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Evaluation of Three-Level Code Division Multiplexing for High-Quality Radio over Fiber Communication

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Abstract

Radio over Fiber system (RoF) technology facilitates the transmission of wireless signals over optical fibers, which provides many benefits, including low signal loss, and immunity to electromagnetic interference. Despite these benefits, conventional RoF systems grapple with signal impairments and limited user capacity, as each user must be allocated a specific frequency. To address these limitations, this paper explores the implementation of the Three-Level Division Multiplexing (3LCDM) technique with RoF, a superior multiplexing strategy that allows two users to share a single channel, thereby doubling capacity. This innovative combination was evaluated for various cases using 2.4 GHz, 5 GHz, and the combination of 2.4 GHz and 5 GHz carrier frequencies, and its performance was compared with traditional RoF systems. Simulations were carried out using OptiSystem in cooperation with the MATLAB simulator. The findings of this study reveal that the 3LCDM-RoF system can accommodate twice the number of users as the conventional RoF system without the need for amplifiers. Furthermore, it supports higher bit rates and longer transmission distances. Specifically, the 3LCDM-RoF system achieved maximum data rates at maximum fiber length of 2 x 1.1 Gbps at 60 km, (2.4 GHz), 2 x 2 Gbps at 40 km (5 GHz), and 2 x 0.5 Gbps per channel at 43 km (combined 2.4 GHz and 5 GHz) respectively. Meanwhile, the conventional RoF with 2.4 GHz, 5GHz and the combination of 2.4 GHz and 5 GHz can only achieve maximum data rate at a maximum fiber length of 1.1 Gbps at 45 km, 1.6 Gbps at 35 km, and 0.4 Gbps at 35 km respectively.

I. INTRODUCTION

Nowadays, the data capacity of communication has been entirely broadened from simple messages and sound to rich multimedia, driven by the growing user demand. Radio over Fiber (RoF) technology emerges as a potential solution for the rapidly increasing demand for bandwidth, flexibility, and transmission capacity. RoF system is a convergence of wired and wireless networks, which entails the use of optical links to transmit and distribute modulated RF signal from a central station (CS) to a base station (BS) [1]. The basic diagram of the RoF system is shown in Figure 1.

At the CS, the optical signal created by the source is modulated by RF signal. This newly modulated signal is then transmitted over an optical fiber link to the base station. Upon arrival at the base station, the optical signal is converted into an electric signal (and vice versa) through the utilization of a photodetector. The RoF system can be used for wireless broadband communications as it can use the ultra-wide bandwidth and low-loss transmission provided by optical fiber [2]. It is also characterized by low attenuation, reduced power consumption, immunity to radio frequency interference, and dynamic resource allocation. However, it is also suffering from different issues such as unwanted frequencies, limited number of users, and low signal quality due to noise [3].

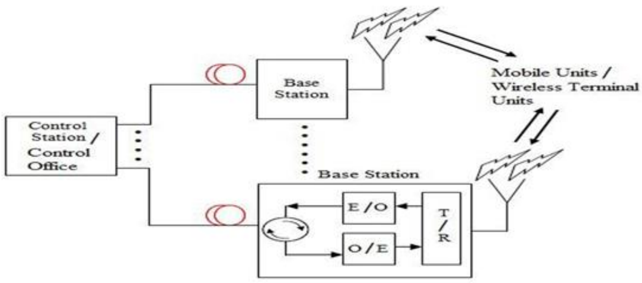


Figure 1. A basic block diagram of RoF system [2]

Despite the wealth of research focused on improving the RoF performance, there are still some gaps that require attention. For example, Das and Zahir explored RoF systems with carrier frequencies of 10 GHz and 15 GHz. They found that the system could only support two users at a maximum data rate of 2.5 Gbps. They also noted some deviation in the optical spectrum at the system's receivers, attributed to the nonlinear effect [4]. Shrimali and Patel clarified the RoF model at a radio frequency signal of 10 GHz and examined data rates up to 3 Gbps over fiber lengths of 50 km. Their study indicates that the Return to Zero (RZ) modulation code outperforms the Non-Return to Zero (NRZ) code in the high-power regime [5]. Eid et al have simulated and evaluated the RoF-based local area networks by using duo-binary modulation and predistortion techniques. Their results proved the effectiveness of the system in improving signal quality and its power since the presence of the predistortion technique led to a reduction in the bit error rate [6]. However, the use of a technique with the presence of optical amplifiers could add more cost to the system.

In light of these findings and existing gaps in the field, this paper aims to design and investigate a RoF system that can cater to multiple users. The proposed system will leverage Three-level code division multiplexing (3LCDM) as a multi-carrier transmission technique. Developed by Mokhtar et al. (2004), the 3LCDM has potential to support two users within a single channel, including both NRZ and RZ line codes [7]. The block diagram of 3LCDM is shown in Figure 2.

