Performance Evaluation of a SCM-OFDM Radio over Fiber System for the Mobile Fronthaul

Oratilwe Jothi[1], Edwin Ataro[2], and Stephen Musyoki[2]
[1] Dept. of Electrical Engineering, Pan African Univ. Inst. of Basic Sciences Technology and Innovation, Nairobi, Kenya
[2] School of Electrical and Electronics Engineering, Technical Univ. of Kenya, 52428-00200, Nairobi, Kenya
Email: oratilwe.jothi@students.jkuat.ac.ke; ataro@tukenya.ac.ke; smusyoki@yahoo.com

***Abstract*—The exponential growth in mobile data traffic caused by the upsurge of Internet users has led to a high demand of capacity on the mobile data networks. High capacity and high data rate requirements created an emergence of Radio over Fiber (RoF) technology which is a possible key in the provision of high bandwidth and cost-effective fronthaul solutions. This paper presents an evaluation on the integration of Subcarrier Multiplexing (SCM) with RoF and Orthogonal Frequency Division Multiplexing (OFDM) technologies to enhance the system capacities. A 4-channel SCM-OFDM architecture combined with RoF technology is examined across three different modulation schemes (i.e., 256-QAM, 64-QAM and 16-QAM) for transmission distances from 10 km to 120 km for two data rates i.e., (5 and 10) Gbps. The performance of the architectures is measured by Bit-error rate (BER), Quality-factor (Q-factor), Signal-to-Noise Ratio (SNR), Error Vector Magnitude (EVM), Eye-Opening Penalty (EOP), received power and of transmitted signals. The simulation results indicates that the SCM-OFDM model at a 10 Gbps data rate gives a better performance under the 256-QAM modulation scheme. Furthermore the performance of all the SCM-OFDM systems is more superior operating at a 10 Gbps data rate when compared to the 5 Gbps data rate.**

***Index Terms*—Radio over Fiber (RoF), Orthogonal Frequency Division Multiplexing (OFDM), Subcarrier Multiplexing (SCM), Wavelength Division Multiplexing (WDM), Signal-to-Noise Ratio (SNR)**

I. INTRODUCTION

There has been a rise in mobile broadband traffic which grows exponentially due to high mobile subscriptions, as mobile devices are used as the primary access to Internet services [1], [2]. There has been a growth in mobile subscriptions and it is estimated that it will grow to 5.7 billion by 2023 [1]. Carrying such a huge quantity of mobile broadband traffic is a massive issue faced by network vendors and operators. The capacity of the mobile data networks has to increase to meet the high traffic capacity demand [3].

It is projected that the fifth generation (5G) mobile network is going to provide not only faster speeds in transmissions, but also a lower latency (≤1ms), greater capacity and larger number of connected mobile devices [4], [5]. This will help relieve the congestions experienced on fourth generation (4G) mobile networks [6]. The Network architecture, Cloud Radio Access Network (C-RAN), is a robust competitor in communication systems, even 5G systems as it has benefits which will meet the 5G requirements and help mitigate challenges, such as reducing operational expenditures (OPEX) and capital expenditures (CAPEX), saving energy and dynamically sharing resources [7]. The C-RAN architecture consists of the three components, being the baseband units (BBUs), remote radio units (RRUs) and fronthaul. The BBUs are centralized in one place creating a virtualized BBU hotel. This enables resources to be dynamically shared among the base stations (BSs) [3].

The fronthaul (link between BBUs and RRUs) has a high bandwidth requirement and this is one of the major challenges for C-RAN. This challenge cannot be met by wireless communication [8]. So Radio over Fiber (RoF) technology has solutions to meeting this requirement as it can provide both high bandwidth and cost-effective fronthaul solutions for 5G services [9]. A RoF system is a cross architecture combining optical and wireless infrastructures [10].

In RoF systems, radio frequency (RF) signals are transmitted through the optical link from the BBUs to the RRUs before travelling wirelessly through the air [10], [11]. Orthogonal Frequency Division Multiplexing (OFDM) technique has been predominant in wireless communications with its ability to eliminate Inter Symbol Interference (ISI) and to mitigate radio channel losses. The combination of optical communication and wireless communication (OFDM-RoF) produces a system characterized by high spectral efficiency, large capacity and high speed [12].

However, A-RoF technology suffers from drawbacks which decrease the performances of these systems through the presence of distortion in the RoF link. It is vulnerable to distortion and noise thanks to nonlinearities created at the laser, optical fiber and photodetector [13]. Specifically, these systems face a signal liability to two distortion sources which are chromatic dispersion of the fiber and the frequency chirp which is false phase signals caused by the laser source [14].

The D-RoF method serves as an alternative solution to evade these drawbacks. The transmission of digital data alleviates the issues of nonlinearity issues generated at

Manuscript received August 6, 2021; revised February 23, 2022; accepted March 30, 2022.

Corresponding author: Oratilwe Jothi (email: oratilwe.jothi@students.jkuat.ac.ke).

doi: 10.18178/ijeetc.11.3.175-183

both the transmitter and receiver sides [13]–[16]. Nonetheless, the D-RoF technique is expensive and this cost escalates with the increase in requirement of high precision analog to digital (A/D) and digital to analog converters (D/A). Likewise, this reduces steadiness of the phase relation between multpile RRHs and also reduces the spectral efficiency [14].

Common Public Radio Interface (CPRI), is a protocol utilized in the fronthaul to implement the interface between the BBU and the RRU requires massive transmission bandwidth for the D-RoF [9]. This factor creates limitations to digital fronthaul solutions due to this great need to transmit much higher bandwidth signals than the actual RF signals due to digitized signals with high sampling resolution [17]. Other factors which limit the fronthaul and the provision of reliable communication over the optical link are noise added by the optical amplifiers and the nonlinear distortions due to the Kerr effect in the optical fiber. The transmission of any optical signal is affected by attenuation, dispersion and nonlinearities in the optical channel and in the wireless channel [18].

Delta-Sigma modulation has been recently proposed as a new digitization interface for a digital fronthaul link [13]–[16]. Nevertheless, these systems have some drawbacks as they require costly, highly efficient and high sampling rate digital signal processing (DSP) circuitry to their performance [13]–[16]. In this regard, A-RoF technology can be utilized, while applying methods to alleviate the nonlinearities can represent a promising solution [19].

