], Muhammad Ibrahim Shaikh[1], Fiza Afroze Baloch[2], QadirDad Baloch[3], Fahim Aziz Umrani[4], Zartasha Baloch[5]

Abstract:

Visible light communication (VLC) is a powerful technology that is already in use in various application areas, such as indoor VLC, outdoor vehicle-to-vehicle communication and, underwater communication. In this study, we present a VLC system design utilizing Blue Light Emitting Diodes (LEDs) along with Multi-Diagonal (MD) codes. Based on the Blue spectrum, the performance of this system is analysed using Opti-system software with Bit Error Rate (BER) and Quality factor (Q). Simulation results reveal that at a data rate of 100Mbps, the system achieves a BER of $2.38744\text{x}10^{-12}$ and a Q-factor of 6.43 over a link range of 1.3Km. Furthermore, performance analysis shows the impact of increasing the link range on BER & Q-factor, and it has shown that using MD codes, VLC is reliable at longer distances, making the proposed system suitable for diverse VLC applications. These findings underscore the potential of Blue LED-based VLC systems in achieving efficient Optical Wireless Communication.

Keywords: *VLC, Blue LED, MD codes, BER, Q-factor, Optisystem.*

1. Introduction

Increased data rates, greater dependability, and longer transmission distances are all benefits of optical communication, which employs light for transmission. Because of these factors, optical communication became a viable option for long-distance, high-capacity data transfer. It became a vital part of the data central infrastructure and internet backbone as a result [1]. VLC is the term for a communication system that uses light to carry the data and is located in the visible light range, which is 380–750 nm of the electromagnetic spectrum [2, 3].

[1]Dept. of Electronics, Mehran UET Jamshoro, Pakistan
[2]School of Business, University of Northeastern Boston, USA
[3]Dept. Of Physics, University of Massachusetts Boston, USA
[4]Dept. of Telecommunication, Mehran UET Jamshoro, Pakistan
[5]Dept. of Computer systems, Mehran UET Jamshoro, Pakistan
Corresponding Author: kehkashan@faculty.muet.edu.pk

This technology is growing and evolving due to the fascinating properties of the visible spectrum (380–750 nm) for data transmission. VLC has many advantages that are not available in conventional radio frequency (RF), like unregulated bandwidth, data rates in megabits and gigabits, improved safety of data, and strong resilience to electromagnetic (EM) interference. These characteristics make VLC ideal for use in indoor networking, automotive communication, underwater transmission, and RF-restricted locations like hospitals and aeroplanes. In addition to transportation, VLC is under research for making cities greener and RF-free. VLC can use existing lighting infrastructure, which will provide a low-cost and huge energy-saving alternative for extending communication networks [6,7]. Optical sources in VLC systems can be LEDs in signal color or multi RGB colors, which work as transmitters, whereas photodiodes like PIN or Avalanche can function as receivers. LEDs have many advantages, such as long life, low cost, and wide use in indoor VLC applications [8]. The core of VLC systems lies in the proper use of LEDs. Among various LED types, Blue LEDs have garnered attention due to their higher modulation bandwidth and reduced latency compared to phosphor-coated white LEDs. However, challenges such as multi-user interference, ambient noise, and limited transmission range still hinder optimal performance.

Several methods are observed in the literature to reduce the effects of ambient light interference [9,10]. As an example: through a capacitor, or a differential amplifier, or through a high pass filter [11]. The other possible alternative approach is to apply coding techniques on the transmitter side. The use of coding methods is critical in improving the system's robustness, as well as scalability. OCDMA codes have many variations, such as Optical Orthogonal Codes (OOC), Zero Correlation Zone (ZCZ), Multi-Diagonal (MD), Zero cross-correlation (ZCC), Modified Double Weight (MDW), Diagonal Double Weight (DDW), Modified Quadratic Congruence (MQC), and many others. We are investigating in this research the possibility of integrating One-Dimensional Multi-Diagonal (1D-MD) codes into a VLC system that uses Blue LED. Such codes are supposed to minimize cross-talk and improve signal integrity, especially with multiple users.

Spectral Amplitude Coding Optical Code Division Multiple Access (SAC-OCDMA) allows multiple users to use the same channel of communication by giving each user unique codes that guarantee that they can share the same channel, resulting in higher bandwidth usage and overall system capacity. It is particularly favorable when a number of users are trying to connect to the same network without interference [12].

These systems often use the Zero Correlation Zone (ZCZ) type of coding. It minimizes interference through the fact that signals of different users do not overlap within a specific zero correlation area. Small distances between users make ZCZ codes good. Nonetheless, as the number of users increases or the distance increases, the performance can be adversely affected to a small extent [13].

Multiple users can transfer data without interference using Optical Orthogonal Codes (OOC) in [14], although an excessive number of users reduces their efficiency. Small networks are ideal for them. For big systems, multi-diagonal (MD) codes work better because they eliminate multiple access interference while maintaining smooth data flow. They are excellent for fibre networks, VLC, and optical communication, and may be scaled for more users. Regardless of the number of users, MD codes offer 0% cross-correlation and are simple to integrate into hardware [15].