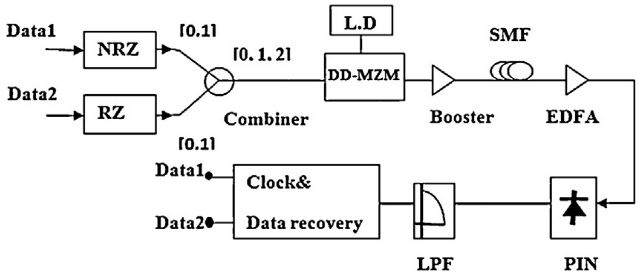


Figure 2. 3 LCDM block diagram [8]

The process of multiplexing two data streams that are NRZ and RZ line codes results in producing a three-level coding sequence represented by 0, 1, and 2 [8]. The code division in the 3LCDM technique is achieved by merging two data streams within the multiple levels instead of the wavelength bandwidth which results in doubling the bandwidth efficiency. Therefore, the 3LCDM technique is selected in this study to be implemented over the RoF system.

II. SIMULATION SETUP

A few configurations of 3LCDM over the RoF system were simulated using Optisystem and co-simulated with MATLAB, as in the following sections.

A. 3LCDM over RoF for 2 users

At the transmitter section, data streams generated from both NRZ and RZ generators are combined using an electrical adder. This combination results in producing a three-level signal which contains two users' data streams. Then, the three-level signal is multiplied by the electrical carrier frequency. The DD-MZM with the CW laser, then modulates the electrically multiplied signal into an optical form, which is transmitted through the optical fiber link. At the receiver's end, the incoming modulated optical signal is filtered through the Gaussian optical filter. Following this, the PIN photodiode detects the filtered signal, and an AM demodulator carries out the final demodulator.

Figure 3 shows the complete block diagram of 3LCDM employed over the RoF system for two users, achieving an aggregated bit rate of 2 x 0.5 Gbps.

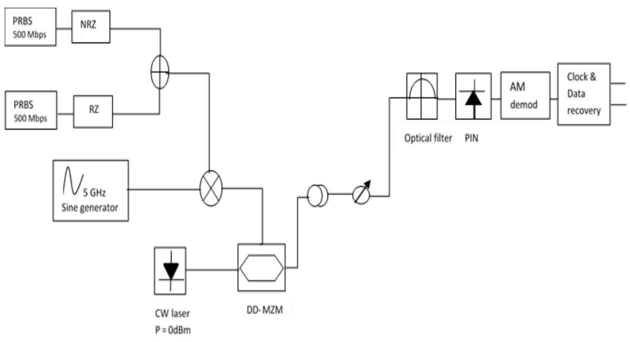


Figure 3. Block diagram for 3LCDM over RoF system for two users

B. 3LCDM over RoF for 4 users

Figure 4 illustrates the configuration of the 3LCDM-RoF system for four users at an aggregated bit rate of 2 x 0.5 Gbps in each channel. Figure 5-(a) displays the simulation setup of 3LCDM over RoF in OptiSystem and figure 5-(b) shows the transmitter components inside the subsystem.

The Central System (CS) consists of four pseudo-random binary sequences (PRBS) generators, four pulse generators (two RZ generators and two NRZ generators), two microwave signal generators at 2.4 GHz and 5 GHz frequencies, one continuous wave (CW) laser, and one Dual-Drive Mach-Zander-Modulator (DD-MZM). The PRBS generator produces a bit sequence of 0 and 1 with corresponding likelihood. In this simulation, the length of the bit sequence is adjusted to 1024. It generates a baseband signal which is used to modulate RF carrier frequency by using electrical modulation which moves this spectrum of the data signal at the carrier frequency. Each electrical RF carrier is multiplied with the combination of two streams of data from NRZ and RZ pulse generators which are produced by the PRBS generator at 0.5 Gbps of data rate. These two mixed carrier signals are joined by an electrical adder that carries both three-level signals containing four users' data streams. After that, the combined signal is modulated through the DD-MZM along with the CW laser at 0 dBm of input power and 1552.5 nm central wavelength which falls under C-Band where the attenuation is the lowest [9]. Then the modulated optical carriers are transmitted through the single-mode fiber (SMF).

At the first Base Station (BS1) where the signal is carried at 2.4 GHz, the optical signal is filtered by a Gaussian optical filter with the frequency of 193.1 THz + 2.4 GHz at the bandwidth of 20 GHz. For the signal carried by 5GHz at the second Base Station (BS2), the signal is filtered by the Gaussian filter with the frequency of 193.1 THz + 5 GHz at the bandwidth of 30 GHz. Then, the filtered optical signal is retrieved by a PIN photodiode and demodulated by the AM demodulator set at 2.4 GHz in BS1 and 5 GHz in BS2 respectively to get back the electrical signals. In the Low Pass Filter (LPF) of the demodulator, the cut-off frequency is set at 0.9 GHz and 0.85 GHz in BS1 and BS2 respectively to decrease the noise.