Analog and digital electrical techniques have been proposed as solutions to reduce the nonlinearities present in A-RoF transmission [20]. Analog predistortion (APD) method is whereby the nonlinearities of the laser source are compensated but the shortcoming of the method is its need for a different predistorter for every single RoF transmitter for its different application to large scale production [14].

Digital predistortion (DPD) method has many approaches such as the usage of memory polynomials whereas a trained predistorter based on Volterra series has been applied to the RoF link [21]. Another DPD approach is based on canonical piecewise-linear (CPWL) function for the intensity modulated/direct detection RoF system. Another DPD technique proposed is based on memory and generalized memory polynomial for Vertical Cavity Surface Emitting Lasers (VCSELs) based RoF links [13]–[15], [19], [22].

Many researchers have come up with solutions for the problem. In [23], a performance of the RoF network of N-channels was analyzed for Wavelength Division Multiplexing (WDM) with Differential Phase Shift Keying (DPSK) and Quadrature Amplitude Modulation (QAM) modulation formats to study the nonlinearity effect. Their WDM-RoF system using the DPSK modulation format showed a positive enhancement in comparison with the QAM format.

In [24], the WDM-RoF network was also analyzed on the transmission performance over different fiber lengths with the channel spacing at 0.4 nm and a fixed input power. Their results showed that the Q-factor was 6.30, the Bit-error rate (BER) was 4.56×10^{-10}. Their system displayed good performance as the Q-factor was greater than 6 and the BER was less than 10^{-9}. In [25], there was an improvement on the system performance due to the combination of the properties of WDM and Subcarrier Multiplexing (SCM) techniques. The OFDM technique and three modulation techniques were used (4-QAM, 16-QAM, and 64-QAM). Their findings showed that the system with 16-QAM-OFDM provides the highest RF signal power.

This paper presents the SCM-RoF system with the OFDM technique which allows for the transmission of 4 RF channels with 16-QAM, 64-QAM and 256-QAM modulation schemes for fiber lengths from 10 km up to 120 km. The proposed system is based on the external modulation of the MZM modulator. A simulation model has been developed to study the performances of the SCM-OFDM RoF system in terms of BER, Q-factor, Signal-to-Noise Ratio (SNR), Eye-Opening Penalty (EOP), for varying fiber lengths and of different data rates. The performance quality is also analyzed through the Error Vector Magnitude (EVM) limit determined by the 3rd Group Partnership Project (3GPP) and European Telecommunications Standard Institute (ETSI) which matches to 12.5%, 8% and 3.5% for 16-QAM, 64-QAM and 256-QAM, respectively [26]. Results are shown for multiple mobile signals operating at a carrier wavelength of 1550 nm on a single optical channel. Optisystem V.17.1, a commercial software, is utilized to obtain the simulation results. The aim of the paper is to design a SCM-OFDM-RoF system which improves the system performances to produce better BER, Q-factor, EOP, SNR system performances in the fronthaul at a higher modulation format as compared to other articles.

This paper is arranged in the following manner: Section II entails the discussion of the SCM multiplexing technique used in this study as well as the theoretical analysis of M-QAM modulation schemes. Section III involves the introduction of the system model of the SCM-OFDM-RoF designs and its operation. Section IV discusses the simulation results of the SCM-OFDM-RoF designs under the 256-QAM, 64-QAM and 16-QAM modulation schemes. The performance of the system is discussed using BER, Q-factor, received power, SNR, EVM and EOP performance metrics. Finally, the whole study is concluded in Section V.

II. Materials and Methods

A. Subcarrier Multiplexing (SCM)

It is a multiplexing technique used in optical systems to increase their bandwidth utilization efficiency. It is more sensitive to noise effects, which limits the data rates and the maximum subcarrier frequencies. In the SCM technique, multiple signals of the RoF system in the RF domain are multiplexed then propagated through a solo wavelength.

The SCM technique offers flexibility and upgradability in its design where analog and/or digital modulation can be utilized to transmit multiple voice, data, and video signals to a great number of users [27].

B. Theoretical Analysis

Theory dictates that higher order M-QAM modulation schemes will have a poorer SNR and received signal power performance since it has a higher spectral efficiency, than lower order M-QAM modulation schemes. This is due to the fact that higher order M-QAM modulation formats are susceptible to errors even though they have higher spectral efficiencies. Though it is possible to transmit more bits/symbol, if the constellation energy remains the same, the points remain the same and are closer together which causes the transmission to be vulnerable to noise. The performance of the demodulator is severely degraded by the estimation error of the channel because the demodulator decision region depends on the channel fading [28], [29].

However, theory also states that the higher data rate will have a lower delay from one point to another when delivering data [30]. In this case, the 10 Gbps will have an increased capability to support a larger number of channels and give a better performance. Also, an increase in the transmission power improves the SNR of the system, allowing the receiver to decode the signals at the high data rates [30]. M-QAM modulation schemes also perform better at higher data rates as they provide an increased bandwidth [31]. The received SNR differs as a result of multipath fading and a constant SNR is maintained by changing several parameters for instance modulation orders, data rates and transmission power[32].

III. System Model

The basic and the main components of the OFDM-RoF system are the transmitter, optical link and receiver. This section discusses the designs of the RoF systems under three modulation schemes (16-QAM, 64-QAM and 256-QAM) with a multi-channel OFDM technique through the use of SCM technique. The SCM-OFDM-RoF were designed using the Optisystem v.17.1 software.

A. SCM-OFDM RoF System Model

The SCM-OFDM RoF system model block diagram is shown in Fig. 1. It shows a 4-channel model with four RF transmitter channels (2.5 GHz, 10.5 GHz, 25 GHz and 32.5 GHz) combined using a 4x1 combiner. The output signal from the combiner then goes through the LiNb MZ Modulator. The signal is then modulated by the semiconductor laser generating an optical signal to be transported through the optical channel towards the receiver. Two Erbium Doped Fiber Amplifiers (EDFAs) are used to boost weak optical signals and compensate for fiber losses.