In [16], a study focused on how an indoor VLC system performs with SAC-OCDMA technology, using the OptiSystem simulation tool. They compared two encoding methods, FBG and WDM MUX, and two spreading codes, ZCZ and OOC. The findings showed that the WDM MUX encoding gave better signal quality than FBG, and the ZCZ code performed better in terms of BER than the OOC code.

An in-depth investigation of an example of the VLC system, which is designed and modeled according to the vendor specifications in the frame of OptiSystem software, is provided in the paper [17]. It examines the parameters that are crucial in performance i.e., BER, eye height, and threshold. The system is intended to be used indoors and has a data rate of 10 kbps when a distance of 10m is covered, and this is an addition to the already existing RF communication. A rectangular optical filter is employed to solve the ambient light interference, and the noise is dramatically reduced, giving a minimal BER. The research is very useful to designers to ensure that they are able to choose the best configurations that yield the best performance and also save time and effort in actual practice.

This paper will suggest a VLC system that is capable of operating both indoors and outdoors. The suggested VLC system provides something new in the design of transmitters, where the Blue LEDS are utilized to transmit coded data to each user. We have employed an MD code that possesses a zero cross-correlation property, a simple design, and a high cardinality feature, making it advantageous over other OCDMA codes. Signal reception is implemented with the help of the Bessel optical filter and photodetector, which is used to design the receiver. Bit error rate (BER) and Quality factor (Q) are some of the important measures of the system performance. By analyzing the impact of varying link ranges and data rates, this work aims to demonstrate the effectiveness of 1D-MD codes in extending communication distance and improving overall system reliability.

The remaining sections of this paper are organized as follows: Section II gives the proposed VLC system model block diagram and provides insights about the benefits of Blue LEDS. Also, it provides an understanding of MD codes. In section III, implementation of the proposed VLC system in Optisystem is discussed, and the transmitter, channel and receiver designs are elaborated. In Section IV, simulation results and discussion are presented. And lastly, Section V gives the conclusion.

2. Proposed VLC System Model

The proposed VLC system block diagram is given in Figure 1. The block diagram is for two users. The user data is line-coded, and then every user is assigned Blue LEDs based on their respective MD code. The system operates within the Blue spectrum, starting at a wavelength of 440 nm with an incremental spacing of 0.8 nm between channels. The multiplexer combines all of them and transmits them onto the channel. Here channel is the atmosphere that adhere to losses. 25dB/m is chosen to represent a highly lossy channel condition [6,16]. A value of 25dB/m is selected to indicate a worst-case or highly lossy channel environment that can occur in realistic free-space optical (FSO) or long-range VLC conditions, and especially when environmental conditions are unfavourable, such as heavy ambient interference, fog, rain, or aerosol-laden atmospheres [16].

At the transmitter side, Multidiagonal (MD) codes are employed to facilitate user separation and minimize interference. These codes are selected due to their zero cross-correlation properties, which significantly reduce multi-user interference. Additionally, MD codes are known for their simple construction and low computational complexity, making them ideal for practical implementation. The specific MD code assignments corresponding to the LED wavelengths for five users are presented in Table 1.

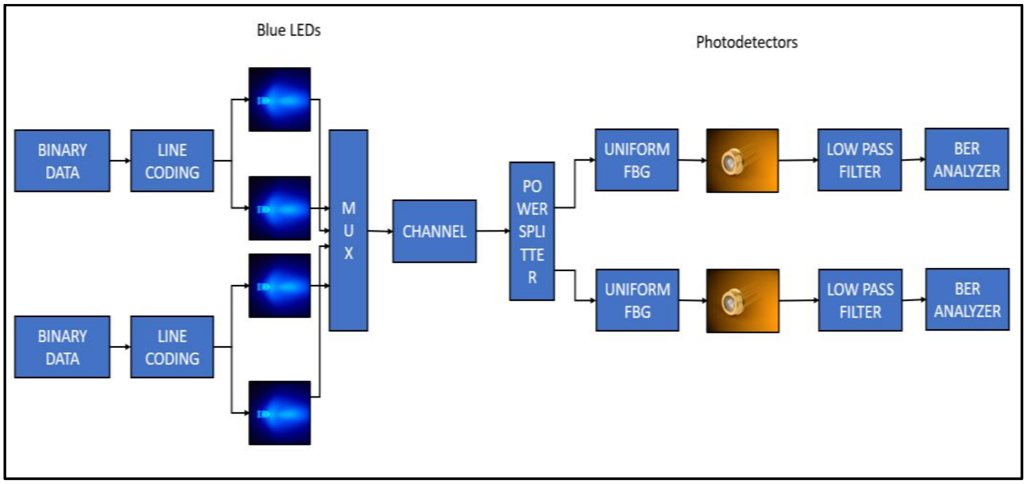

Figure1: Block Diagram of proposed VLC system

Table1: MD code using Blue spectrum for five users

	LED1	LED2	LED3	LED4	LED5	LED6	LED7	LED8	LED9	LED10
	440nm	440.8 nm	441.6 nm	442.4 nm	443.2 nm	444nm	444.8 nm	445.6 nm	446.4 nm	447.2 nm
User1	1	0	0	0	0	0	0	0	0	1
User2	0	1	0	0	0	0	0	0	1	0
User3	0	0	1	0	0	0	0	1	0	0
User4	0	0	0	1	0	0	1	0	0	0
User5	0	0	0	0	1	1	0	0	0	0