As shown in Figure 4, the de-multiplexer functions as a clock and data recovery which includes an X-OR gate for recovering the original signals [10]. The two MATLAB components in Figure 5 (a) are used to call MATLAB functions. Each MATLAB component has three inputs (two binary and one electrical).

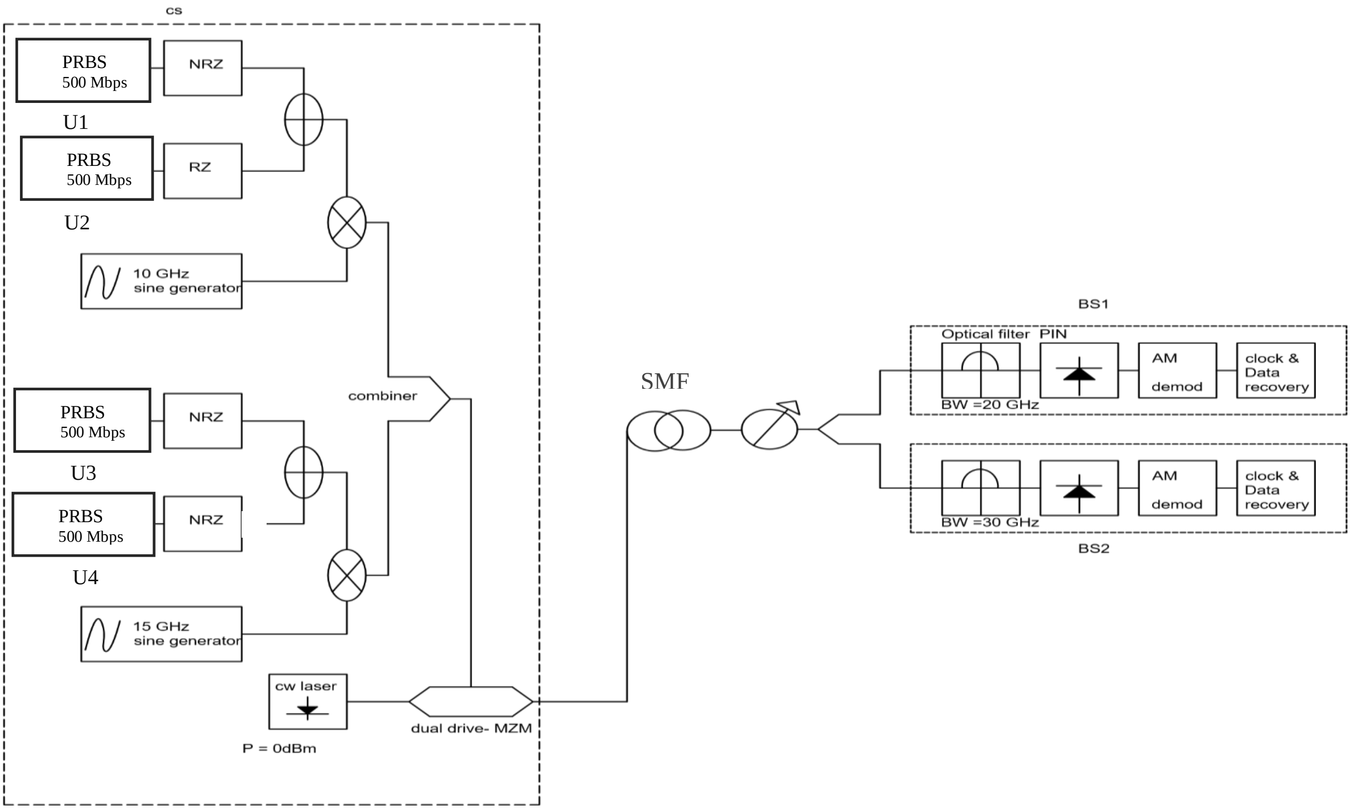
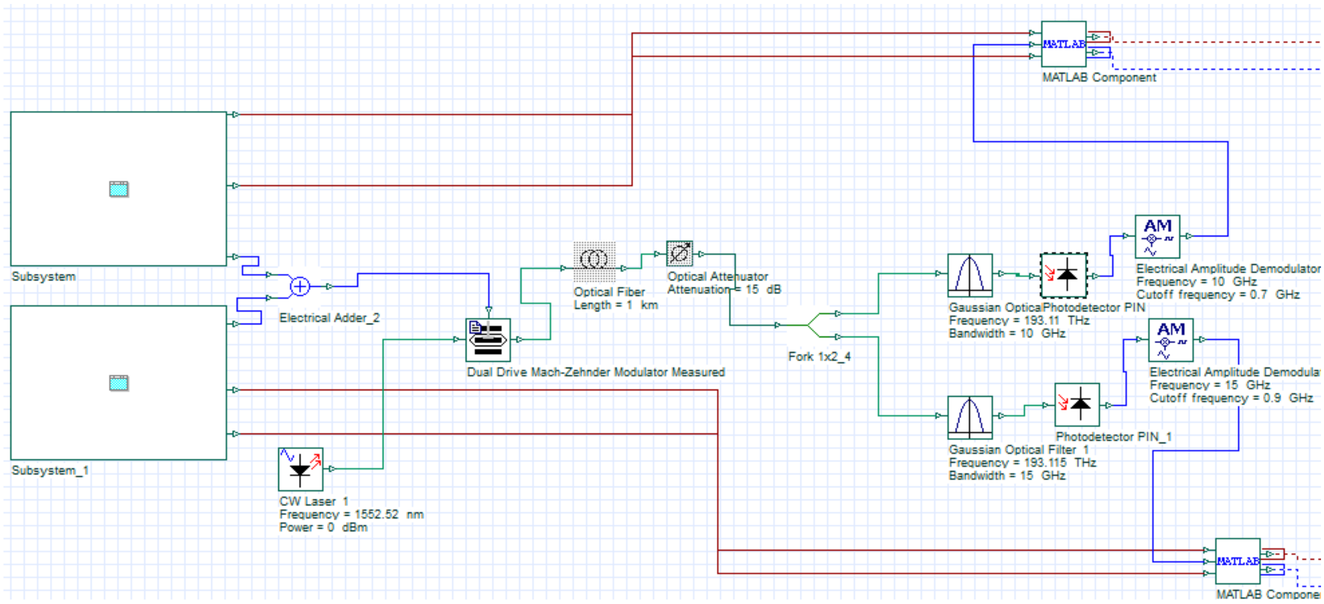
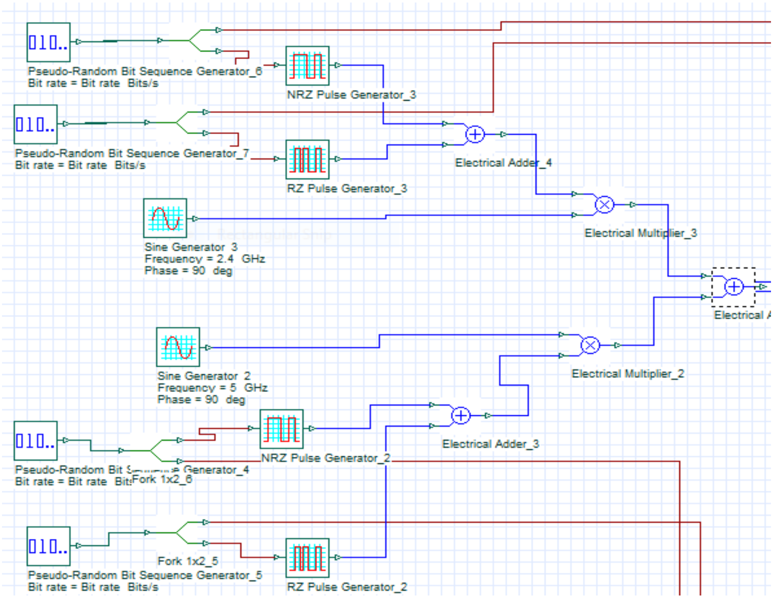