The receiver comprises of two parts which are the optical side and the RF side. At the optical side of the receiver, the Positive Intrinsic Negative (PIN) photodetector is used to detect the optical signal transmitted through the optical channel. There is a signal conversion from an optical form into an electrical form by the PIN photodetector is then passed through a 1×4 Fork to reiterate the input signal into four output signals.

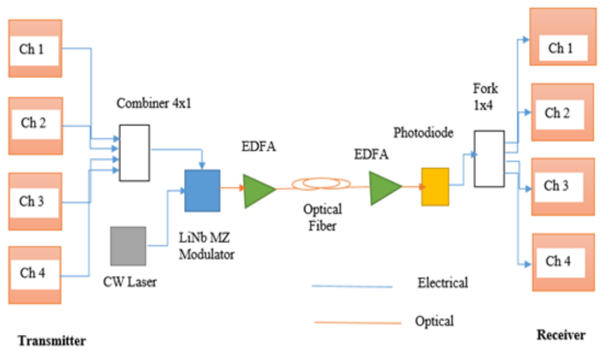

Fig. 1. SCM-OFDM RoF system model.

Fig. 2 displays the RF transmitter of the second channel of the 4-channel SCM-OFDM-RoF model as designed in Optisystem v.17.1. The first component is the Pseudo Random Bit Sequence (PRBS) generator which is responsible for generating a bit rate signal. It is linked to the QAM sequence generator which is also linked to the M-ary pulse generator inside the subsystem.

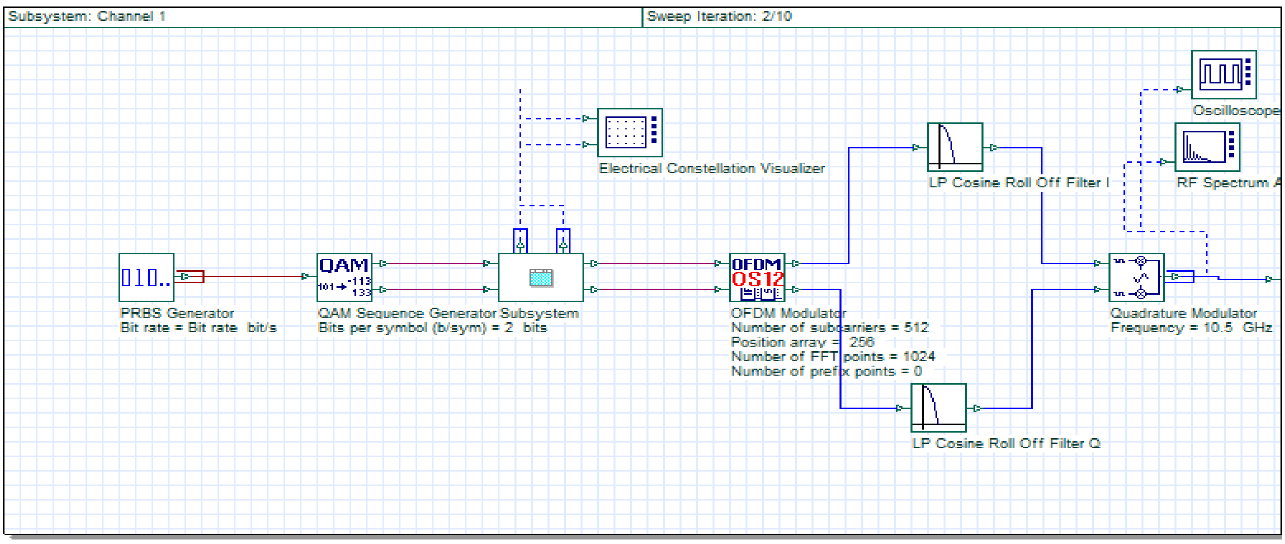

Fig. 2. RF transmitter of the SCM-OFDM channel 1.

The subsystem contents are as shown in Fig. 3. The M-ary Pulse Generators are used to transmit low data rate streams over various narrowband subcarriers after splitting high data rate streams. This is then attached to the OFDM modulator and low pass roll-off filters. Then a Quadrature modulator is connected to up-convert the signal to a high RF frequency.

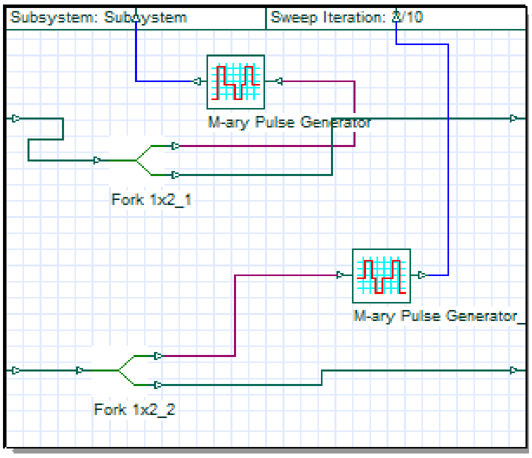

Fig. 3. M-ary pulse generator subsystem.

Fig. 4 displays the second channel at the RF receiver, which shows an electrical amplifier in the system which is used to regenerate the power lost due to the fiber loss mechanisms. The OFDM demodulator is utilized to demodulate the signal to extract the symbols decoded and recover the original bits from the transmitter.

TABLE I: SIMULATION PARAMETERS OF THE ROF SYSTEM MODEL

Unit	Subunit	Parameter	Value
Baseband Unit (BBU)	OFDM Modulator	Number of Subcarriers	512
		Number of FFT points	1024
		Number of prefix points	0
	CW Laser	Wavelength	1550 nm
		Power	0 dBm
		Line width	0.1 MHz
	LiNb MZ Modulator	Extinction Ratio	30 dB
		Switching bias voltage	4 V
		Switching RF voltage	4 V
		Insertion Loss	2 dB
Optical Link	EDFA 1	Gain	13 dB
		Noise Figure	4 dB
	Single Mode Fiber	Wavelength	1550 nm
		Attenuation	0.2 dB/km
		Dispersion	16.75 ps/nm/km
		Dispersion slope	0.075 ps/nm2/km
	EDFA 2	Gain	12 dB
		Noise Figure	4 dB
Remote Radio Unit (RRU)	Photodiode PIN	Responsively	1 A/W
		Center Frequency	193.1 THz