Table 2: LEDs and their comparison

LED color	Wavelength range	Modulation BW	SNR	Suitability
Blue	~450 nm	Highest (~20 MHz+)	High	Best for high-speed VLC
Green	~520 nm	Moderate (~5–10 MHz)	Good	Useful for hybrid lighting + data
Red	~630 nm	Lowest (~2–5 MHz)	Lower	Less ideal for fast data transmission
White (phosphor based)	Composite	Very low (~1–3 MHz)	Variable	Good for ambient lighting, poor for speed

Blue LED is chosen because it provides:

- Fast Response Time: Blue LEDs have the shortest carrier lifetime, allowing faster switching and higher modulation bandwidth.
- Higher Data Rates: Systems using Blue LEDs have achieved data rates exceeding 100 Mbps in lab settings.
- Better SNR: Blue light is less affected by ambient noise compared to red or white LEDs.

Table 2 gives the comparison of different color LEDs based on wavelengths, modulation bandwidth, signal-to-noise ratio (SNR), and suitability in VLC systems. Blue LEDs are best suited for high-speed VLC systems.

3. Implementation of Proposed VLC system using Optisystem

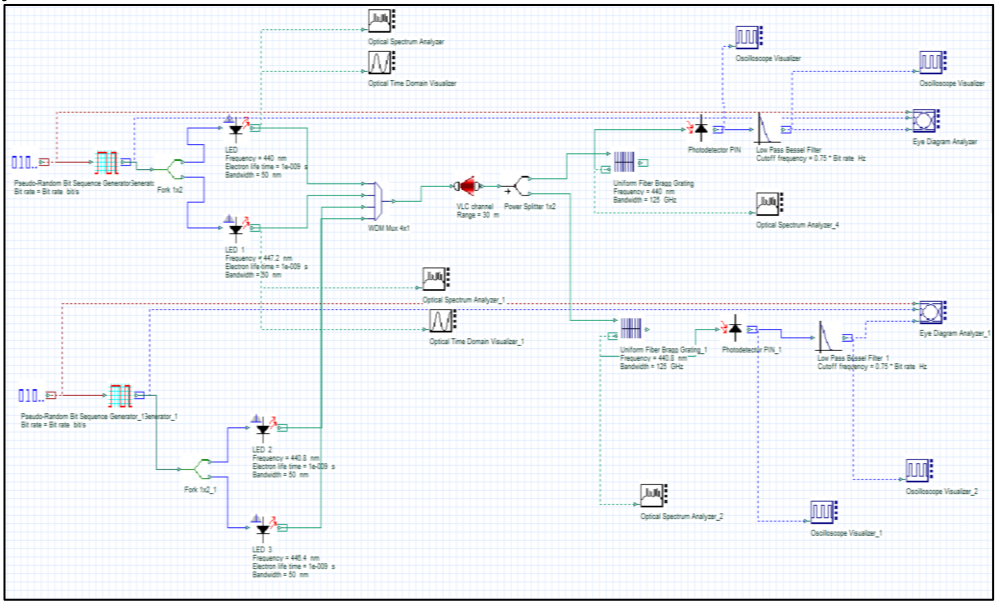

Figure 2: Proposed VLC system using Optisystem Software

Figure 2 shows a two-user VLC system designed in Optisystem simulation software. The transmitter is zoomed in Figure 3. The transmitter consists of a Pseudo Random Bit Sequence Generator which is passed to the Non-Return to Zero (NRZ) line coder. This user data is connected with two LEDs with wavelengths in the Blue spectrum, taken from Table 1 for user 1 and user 2. Based on the MD code the user1 is using 2 LEDs, which are further multiplexed with the light signals of the second user. This multiplexed data is transmitted in the VLC channel at 25dB/m attenuation to resemble a highly attenuated channel. The channel is shown in Figure 4. At the receiver, shown in Figure 5, the multiplexed optical signal is power split using a power splitter and applied to a uniform Fiber Bragg Grating (UFBG). Here, the UFBG is used as a filter to extract the required wavelength assigned to user 1 and user 2. In the MD code, every user is assigned two wavelengths as given in Table 1. But due to the advantage of zero cross-correlation in MD codes, even if one wavelength is detected, the signal reception is successful. Hence, only one UFBG is required for each user. The filtered wavelength from UFBG is then applied to the PIN Photodetector, which converts optical data into electrical data, and that is applied to the low-pass filter for noise removal. Finally, the signal is analysed on the Eye diagram analyser. The simulation parameters are given in Table 3.

4. Simulation Results and Discussion

4.1. BER & Quality Factor of two users at 150MB/s

Below is the result of the simulation of proposed VLC system at 150MB/s. The Table 4 shows BER and Max. Q for user1 and user2. It can be seen that the simulation is done for the link range of the VLC channel at 10m to

100m. And it can be observed that the performance of the proposed work is satisfactory up to 90m with BER of 6.62451×10^{-9} for user1 and 1.49577×10^{-9} for user2. Max Q factor for user1 and user2 is 5.05837 and 5.10812, respectively. It must be noted that the performance of both users is approximately the same. This is due to the high cardinality property of MD codes used at the transmitter side.