Figure 4. Block diagram of 3LCDM over RoF system for four users at 2.4 Hz and 5GHz carrier frequencies.



(a)



(b)

Figure 5. (a) Simulation model of 3LCDM-RoF system, (b) the transmitter components inside the subsystem

This component is important to export the signals from OptiSystem into MATLAB environments so that MATLAB calculates results and shows graphs of the eye diagram, log BER, Q factor, eye height and threshold. In practice, this operation could be carried out by digital processors.

The parameters of some components that are considered to accomplish the best operation for 3LCDM over the RoF system are summarized in Table 1.

Table 1
Parameters for the Simulation of 3LCDM over RoF

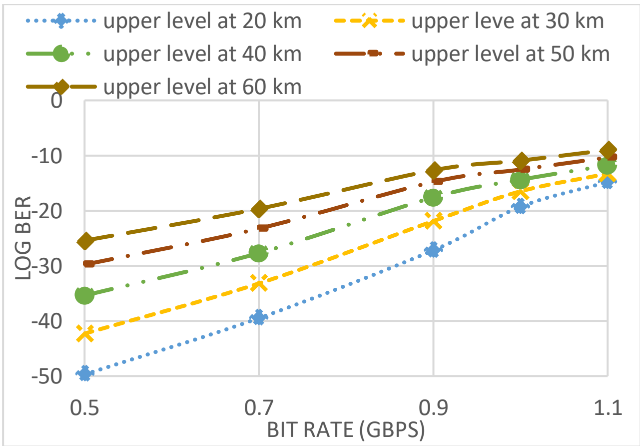
Parameter	Value
Electrical carrier frequencies	2.4 GHz and 5 GHz
Data rate	2 x 0.5 Gbps for each carrier
Wavelength	1552.52 nm
Power	0 dBm
Attenuation in SMF	0.2 dB/km
Dispersion in SMF	16.75 ps/nm/km
The splitting ratio for DD-MZM	1
Bias voltages for DD-MZM	Vb1 is -2.3 V and Vb2 is 2.3 V
The bandwidth of the optical bandpass filters	20 GHz for 2.4 GHz carrier and 30 GHz for 5 GHz carrier
Cuttoff-frequencies of low pass filters in AM demodulators	0.9 GHz for 2.4 GHz carrier and 0.85 GHz for 5 GHz carrier

III. RESULTS AND DISCUSSION

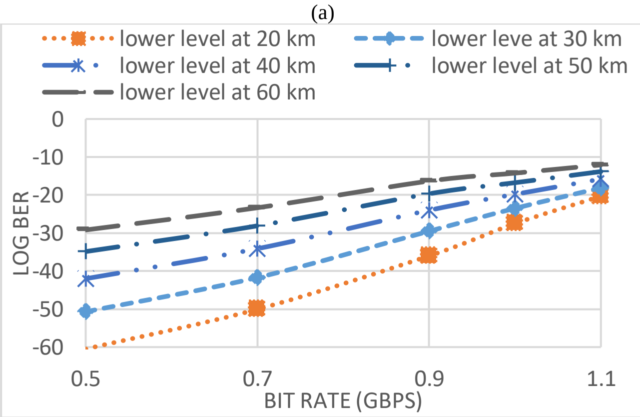
The effect of varying bit rates on the BER is shown in this section to determine the maximum data rate and maximum distance that each system can support. The evaluation considers the best and the worst performance amongst levels, since the 3LCDM technique is evaluated, depending on the upper and lower levels. The upper level addresses the BER of levels 2 and 1, while the lower level addresses the BER of levels 1 and 0. More derivation on the BER probabilities on the 3LCDM is given in [7].

A. 3LCDM-RoF with 2.4 GHz carrier frequency

The transmission of a range of data rates was simulated and drawn versus log BER at different fiber lengths for both 3LCDM over RoF and conventional RoF systems without using any amplifier. As illustrated in Figures 6(a) and 6(b), the 3LCDM-RoF system with 2.4 GHz carrier frequency can support 2 users at 2 x 1.1 Gbps of maximum data rate and 60 km of maximum fiber length.



(a)



(b)

Figure 6. (a) Performance of Bit Rate versus Min BER for 3LCDM over RoF system with 2.4 GHz carrier frequency for lower level and (b) for upper level

The inference was made as the upper level (worst performance level) reached around 10^{-9} min BER and the lower level (best performance level) reached around 10^{-12} min BER at 1.1 Gbps and 60 km fiber length. Meanwhile, the conventional RoF system with 2.4 GHz carrier frequency supports only 1 user at 1.1 Gbps maximum data rate and 45 km maximum fiber length as shown in figure 7.

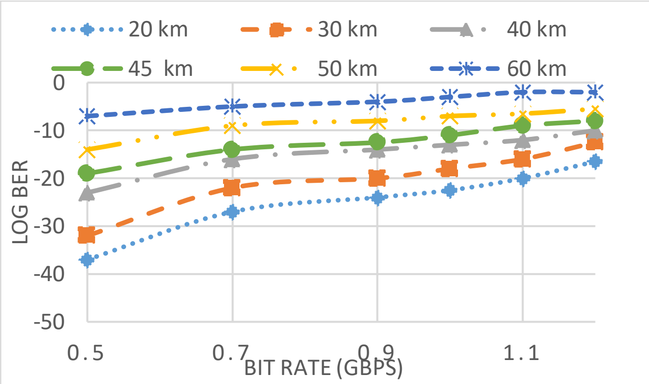


Figure 7: Performance of Bit Rate versus log BER for conventional RoF system with 2.4 GHz carrier frequency

Figure 8 shows the performance of fiber length versus the Q factor for both systems at a maximum data rate of 1.1 Gbps. It can be observed that the Q factor of 6, which is the acceptable value can be achieved by the 3LCDM-RoF system at 60 km of fiber length. On the other hand, a Q factor of 6 can be achieved by the RoF system at 45 km.