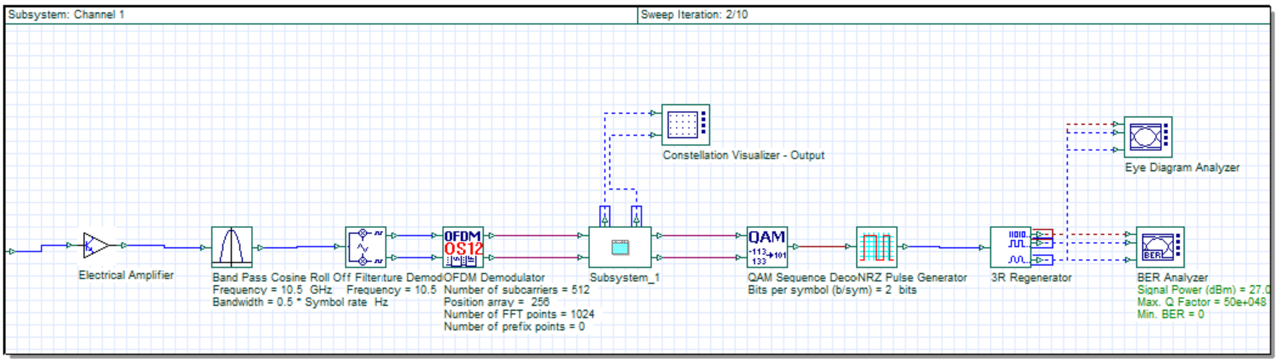

Fig. 4. RF receiver of the SCM-OFDM channel 1.

The simulation parameters of the RoF system model are listed in Table I.

IV. RESULTS AND DISCUSSION

This section presents the simulation results for the SCM-OFDM model on the RoF link. This will utilize the combination of SCM and OFDM techniques for three modulation schemes for 5 Gbps and 10 Gbps data rates.

A. SCM-OFDM System

Fig. 5 displays the Q factor of the SCM-OFDM system utilizing the 256-QAM modulation scheme over the transmission distance of 120km. The Q-factor is maintained at 9.537×10^{21} for the transmission distance of 10km to 120km and it only lowers to 2.328×10^{11} at the 70km and 120km distance. The decrease in Q-factor at 70 km and 120 km may be caused by a slight degradation in the system due to attenuation experienced in the optical fiber. Even with the drop to 2.328×10^{11}, the Q-factor value is still very high and this is constant for all three modulation schemes. This Q-factor value is also constant for all modulation.

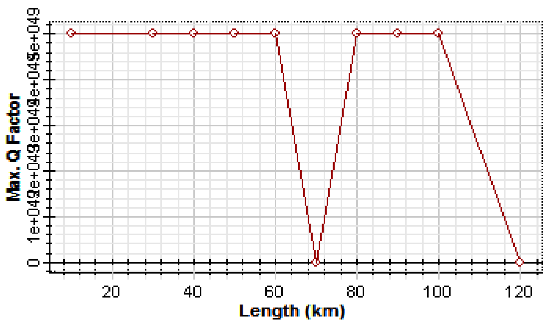

Fig. 5. Q-factor for 256-QAM modulation scheme.

Fig. 6 displays the BER of the system over the fiber length of 120km. It shows a minimum value of zero for the whole transmission distance from 10km to 120km for all three modulation schemes (16-QAM, 64-QAM and

256-QAM) studied. The overall Q-factor and BER for all the SCM-OFDM RoF systems is 9.537×10^{21} and 0 respectively, for all the three modulation schemes studied for both data rates 5Gbps and 10Gbps. The Q-factor and BER are extremely too high and too low, respectively, because of high spectral efficiency, large capacity and high speed associated with OFDM-RoF systems and the set parameters in Table I.

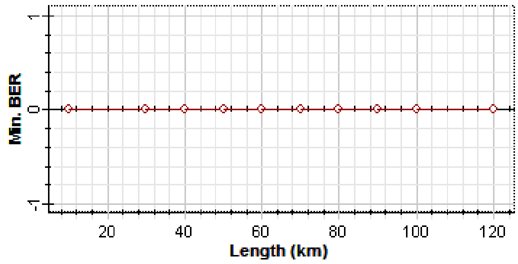

Fig. 6. BER for 256-QAM modulation scheme.

The received power versus transmission distance at a 5Gbps data rate is shown on Fig. 7, for different modulation schemes (16-QAM, 64-QAM and 256-QAM). Fig. 7 depicts how SCM-OFDM system model under the 256-QAM scheme performs better than the 64-QAM and 16-QAM scheme in the RoF link. This is due to 256-QAM modulation scheme having a higher spectral efficiency, giving more provision for more data to be transmitted over the optical link in a small spectrum followed by the 64-QAM modulation scheme as compared to the 16-QAM modulation format. At the transmission distance of 120 km, the 256-QAM scheme has a received signal power of -82.21 dBm, followed by 64-QAM with -91.36 dBm and lastly the 16-QAM scheme having a received signal power of –100dBm. The received power versus transmission distance at a 10 Gbps data rate is displayed in Fig. 8, for different modulation schemes. The SCM-OFDM model at a 10 Gbps data rate, similar to 5Gbps, shows a better performance under the 256-QAM scheme, followed by the 64-QAM scheme then the 16-QAM scheme. This is as a result of higher order M-QAM modulation formats (256-QAM and 64-QAM) having a higher spectral efficiency as compared to lower order M-QAM modulation formats (16-QAM). At the fiber length of 120km, 256-QAM, 64-QAM and 16-QAM modulation schemes have signal powers of -81.57 dBm, –86.97dBm and –89.08dBm, respectively. Comparing Fig. 7 with Fig. 8, Fig. 8 shows a better system performance comparatively in terms of received power because the bandwidth of RF-channels increases with an increasing data rate.