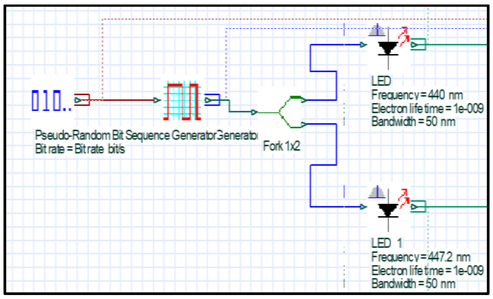

Figure 3: Proposed Transmitter circuit

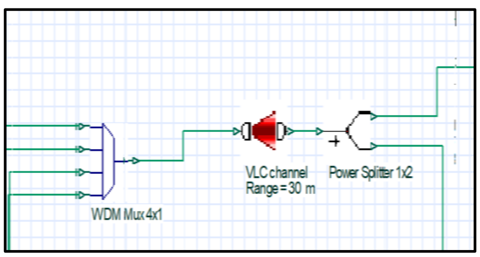

Figure 4: VLC Channel

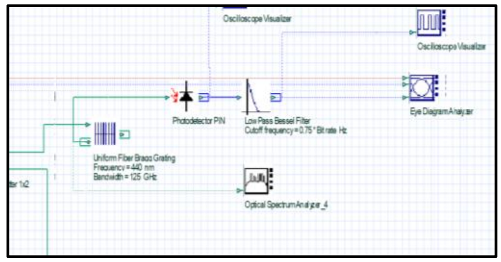

Figure 5: Proposed receiver circuit

Table3: Simulation parameters for proposed VLC system

Parameters	Value
Data rate	100MB/s & 150MB/s
Link range	10 to 1300 m
Attenuation	25dB/m
Blue LED wavelengths	440 nm to 490nm
OCDMA code	Multidiagonal code
Responsivity	0.85A/W
Dark current	5nA

Figure 6 and figure7 provide a graphical visualization of BER and Q-factor versus the VLC channel link range from 10 to 100m. The graphs provide clear evidence of a steady and robust response of the proposed VLC system up to 90m. Increasing the link range beyond 90m at 150MB/s gives undesirable BER and Q factor.

Table4: BER & Quality factor of 2 users at 150MB/s

Link range	BER User1	BER User2	Q-factor User1	Q-factor User2
10	8.0152e-013	3.07614e-012	7.05824	6.86243
20	1.93462e-012	9.50167e-011	6.93112	5.99043
30	8.94641e-012	1.52318e-011	6.99997	5.78208
40	4.89946e-011	1.74789e-010	5.3983	5.54214
50	1.21497e-010	1.30792e-010	5.31624	5.46043
60	8.4818e-010	4.67716e-010	5.23756	5.34381
70	1.18846e-010	1.47118e-009	5.16625	5.28646
80	7.13447e-009	2.57171e-009	5.10832	5.1847
90	6.62451e-009	1.49577e-009	5.05837	5.10812
100	3.43245e-008	1.54622e-008	4.41164	4.27683

4.2 BER & Quality Factor of five users at 100MB/s

The second performance analysis is done by increasing the number of users to 100MB/s. These results are shown in tabular form in Table 5 and table 6. Table 5 gives the BER for 5 users at a link range of 10 to 1600m, and the Table 6 provides the Quality factor for 5 users at link range of 10 to 1600m. It is observed that all users respond in a similar fashion with reaching a distance of 1300m successfully. At 1300m link range, the achieved BER is 2.38744 $x10^{-12}$ And the Q factor is 9.64761 for user1. Similar results are received for all other users.

The attenuation experienced is sharp at frequencies above 1300 m at 100 Mbps, as is expected by the physical constraints of the VLC channel when attenuation is assumed to be 25 dB / m. Optical signal loses much power at a greater distance, decreasing the signal-to-noise ratio (SNR). Although MD codes reduce the multi-user interference due to their zero cross-correlation property, they are not able to achieve a complete compensation of the exponential distance dependence of the path loss.

The system has more performance requirements in the modulation bandwidth and timing accuracy at 100Mbps. Since the range of link goes above 1300m, severe attenuation, dispersion, and diminished optical power result in a rapid rise in BER and subsequent decrease in Q-factor. This sudden change describes the threshold behaviour of optical communication systems where the behaviour of the system does not change drastically until a given range and then it starts to deteriorate exponentially as the received SNR is below the detection threshold of the photodiode.