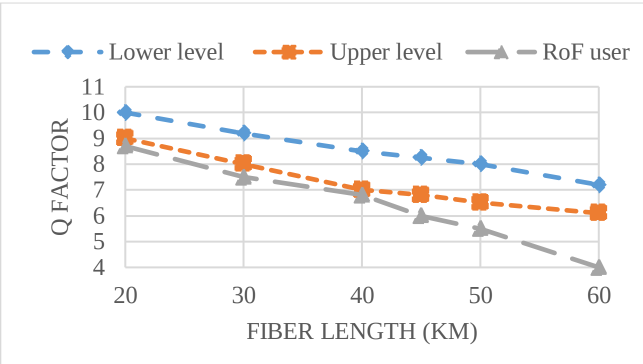
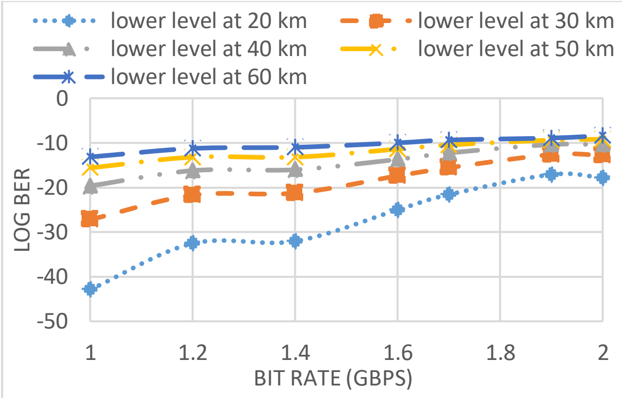


Figure 8: Performance of Fiber Length versus Q factor for both 3LCDM-RoF and conventional RoF systems at 2.4 GHz carrier frequency

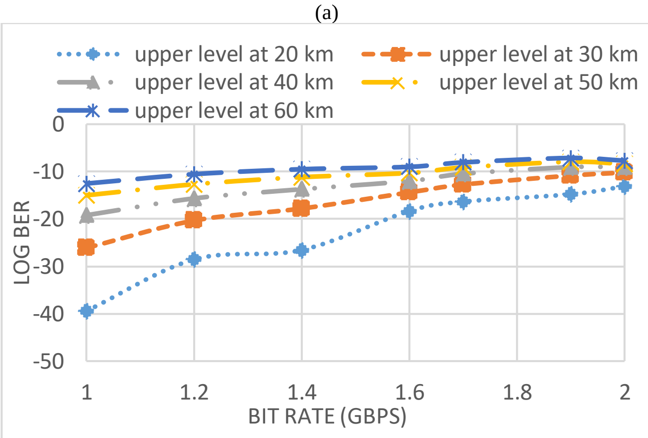
B. 3LCDM-RoF with 5 GHz carrier frequency

The transmission of 1 Gbps to 2 Gbps was simulated and drawn versus log BER at different fiber lengths at 5 GHz carrier frequency for both systems of 3LCDM over RoF and conventional RoF. For the 3LCDM-RoF system, Figures 9(a) and 9(b) show the capability of the system to perform at two distinct levels. The lower level, displaying superior performance, can accomplish a BER of approximately 10^{-10}, while the upper level (worst performance level) can achieve around 10^{-9} BER at 2 Gbps and a fiber length of 40 km. These results show the system's ability to support two users at a maximum bit rate of 2x 2 Gbps across a span of 40 km. In contrast, the conventional RoF system operating at 5 GHz carrier frequency shows limitations, supporting only one user at a peak data rate of 1.6 Gbps, and a maximum transmission distance of 35 km, as illustrated in Figure 10.

Figure 11 illustrates the performance of the bit rate versus the Q factor for both systems at 35 km fiber length. It is witnessed that the performance of the proposed combination is better than that of conventional RoF in terms of the Q factor. It is also clear that there is a decline in the conventional RoF performance after 1.6 Gbps since the Q factor is less than 6.



(a)



(b)

Figure 9. Performance of bit rate versus log BER for 2 users- 3LCDM- RoF system with 5 GHz carrier frequency for (a) lower level and (b) upper level

Based on the results shown, it is evident that the 3LCDM-RoF system offers distinct advantages over the conventional RoF. Not only does the 3LCDM-RoF system have the capacity to serve twice as many users, but it also achieves a higher data rate and a longer transmission distance compared to its conventional counterpart. Furthermore, it is worth noting that systems utilizing a 5 GHz carrier frequency outpace those with a 2.4 GHz carrier in terms of data rate, yet it falls short in transmission distance compared to its 2.4 GHz counterpart. This discrepancy can be explained by the relationship between bandwidth and signal frequency. A signal with greater bandwidth, which corresponds to higher signal frequencies, undergoes more variations per second. The rate of these variations impacts the rate of information that can be transferred. Therefore, the higher carrier frequencies indicate more available bandwidth, illustrating a higher achievable data rate [11].