Fig. 9 displays the SNR versus the transmission distance at 5Gbps data rate for three different modulation schemes. From Fig. 9, the 256-QAM modulation scheme gives a better system performance with a higher SNR as compared to 64-QAM and 16-QAM modulation schemes as a result to 256-QAM being more bandwidth efficient than 64-QAM and 16-QAM even when subjected to noise in the channel. The 256-QAM scheme has a SNR equal to 17.79dB at a distance of 120km whilst the 64-QAM and 16-QAM schemes have an SNR of 8.64dB and 0dB at the same distance, respectively. The SNR versus the transmission distance at a 10 Gbps data rate is displayed in Fig. 10. It shows the SCM-OFDM system model utilizing the 256-QAM modulation scheme to have a better performance in comparison with the 64-QAM and 16-QAM modulation schemes. This is due to 16-QAM and 64-QAM having a lower spectral efficiency than the 256-QAM at a higher data rate. At the fiber length of 120 km, 256-QAM, 64-QAM and 16-QAM modulation schemes have a SNR of 18.43dB, 13.03dB and 10.92dB, respectively. Fig. 10 shows superiority over Fig. 9 in terms of SNR over various fiber length across (256-QAM, 64-QAM and 16-QAM) modulation schemes as theory dictates that M-QAM modulation schemes achieve a higher SNR at higher data rates as they provide an increased bandwidth.

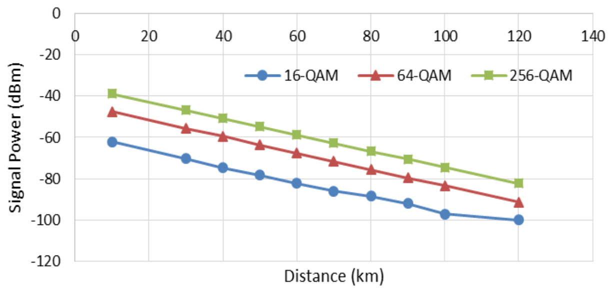

Fig. 7. Received power vs transmission distance at 5Gbps data rate for three different modulation schemes.

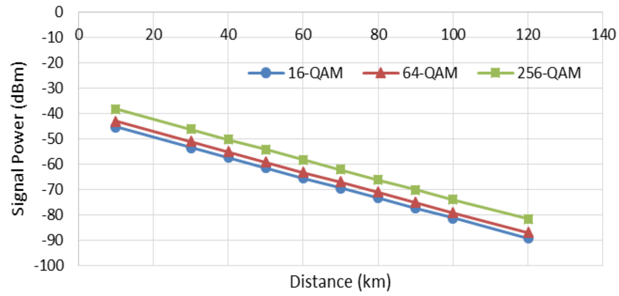

Fig. 8. Received power vs transmission distance at 10Gbps data rate for three different modulation schemes.

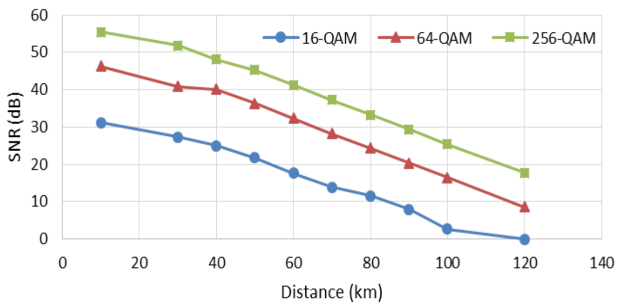

Fig. 9. SNR vs transmission distance at 5Gbps data rate for three different modulation schemes.

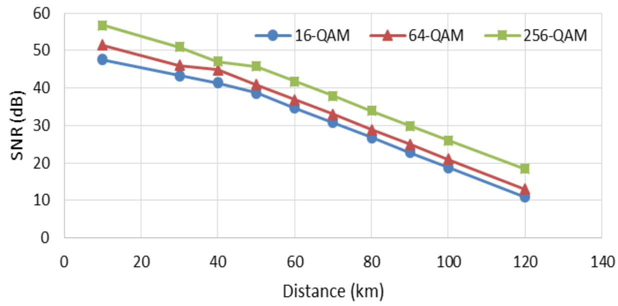

Fig. 10. SNR vs transmission distance at 10Gbps data rate for three different modulation schemes.

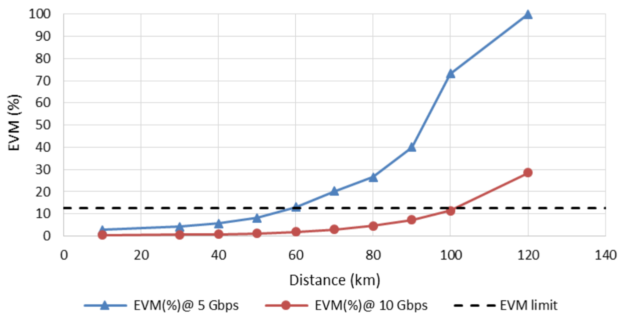

Fig. 11. EVM vs fiber length for the 16-QAM modulation scheme.

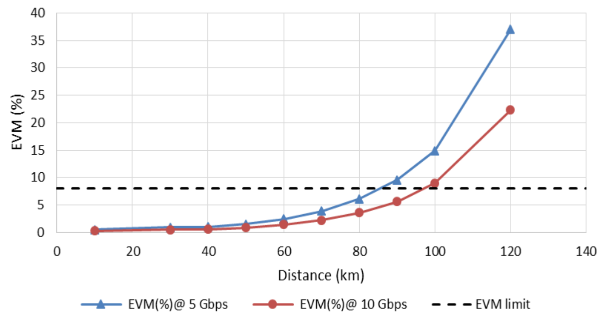

Fig. 12. EVM vs fiber length for the 64-QAM modulation scheme.

Fig. 11 shows the EVM in relation to the transmission distance for the 5 Gbps and 10 Gbps data rates, for a 16-QAM modulation scheme. The allowable distance when the EVM value does not exceed the EVM limit of 12.5% during transmission for a 5 Gbps and 10 Gbps data rates is up to 60 km and 100 km, respectively. The increase of the EVM value at 5 Gbps is due to the effect of distortion in the optical fiber as compared to at 10 Gbps.

Fig. 12 shows the performance of EVM in relation to the transmission distance for the 5 Gbps and 10 Gbps data rates, for a 64-QAM modulation scheme. The allowable distance when the EVM value does not exceed the EVM limit of 8% during transmission for 5 Gbps and 10 Gbps data rates is up to 85 km and 99 km, respectively. The same as for the 16-QAM modulation scheme, the steep increase of the EVM value at 5 Gbps is due to the effect of distortion experienced in the optical fiber as compared to at 10 Gbps.