Table 5: BER of 5 users at 100MB/s

Link range	BER user1	BER user2	BER user3	BER user4	BER user5
10	1.32872e-029	7.78713e-029	3.49788e-031	1.10841e-032	1.26081e-032
20	3.25318e-028	2.22011e-028	2.08845e-031	7.71881e-029	3.08705e-031
30	1.34941e-028	1.69458e-028	6.67026e-029	6.00605e-029	1.68584e-030
40	9.13649e-027	1.58382e-028	2.31819e-029	5.90329e-029	1.15857e-028
50	6.63747e-027	4.92689e-027	1.08879e-028	2.53992e-029	1.13307e-028
60	6.09108e-026	2.28164e-027	6.40321e-027	1.46752e-029	3.56007e-027
70	3.92844e-026	1.44637e-027	3.1886e-027	9.2771e-028	2.92883e-027
80	3.186e-026	5.72006e-026	3.8306e-027	2.50944e-027	2.55497e-026
90	1.06063e-026	3.35601e-026	2.49393e-027	6.59706e-026	1.51541e-026
100	8.32095e-025	1.74915e-026	1.72982e-026	1.31675e-025	4.26309e-026
200	6.8727e-025	6.2252e-025	9.05803e-025	1.01487e-025	4.22173e-026
300	2.3114e-025	6.05968e-025	8.10539e-025	4.42352e-023	6.47304e-025
400	1.58031e-025	4.41401e-025	7.60308e-025	1.37147e-023	2.22022e-025
500	5.65594e-025	4.56167e-024	2.43382e-025	2.25109e-022	2.51067e-024
600	2.54237e-024	1.26744e-024	1.60676e-024	1.29711e-022	2.07815e-024
700	2.33621e-024	5.78077e-023	1.8295e-024	3.34379e-021	1.33631e-024
800	9.18501e-023	2.07122e-023	1.49695e-024	3.28238e-021	3.95618e-023
900	5.2995e-023	2.23144e-022	2.60282e-023	1.90725e-021	1.54084e-022
1000	1.59076e-021	4.82885e-021	1.99134e-023	1.99501e-020	1.85987e-021
1100	5.34018e-019	9.64018e-019	1.9818e-022	1.43254e-020	1.27713e-021
1200	6.64018e-014	1.00306e-019	1.03992e-015	1.21919e-019	4.17679e-017
1300	2.38744e-012	5.45463e-011	4.13315e-014	2.76804e-015	2.08185e-014
1400	2.4278e-008	7.27305e-008	3.13244e-007	1.73155e-007	2.96787e-008
1500	0.000226675	0.00040915	0.000126272	0.000267395	0.000566669
1600	1	0.0323313	1	1	1

Table 6: Q-factor of 5 users at 100MB/s

Link range	Max Q user 1	Max Q user 2	Max Q user 3	Max Q user 4	Max Q user 5
10	10.6829	9.30647	10.7077	11.2135	10.7179
20	10.2276	10.935	11.5396	10.748	9.67552
30	10.7956	11.2202	10.2008	11.0642	11.401
40	8.73504	10.356	10.7444	9.19712	10.1521
50	10.2592	10.2188	10.3183	11.8305	11.0242
60	10.7544	10.0878	11.5837	10.44	10.5303
70	11.0652	10.7855	11.076	9.91749	11.824
80	10.9937	9.90934	9.88373	9.35511	9.41757
90	10.5029	10.5063	10.5636	9.63697	11.0343
100	10.4555	10.1948	10.6635	11.0881	10.0861
200	9.77832	10.6132	11.0332	9.693	10.3222
300	10.5673	11.0151	11.1717	11.1674	10.2201
400	9.88035	10.8563	10.1401	11.0871	9.81274
500	10.9693	10.3163	9.65335	10.3983	9.45481
600	10.2253	10.0067	10.191	10.3711	10.4829
700	10.029	10.32	9.85857	9.41437	10.7327
800	10.1571	10.4872	10.1325	10.8405	11.5509
900	9.3192	10.6293	10.1178	9.35879	10.5821
1000	10.9994	9.36702	10.7245	9.16408	10.4854
1100	8.98845	9.72901	10.2082	9.80344	10.1106
1200	9.64761	10.4541	7.91835	8.97515	8.30182
1300	6.43432	6.89723	7.44974	7.79901	7.53193
1400	5.24664	5.45169	4.97486	5.08944	5.41027
1500	3.34329	3.50289	3.65385	3.45907	3.25087
1600	1.84744	0	0	0	0