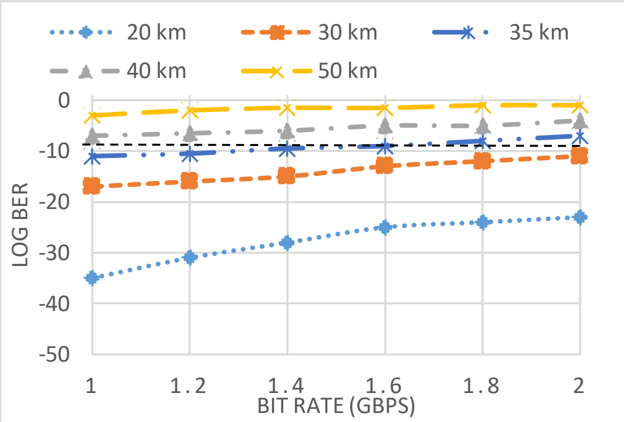


Figure 10. Performance of Bit Rate versus log BER for conventional RoF system with 5 GHz carrier frequency.

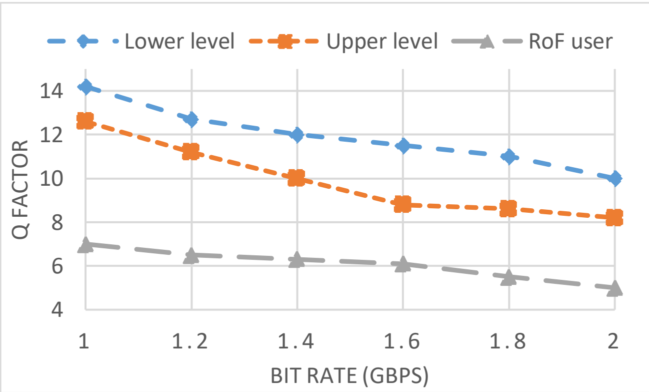


Figure 11. Performance of Bit Rate versus Q Factor for both 3LLCDM-RoF and conventional RoF systems at 5 GHz carrier frequency

C. *3LCDM-RoF with the combination of 2.4 GHz and 5GHz carrier frequencies*

Based on the simulation data presented in Table 2; Figure 12 shows the effect of changing bit rates on the BER, thereby determining the maximum data rate that the proposed system can support. The analysis focused on the bit rate range of $0.2 - 0.6\ Gbps$, as the corresponding BER values were around 10^{-9}, which is the acceptable value.

Table 2
Log BER for many values of data rate at different lengths of fiber

Data rate (Gbps)	Log BER at 10 km	20 km	30 km	40 km	50 km
0.2	-59.7	-38.9	-24.5	-17.7	-13.8
0.35	-40.7	-24.6	-16.8	-12.7	-10.1
0.4	-31.4	-22.2	-16.4	-12.7	-10
0.5	-22.1	-16.1	-12	-9.5	-8
0.6	-19.2	-14.3	-10.9	-8.7	-7.2

This range would be adequate to quantify the preliminary results of the 3LCDM performance over RoF without using any amplifier. A lower bit rate system without amplifiers has lower interference, lower cost, lower latency, and lower power consumption. As it can be less susceptible to interference, leading to more reliable data transmission. This is because amplifiers can amplify not only the desired signal but also any noise or interference that may be present in the signal, as well as it introduces additional processing time, leading to higher latency. Lower bit rate may be preferred in RoF systems used in wireless communication networks, distributed antenna systems, and radar systems, to ensure reliable transmission of the signal over a longer distance and to minimize the noise and distortion.

Figures 12 and 13 illustrate the performance of transmission 0.2 Gbps to 0.6 Gbps data rate versus log BER for the worst level among the four levels in the 3LCDM-RoF system and for the worst user among two users in the conventional RoF system respectively. The results show that the 3LCDM-RoF with the combination of 2.4 GHz and 5 GHz carrier frequencies can support 4 users at a maximum bit rate of 2 x 0.5 Gbps and 40 km fiber length, where the BER is around 3 x 10^{-10} which is -9.5 of log BER. Whereas the conventional RoF with the combination of 2.4 GHz and 5 GHz carrier frequencies supports tw users at 0.4 Gbps maximum data rate and 35 km maximum fiber length.