Fig. 13 below shows EVM versus the fiber length for the 256-QAM modulation scheme measured at the receiver. It shows that the allowable distance when the EVM value does not exceed the EVM limit of 3.5% during transmission for both 5 Gbps and 10 Gbps data rates is up to 90 km. This steep increase of the EVM value at 5 Gbps and 10 Gbps is due to the effect of distortion in the optical fiber. EVM has a significant effect on the maximum transmission distance of the system as the maximum transmission is seen to vary in Fig. 11, Fig. 12 and Fig. 13 depending on the modulation format and data rate of the system. It also highlights that the 256-QAM scheme has an achievable transmission distance of 90 km at 5 Gbps and 10 Gbps data rates showing a similarity in performance between the two data rates as compared to the 16-QAM and 64-QAM schemes and an improved performances under a 5 Gbps data rate.

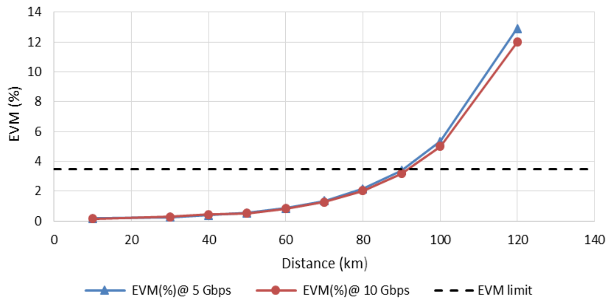

Fig. 13. EVM vs Fiber Length for the 256-QAM modulation scheme.

The EOP of the SCM-OFDM system was also studied for the three different modulation schemes. The EOP helps to quantify the quality of the signal. Fig.14 displays the relationship between EOP and the fiber length measured from the 256-QAM scheme and identical with all three modulation schemes at 5 Gbps and 10 Gbps data rates. The EOP on Fig. 14 shows a constant value of 0dB with an increasing fiber length as the eye-opening height remains open for the whole fiber length as shown on Fig. 15 below displaying the eye diagram of the 256-QAM scheme at a 90 km transmission distance. This result gives an instant indication on the quality of the received signal.

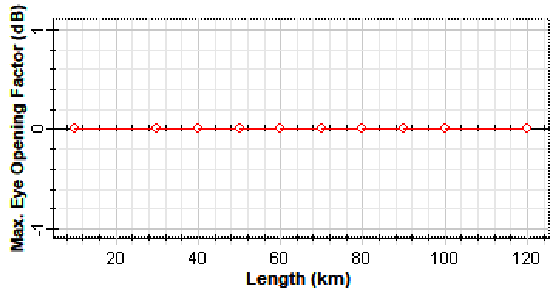

Fig. 14. EOP vs Fiber Length for the 256-QAM modulation scheme.

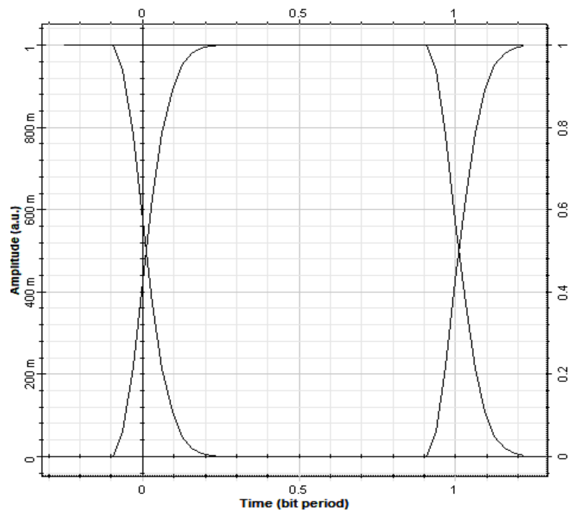

Fig. 15. Eye diagram for the 256-QAM modulation scheme.

Table II shows the comparison in performance between existing and proposed design systems of SCM-OFDM on received power. Results of the proposed SCM-OFDM systems are compared to the results of reference [25]. Table II shows how the proposed designs are better in terms of performance in regard to received signal power of 16-QAM modulation schemes at different data rates of (5 and 10) Gbps and a fiber length of 100 km. This is because the proposed systems have a higher received signal power than [25] which highlights the increased bandwidth in the proposed systems. Table III compares the existing design systems of references [24], [33]-[35] with the proposed SCM-OFDM design systems. The performance metrics in comparison here are Q-factor and BER. It shows that the proposed SCM-OFDM system outperforms the existing systems for the same transmission distances.

TABLE II: RESULTS COMPARISON OF EXISTING AND PROPOSED DESIGNS ON RECEIVED POWER

Work	Fiber length (km)	Received power (dBm)	
		5 Gbps 16-QAM	10 Gbps 16-QAM
[25]	100	-98.0	-102.0
Proposed design	100	-97.29	-81.22

TABLE III: RESULTS COMPARISON OF EXISTING AND PROPOSED DESIGNS ON Q-FACTOR AND BER

Work	Transmission distance (km)	Q-factor	BER
[24]	60	6.30	4.56×10−10
[33]	60	9.22647	0.0029295
Proposed design	60	9.537× 10+21	0
[34]	20	17.77	5.2×10-71
Proposed design	20	9.537× 10+21	0
[35]	120	8.05	4.05×10-18
Proposed design	120	9.537× 10+21	0

V. CONCLUSION

In this research, the performance of the system was enhanced by combining the properties of SCM and OFDM techniques and using high order modulation schemes (256-QAM, 64-QAM and 16-QAM) operating at (5 and 10) Gbps data rates, respectively. The OFDM technique has proven to be useful in optical networks through the combination with RoF systems providing highly efficient communication. Three modulation schemes (16-QAM, 64-QAM and 256-QAM) were used in the SCM-OFDM-RoF system. The system displays a good overall performance from the Q factor, BER, EVM and EOP measured for all three modulation schemes at distances from 10km to 120km with the 256-QAM-SCM-OFDM system on the RoF showing a superior performances compared to the 64-QAM and 16-QAM schemes.