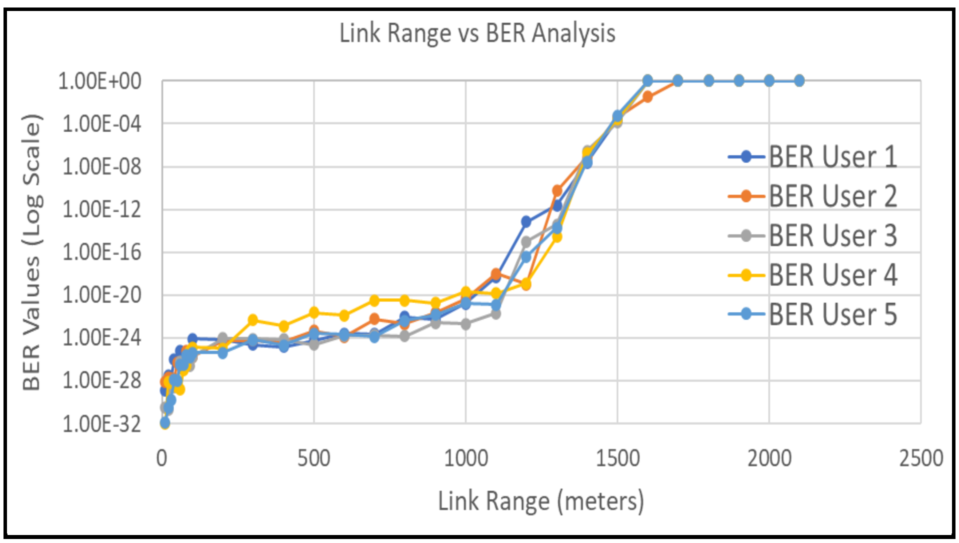

Figure 6: BER vs Link range at 100MB/s

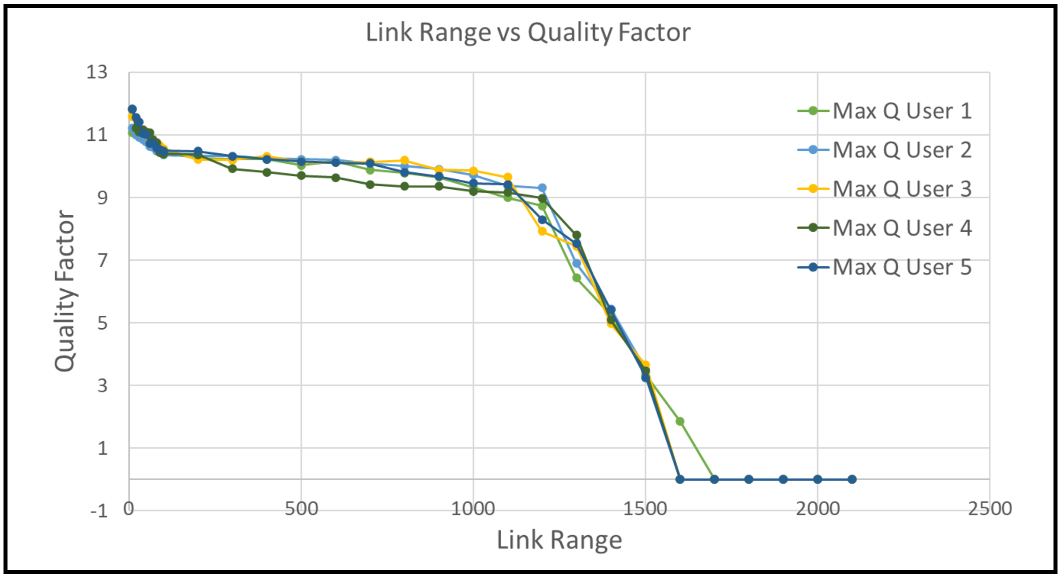

Figure 7: Q factor Vs Link range at 100MB/s

4.3 Impact of data rate on BER and Quality factor at different link ranges

Figure 8 and 9 provide the analysis of changing data rate on BER and Q factor while also changing the link ranges. The Table 7 and 8 provide a clear analysis of how the BER and Q factor fall with increasing the data rate. The reliability of using LED-based VLC system for the proposed system design is up to 1.3km at 100m, which is sufficient for various applications if VLC systems

Table 7: Data rate Vs BER at different link ranges

Data Rate (MB/s)	1300m BER	1000m BER	500m BER	100m BER	70m BER	10m BER
100	2.39e-12	2.97e-21	2.34e-25	8.32e-25	1.63e-27	5.30e-21
150	2.33e-06	1.56e-10	4.39e-11	2.06e-11	8.21e-10	4.17e-13
160	-	-	-	-	-	7.92e-11
170	-	-	-	-	-	2.13e-09
200	-	2.81e-06	1.48e-07	1.39e-07	2.47e-07	4.27e-06

Table 8: Data rate Vs Q factor at different link ranges

Data Rate (MB/s)	1300m Q	1000m Q	500m Q	100m Q	70m Q	10m Q
100	6.43432	10.9994	10.9693	10.4555	11.0652	10.6829
150	4.38781	6.40645	6.17901	7.00888	7.15741	6.57456
160	-	-	-	-	-	5.84788
170	-	-	-	-	-	4.87353
200	-	4.65385	4.27196	5.17675	4.1603	4.8334