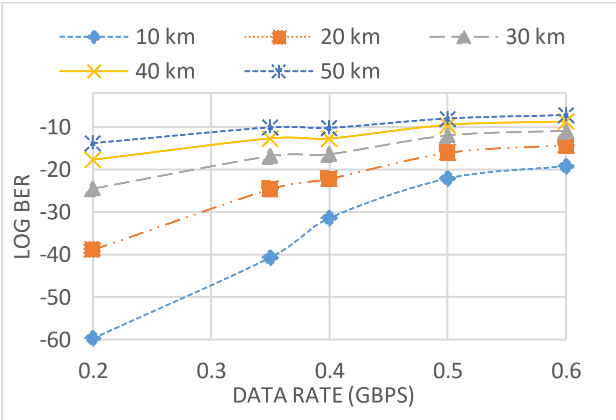


Figure 12. Performance of log BER versus data rate for the worst level in 3LCDM-RoF system with 2.4 GHz and 5 GHz

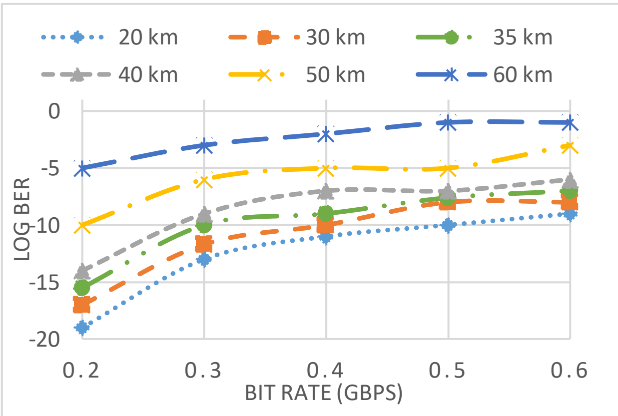


Figure 13. Performance of log BER versus data rate for the worst user in conventional RoF system with 2.4 GHz and 5 GHz carriers

Figure 14 shows the performance of fiber length versus Q factor for all levels of the 3LCDM-RoF system and both users of the conventional RoF system at a bit rate of 2 x 0.5 Gbps in each channel. It can be observed that the lower level and the upper level in 5 GHz carrier frequency have similar performance at around 6 Q factor at 43 km fiber length. Moreover, the signals in the RoF system for two users will not be transmitted properly beyond a 30 km of distance since the Q factor will be less than 6.

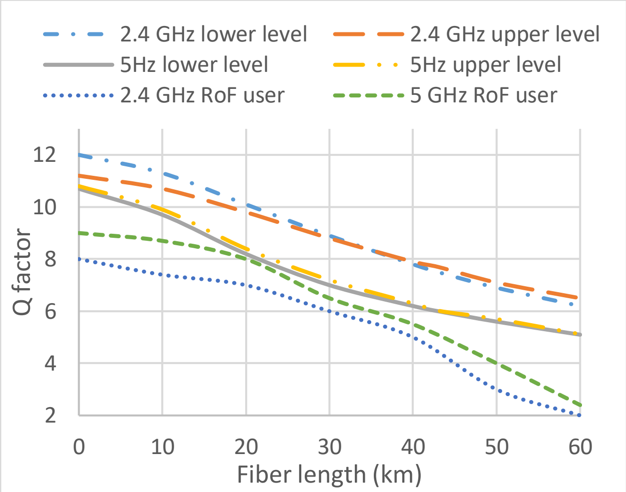


Figure 14. The performance of fiber length versus Q factor for both 3LCDM-RoF and conventional RoF systems at the combination of 2.4 GHz and 5 GHz carrier frequencies.

From all the previous findings, it can be found that the 3LCDM-RoF and conventional RoF systems with the combination of the two carrier frequencies (2.4 GHz & 5 GHz) can support more users at a lower bit rate in comparison with the cases at the single carrier frequency. The 3LCDM-RoF system with the combination of both carrier frequencies supports four users in each 3LCDM-RoF with the single carrier frequency supports two users even though each of the systems uses only one optical modulator.

IV. CONCLUSION

This paper presents a simple, competent, and cost-effective 3LCDM over RoF system utilizing carrier frequencies of 2.4 GHz, 5 GHz, and a combination of both. This study also evaluates the performance of the system to find the optimum tradeoff between bit rate and fiber length, and then compares it with the conventional RoF system. Through the simulation of various data rates transmitted across 20 km to 60 km optical fiber at a wavelength of 1552.5 nm, the findings reveal a significant advantage in the proposed 3LCDM-RoF system. Not only does the 3LCDM-RoF system have the capacity to support double the number of users compared to its conventional RoF, thereby enhancing capacity and reducing both cost and complexity, but it also demonstrates the capability to achieve a higher data rate and a longer transmission distance. These positive results were obtained without the need for amplifiers, attesting to the inherent efficiency of the proposed system. These promising findings suggest that the 3LCDM-RoF system holds substantial potential to meet the demands of future telecommunication systems. One recommendation for future work is to explore the implementation of 3LCDM over RoF at larger data rates and higher carrier frequencies, potentially utilizing millimeter-wave carrier generation to facilitate data rate compression.

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