The simulation results were shown in terms of received power, SNR, EVM, EOP and they show that the 256-QAM-SCM-OFDM system gives a better performance than the other modulation schemes at a 5Gbps data rate. The SCM-OFDM model at a 10Gbps data rate gives a better performance under the 256-QAM modulation scheme highlighting once again the increased bandwidth and high spectral efficiency experienced by high order modulation schemes despite the presence of noise in the systems over varying fiber lengths. The performance of all the studied systems is more superior operating at a 10 Gbps data rate over a 5Gbps data rate.

APPENDIX A CONSTELLATION DIAGRAMS

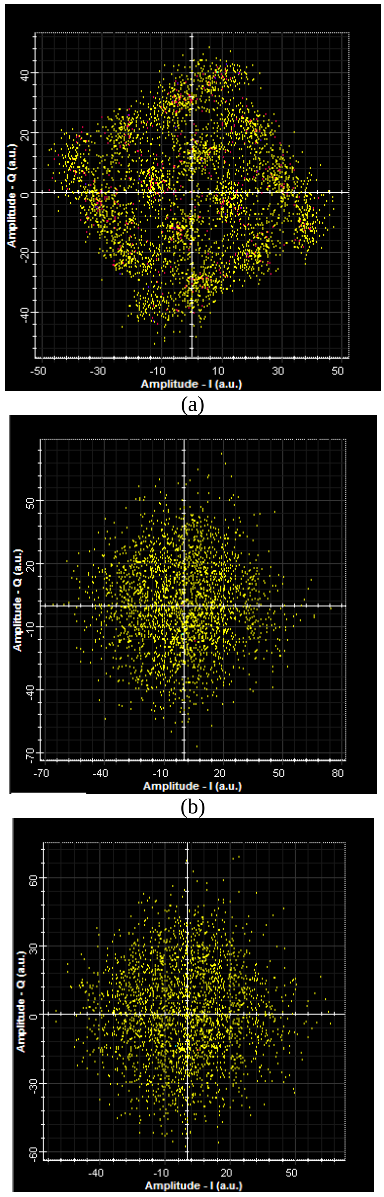

Fig. 16. SCM-OFDM RoF system constellation diagram at 90 km for 10 Gbps data rate, (a) 16-QAM, (b) 64-QAM and (c) 256-QAM.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Oratilwe JOTHI conducted the research, carried out the designs of the experiments, simulations and results analysis and wrote the paper; Edwin ATARO supervised the work; Stephen MUSYOKI supervised the work; all authors had approved the final version.

ACKNOWLEDGMENT

The authors would like to acknowledge the sponsor of this research, the African Union (AU) for financial assistance and give gratitude to their colleagues who assisted in the research.

REFERENCES

[1] S. O'Dea. (Jan. 2021). Mobile subscribers growth worldwide 2023 Statista. [Online]. Available: https://www.statista.com/statistics/1190254/mobile-subscribers-growth-worldwide/

[2] S. O'Dea. (Jul. 2021). Smartphone users 2020 | Statista. [Online]. Available: https://www.statista.com/statistics/330695/number-of smartphone-users-worldwide/

[3] M. F. Hossain, A. U. Mahin, T. Debnath, F. B. Mosharrof, and K. Z. Islam, “Recent research in cloud radio access network (C-RAN) for 5G cellular systems - A survey,” *J. Netw. Comput. Appl.*, vol. 139, pp. 31–48, April 2019.

[4] Advantages of 5G and how will benefit IoT. [Online]. Available: https://www.iotsworldcongress.com/advantatges-of-5g-and-how-will-benefit-iot/

[5] Benefits of 5G Technology: 5G Features and Advantages | Intel. [Online]. Available: https://www.intel.com/content/www/us/en/wireless-network/5g-benefits-features.html

[6] K. Fitchard, F. Rizzato, and I. Fogg, “The 5G opportunity - How 5G will solve the congestion problem of today’s 4G networks,” *OpenSignal*, 2019.

[7] M. Zhu, “High-capacity communication systems using advanced optical and wireless technologies,” Ph.D dissertaion, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia, 2015.

[8] T. Salman. (2016). Cloud RAN: Basics, Advances and Challenges. [Online]. Available: https://www.cse.wustl.edu/~jain/cse57416/ftp/cloudran/.

[9] R. Karthikeyan and S. Prakasam, “A survey on radio over fiber (RoF) for wireless broadband access technologies,” *Int. J. Comput. Appl.*, vol. 64, no. 12, pp. 14–19, 2013.

[10] B. R. Ballal, “Performance comparison of analog and digital radio over fiber link,” *Int. J. Comput. Sci. Eng. Technol.*, vol. 3, no. 6, pp. 193–198, June 2012.

[11] What is Radio over Fiber?–Fosco Connect. [Online]. Available: https://www.fiberoptics4sale.com/blogs/archiveposts/95043078-what-is-radio-over-fiber.

[12] Y. K. Wong, S. M. Idrus, and I. A. Ghani, “Performance analysis of the OFDM scheme for wirelessover fiber communication link,” *Int. J. Comput. Theory Eng.*, vol. 4, no. 5, pp. 807–811, Oct. 2012.

[13] M. U. Hadi, H. Jung, S. Ghaffar, P. A. Traverso, and G. Tartarini, “Optimized digital radio over fiber system for medium range communication,” *Opt. Commun.*, vol. 443, pp. 177–185, March 2019.

[14] M. U. Hadi, J. Nanni, J. L. Polleux, P. A. Traverso, and G. Tartarini, “Direct digital predistortion technique for the compensation of laser chirp and fiber dispersion in long haul radio over fiber links,” *Opt. Quantum Electron.*, vol. 51, no. 6, June 2019.

[15] M. U. Hadi, N. Aslam, and H. Jung, “Performance appraisal of sigma delta modulated radio over fiber system,” *J. Opt. Commun.*, pp. 1–7, Jan. 2019.

[16] M. U. Hadi, N. Aslam, R. Ali, *et al.*, “Experimental demonstration of MASH based sigma delta radio over fiber system for 5G C-RAN downlink,” *J. Opt. Commun.*, Feb. 2019.

[17] P. Chanclou, A. Pizzinat, F. L. E. Clech, and T. Reedeker, “Optical fiber solution for mobile fronthaul to achieve cloud radio access network,” in *Project: FP7 COMBO*, Lisbon, 2013, p. 11.