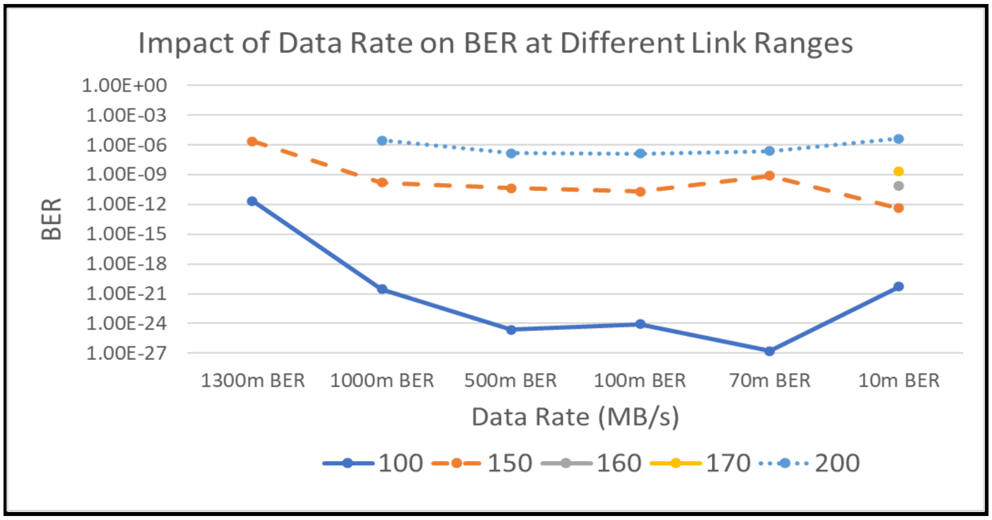

Figure 8: Impact of Data rate on BER at different link ranges

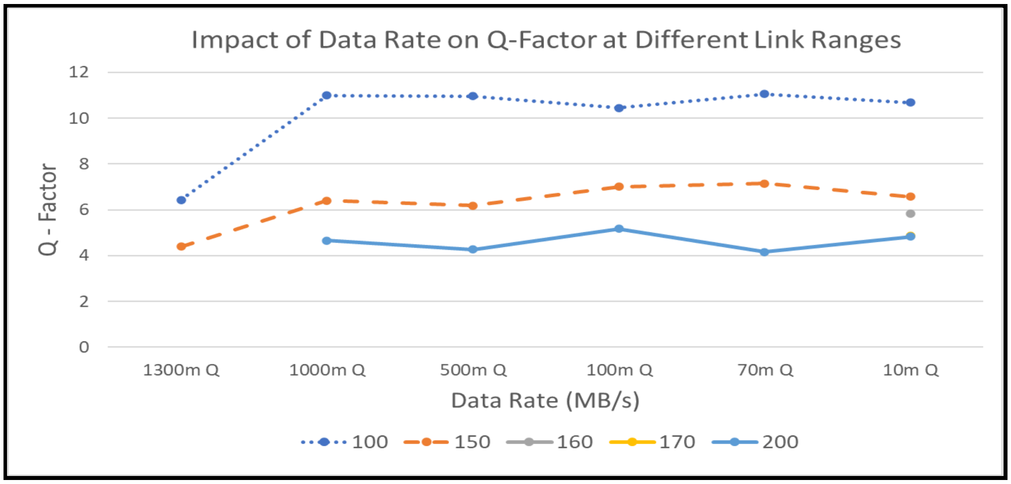

Figure 9: Impact of Data rate on Q factor at different link ranges

Moreover, it is observed from Table 7 that for a data rate 170MB/s, the link range can go up to 10m. And at 150MB/s, the link range can be used up to 1000m.

To further clarify the novelty of our work, we compared the proposed MD-coded Blue LED VLC system with prior VLC implementations using OOC and ZCZ codes. While OOC and ZCZ codes have been shown to provide good correlation properties, their performance typically degrades at longer transmission distances and higher user counts. For example, OOC-based VLC systems often require long code lengths with small weights, leading to increased complexity and reduced scalability. On the same note, ZCZ codes, despite their effectiveness in reducing multiple access interference, have been characterized to operate well only in short-distance indoor set-ups. Conversely, our MD-coded VLC system can be transmitted reliably with 1.3 km at 100 Mbps at low BER and high Q-factor even with multiple users. The product of MD codes and the Blue LEDs allows this increased range of link and power density, as the modulation bandwidth and SNR of the latter are better than traditional LED sources. Therefore, the suggested system not only goes beyond the constraints of OOC/ZCZ VLC research, but it also creates a viable system of long-range, high-speed, and scalable uses of VLC.

Table 9: Proposed work compared to other coding scheme.

Coding Scheme	Key Properties	Performance Trends	Scalability
Optical Orthogonal Codes (OOC) [14]	Minimum code weight, Low cross-correlation	Good BER at small networks; performance decreases with number of users	Lack of scalability because of long lengths of codes
Zero Correlation Zone (ZCZ) [16]	No correlation in specified zone	Its performance is superior to OOC in BER over small distances; applicable to small groups	Moderate scalability
Multi-Diagonal (MD) Codes [15]	No cross-correlation, easy to construct, high cardinality	Removes access interference at multiple distances; high BER / Q -factor	Very good scalability; can be used by a larger number of users
Blue LED + MD Codes (Proposed System)	Both high modulation bandwidth and high SNR and zero cross-correlation	BER = 2.39e-12 and Q-factor = 6.43 at 1.3 km (100 Mbps)	Scales well past 5 users, scales at least to 25 dB/m attenuation

Table 9 contains the summary of the comparative performance of OOC, ZCZ, and MD codes that were reported in previous VLC works, and the suggested MD-coded Blue LED system. The findings indicate the high scalability and stability of MD codes, especially when used together with the Blue LEDs in high-speed VLC.

5. Conclusion

The VLC architecture presented in this work integrates blue-LED transmitters with Multi-Diagonal (MD) coding that provides outstanding data integrity and fidelity of transmission. Simulation on Optisystem shows that the system has a robust performance and can maintain a low BER and high Q-factor, thus demonstrating scalability and resilience. MD codes are effective in reducing the multi-user interference and at the same time enhance reliability under a variety of VLC conditions. This twin benefit indicates that MD coding with the use of blue-LED lighting maintains signal fidelity and, at the same time, boosts the overall system type with varying optical environments.
All of these findings suggest that blue-LED-based VLC shall remain one of the fastest, noise-resistant, and energy-efficient frameworks of communication, open to a wide range of potential applications-which include indoor, vehicular, and underwater optical wireless networks.

AUTHOR CONTRIBUTION

Kehkashan: article concept, VLC circuit designed. M. Anus, M. Ibrahim: conducted literature review. Fiza: created results graphics. QadirDad: write up. Fahim: performed review. Zartasha: writing of an article, formatting.

CONFLICT OF INTEREST

It is declared that there is no conflict of interest regarding this work to be published.

FUNDING

This work did not receive funding from any source.

ACKNOWLEDGMENT

We would like to acknowledge Mehran University of Engineering & Technology, Jamshoro for providing support to carry out this work.

REFERENCES

[1] Sarbazi, E.; Kazemi, H.; Crisp, M.; El-Gorashi, T.; Elmirghani, J.; Richard, V.; Penty, R.V.; White, I.H.; Safari, M.; Haas, H. Design and Optimization of High-Speed Receivers for 6G Optical Wireless Networks. IEEE Trans. Commun. 2024, 72, 971–990

[2] Sejan, M.A.S.; Rahman, M.H.; Aziz, M.A.; Kim, D.-S.; You, Y.-H.; Song, H.-K. A Comprehensive Survey on MIMO Visible Light Communication: Current Research, Machine Learning and Future Trends. Sensors 2023, 23, 739

[3] Alrakah, H.; Gutema, T.; Offiong, F.; Popoola, W. PAPR Reduction in DCO-OFDM and PAM-DMT Based VLC Systems. In Proceedings of the 2022 Conference on Lasers and Electro-Optics (CLEO), San Jose, CA, USA, 15–20 May 2022; pp. 1–2

[4] Georlette, V.; Moeyaert, V.; Bette, S.; Point, N. Visible Light Communication Challenges in the Frame of Smart Cities. In Proceedings of the 2020 22nd International Conference on Transparent Optical Networks (ICTON), Bari, Italy, 19–23 July 2020; pp. 1–4.

[5] Eldeeb, H.B.; Uysal, M. Visible Light Communication-Based Outdoor Broadcasting. In Proceedings of the 2021 17th International Symposium on Wireless Communication Systems (ISWCS), Berlin, Germany, 6–9 September 2021; pp. 1–6.

[6] Hassan, E.S.; Jabbari, A.; Alharbi, A.A. Evaluating MIMO-VLC System Performance: Modulation Techniques and Ambient Light Interference Effects. Photonics 2025, 12, 649. https://doi.org/10.3390/ photonics12070649

[7] Latif Ullah Khan, Visible light communication: Applications, architecture, standardization and research challenges, Digital Communications and Networks,Volume 3, Issue 2,2017,Pages 78-88,ISSN 2352-8648,https://doi.org/10.1016/j.dcan.2016.07.004

[8] Farid, S.M.; Saleh, M.Z.; Elbadawy, H.M.; Elramly, S.H. ASCO-OFDM based VLC system throughput improvement using PAPR precoding reduction techniques. Opt. Quant. Electron. 2023, 55, 410

[9] Sonmez, M.; Sökmen, Ö.G. Ambient Light Effect on Receiver for Visible Light Communication Systems. Gazi Univ. J. Sci. 2022, 35, 1393–1403

[10] Alsalami, F.M.; Haas, O.C.L.; Al-Kinani, A.; Wang, C.-X.; Ahmad, Z.; Rajbhandari, S. Impact of Dynamic Traffic on Vehicle-to Vehicle Visible Light Communication Systems. IEEE Syst. J. 2022, 16, 3512–3521

[11] Won,Y.-Y.; Yoon, S.M.; Seo, D. Ambient LED light noise reduction using adaptive differential equalization in Li-Fi wireless link. Sensors 2021, 21, 1060

[12] M. Anus, M. Ibrahim and K. Asma Memon, "MD Code-Based VLC: A High Efficiency Data Transmission Framework," *2025 International Conference on Emerging Technologies in Electronics, Computing, and Communication (ICETECC)*, Jamshoro, Pakistan, 2025, pp. 1-6, doi: 10.1109/ICETECC65365.2025.11070245.

[13] I. M. M Mohamed and O. M. Abdulrahman, “SAC-based OCDMA codes: A comparison,” ELEKTRIKA- Journal of Electrical Engineering, vol. 21, no. 1, pp. 20–24, Apr. 2022, doi: 10.11113/ELEK- TRIKA.V21N1.340

[14] N. Das, M. J. Islam, and A. Guho, “Comparison of different codes on the Performance of SAC OCDMA over FSO Link,” International Con- ference on Recent Progresses in Science, Engineering and Technology, ICRPSET 2022, 2022, doi: 10.1109/ICRPSET57982.2022.10188539.

[15] Thanaa Hussein Abd, S.A. Aljunid, Hilal Adnan Fadhil, R.A. Ahmad, N.M. Saad, Development of a new code family based on SAC-OCDMA system with large cardinality for OCDMA network, Optical Fiber Technology, Volume 17, Issue 4, 2011, Pages 273-280, ISSN 1068-5200, https://doi.org/10.1016/j.yofte.2011.04.002.

[16] Ouis, Esma & Benattou, Fassi & Driz, Samia. (2019). Performance Analysis of Indoor VLC-ZCZ-OCDMA System using High Performance Photodetector.

[17] K. Sindhubala and B. Vijayalakshmi, “Design and performance analysis of visible light communication system through simulation,” Proceedings of the International Conference on Computing and Communications Technologies, ICCCT 2015, pp. 215–220, Oct. 2015, doi: 10.1109/IC-CCT2.2015.7292748.