[18] R. S. Asha, “Performance improvement of radio over fiber communication system with dispersion and nonlinearity compensation” Ph.D dissertaion, Dept. Elect. Eng., Model Eng. Col., Cochin, India, 2017.

[19] M. U. Hadi, J. Nanni, O. Venard, *et al.*, “Linearity improvement of VCSELs based radio over fiber systems utilizing digital predistortion,” *Adv. Sci. Technol. Eng. Syst.*, vol. 4, no. 3, pp. 156–163, 2019.

[20] F. Fuochi, M. U. Hadi, J. Nanni, P. A. Traverso, and G. Tartarini, “Digital predistortion technique for the compensation of nonlinear effects in radio over fiber links,” in *Proc. IEEE 2nd Int. Forum Res. Technol. Soc. Ind. Leveraging a Better Tomorrow, RTSI 2016*, 2016.

[21] M. U. Hadi, J. Nanni; P. A. Traverso, *et al.*, “Experimental evaluation of digital predistortion for VCSEL-SSMF-based radio-over-fiber link,” in *Proc. Int. Top. Meet. Microw. Photonics*, 2018.

[22] M. U. Hadi, H. Jung, P. A. Traverso, and G. Tartarini, “Digital radio frequency transport over optical fiber for 5G fronthaul links,” *J. Opt. Commun.*, March 2019.

[23] B. Ait Ahmed, O. Aghzout, M. Chakkour, F. Chaoui, and A. Naghar, “Transmission performance analysis of WDM radio over fiber technology for next generation long-haul optical networks,” *Int. J. Opt.*, vol. 2019, Jan. 2019.

[24] A. H. Ali and A. D. Farhood, “Design and performance analysis of the WDM schemes for radio over fiber system with different fiber propagation losses,” *Fibers*, vol. 7, no. 3, pp. 12, Feb. 2019.

[25] F. M. Ali, E. Al-Hilo, and M. G. Tarbul, “Performance analysis of radio over optical fiber system with OFDM using multiplexing techniques,” *Int. J. Appl. Eng. Res.*, vol. 13, no. 12, pp. 10831–10844, 2018.

[26] 3GPP TS36.104 V12.10.0, Evolved Universal Terrestrial Radio Access (E-UTRA) Base Station (BS) Radio Transmission and Reception (Release 12), January 2016.

[27] Subcarrier Multiplexing (SCM) – Fosco Connect. [Online]. Available: https://www.fiberoptics4sale.com/blogs/wave-optics/subcarrier-multiplexing

[28] Comparison of QAM Modulation Types - Gigabit Wireless. [Online]. Available: https://www.gigabit-wireless.com/gigabit-wireless/comparison-8-qam-16-qam-32-qam-64-qam-128-qam-256-qam-types/

[29] S. W. Pallam, M. K. Luka, and M. Aminu, “BER evaluation of M-QAM modulation in wireless transmission over AWGN channel,” *Int. J. Sci. Res. Sci. Eng. Tech.* , vol. 1, no. 1, pp. 162–167, Feb. 2015.

[30] Performance Considerations > WLAN Design: Range, Performance, and Roaming Considerations | Cisco Press. [Online]. Available: https://www.ciscopress.com/articles/article.asp?p=1613796&seqNum=3

[31] Enhance Data Rates and Bandwidth with Quadrature AmplitudeModulation. [Online]. Available: https://resources.system-analysis.cadence.com/blog/msa2021-enhance-data-rates-and-bandwidth-with-quadrature-amplitude-modulation

[32] P. K. Singya, P. Shaik, N. Kumar, V. Bhatia, and M. S. Alouini, “A survey on higher-order QAM constellations: Technical challenges, recent advances, and future trends,” *IEEE Open Journal of the Communications Society*, vol. 2, pp. 617-655, Mar. 2021.

[33] S. Sharma, D. Parkash, and S. Singh, “Performance optimization of coherent detection OFDM using different QAM modulation technique,” in *Proc. ACM Int. Conf. Proceeding Ser.*, India, 2019, p. 6.

[34] S. Modgil and D. Prakash, “Performance analysis of radio over fiber simulation model using DPSK modulation technique,” *Int. J. Recent Technol. Eng.*, vol. 8, no. 2, pp. 5117–5119, July 2019.

[35] M. Singh and K. Kaur, “Coherent detection WDM optical OFDM system,” *Int. J. Adv. Res. Comput. Commun. Eng.*, vol. 2, no. 12, pp. 4793–4797, Dec. 2013.

Oratilwe Jothi received his Bachelor’s degree in Electrical and Electronics Engineering (B.Eng.) from University of Botswana in Gaborone, Botswana in 2017. He is currently pursuing his Master’s degree in Electrical Engineering (Telecommunications option) (M.Sc.) at Pan African University Institute for Basic Sciences, Technology and Innovation (PAUISTI) hosted by Jomo Kenyatta University of Agriculture and Technology.

(JKUAT) in Nairobi, Kenya. His research interests include Radio over Fiber, hybrid WDM systems and wireless-optical communication systems.

Edwin Ataro received his Bachelor's degree in Electrical and Communication Technology (B.Tech.) from Moi University in Eldoret, Kenya in 1989. He received his Masters of Science (M.Sc.) and Doctor in Engineering (D.Eng.) in Electrical and Communications Engineering from University of Kassel, Germany in 2000 and 2005, respectively. He is currently the Executive Dean for the Faculty of Engineering at The Technical University of Kenya (TUK) in Nairobi, Kenya. His research interests include optical communications systems and renewable energy.

Stephen Musyoki received his Bachelor's degree in Electrical Engineering from University of Sierra Leone, Sierra Leone in 1977. He received his Masters of Engineering (M.Eng.) in Engineering and Electro-communications from Denkitsushin Daigaku, Japan in 1985 and his Doctor in Engineering (D.Eng.) in Electrical Engineering from Tohoku University, Japan in 1991. He received a Certificate in Fundamentals of Management at Temple University, Japan in 2001. He is currently an Associate Professor at The Technical University of Kenya (TUK) in Nairobi, Kenya. Prof. Musyoki is a member of the Institution of Electrical & Electronic Engineers (IEEE) society.