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A REVIEW ON RADIO OVER FIBER SYSTEMS FOR LONG DISTANCE COMMUNICATION

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ABSTRACT

It is well-known that the Wireless Communication cannot provide long distances, Because the radio signals have a limited bandwidth and are susceptible to atmospheric noise and distortion. Recently, optical fiber communication played a significant role in the communication systems, where it is stated as one of the best transmission technique in the modern telecommunication systems since it transmits the signal for longer distances with lower loss and higher quality. As result, to provide the recipient of the radio signals with a high quality for long distances, the traditional cables are replaced by optical fiber link and an advanced optical fiber technology known as Radio over Fiber (RoF) can be utilized faithfully. RoF is a technology that modulates the light signal by radio signal and transmit it across a fiber optic link to extend the transmission and wireless access. Currently, this technology has become matured technology in terms of coverage, security and reliability. The RoF system has been implemented for the enhanced performance radio system having larger bandwidth for mobile communications. In addition, these systems have various advantages over traditional systems including higher bandwidth, easy Installation and Maintenance, lower attenuation, dynamic resource allocation, immunity against the RF interference and can transfer high frequency signals that support 5G and beyond 5G network technologies. This paper provides a comprehensive review on the currently existing RoF systems for long distance communication to provide the reader with the techniques used for delivering the radio signals for the longest distance with minimum Bit-Error-rate (BER) and highest Quality Factor (QF).

Keywords: Radio over Fiber (ROF), Long Distance Communication, Modulation Techniques, Encoding Techniques, Base Station (BS), Central Station (CS).

1. Introduction

It is well known that the human life has been seriously affected by the fast evolution of communication technologies and rapid advancement in wireless systems conducted in the past decades. Nowadays, wireless communication systems became very important in day-to-day activities and are extensively used in several civilian and military applications such that without it, it will be impossible for people to transmit private information like credit card information, energy pricing and e-health data [1]. In addition, it is difficult to imagine the human life without novel applications provided by wireless technology such as online high-definition video streaming, artificial intelligence (AI) as well as novel bandwidth-intensive user applications like YouTube, Netflix, etc. Through which all these applications require minimum latency, large bandwidth and high transmission speed [2].

In early beginnings of the telecommunication, wireless network applications such as General Packet Radio Service (GPRS) and Global System for Mobile (GSM) could accept low data rates. However, due to the rapidly increasing number of next generation mobile users and their huge demand on the bandwidth intensive applications, today's Wireless communication network require higher data rates and higher bandwidth [3]. As a result, high-transmission speed, large bandwidth and reliable mobility became most vital requirements that should be offered by today's wireless communication systems [4, 5].

However, these requirement cannot be performed directly because the operating Radio Frequency (RF) spectrum is already congested and operating in a higher frequency band is increasingly difficult [6]. In order to overcome these limitations, two solutions where discovered. The first solution was known as

Micro/Pico cell concept which is the process of reducing the cell size to support more subscribers [7]. The second solution was to operate in higher frequency band to avoid the spectral congestion in the lower frequency band [3].

However, by performing these techniques, several other problems will take place. Through which by minimizing the size of the cell to accommodate higher number of users, a greater number of Base Stations (BSs) will be needed to cover the entire service area and this leads to an increase in the overall cost. While operating in a higher frequency band on the other hand will contribute higher maintenance, installation and equipment's cost.

In the past decades, optical fiber communication played a significant role in the communication systems, where it is stated as one of the most vital and best transmission technique in the modern telecommunication systems since it provides a high data rate and large bandwidth. Recently, due to the exponential growth of the optical fiber communication, the traditional coaxial and copper cables has been replaced by optical cables to be used over greater distance with lower level of losses and higher data rates, because it has a significant immunity against electromagnetic interference (EMI), a huge bandwidth and provides long haul communication [5, 8, 9]. So, utilizing the optical fiber instead of copper cables in the wireless systems will make the design of both new sites and the physical deployment of the hardware much easier. In addition, the combination of optical and wireless networks offers immunity from fading and security at physical level [6, 10]. As a result, the huge data traffic, high data rate and large bandwidth requirements of the today's wireless communication network can be controlled through using a system architecture that uses the optical fiber as a transmission medium and whose expensive and complex processes are implemented at a Central Unit (CU) rather than at the Base Station (BS) to reduce the system cost and complexity.

One of the most advanced optical fiber technology for broadband wireless network that uses optical fiber as a transmission medium was developed in 1990's under the name of radio-over-Fiber (RoF). RoF technology is an integration of both wireless and optical communication system's that will provide higher data rate, higher capacity, reduced latency and reduced cost solutions due to its various advantages of large bandwidth, reduced power consumption, immunity to radio frequency interference, dynamic resource allocation and multi-operator and multi service [8, 11-14]. This technique has the ability to incorporate both wireless system and optical fiber by distributing the RF signals over several BS using optical fiber links as shown in figure (1) [15-17].

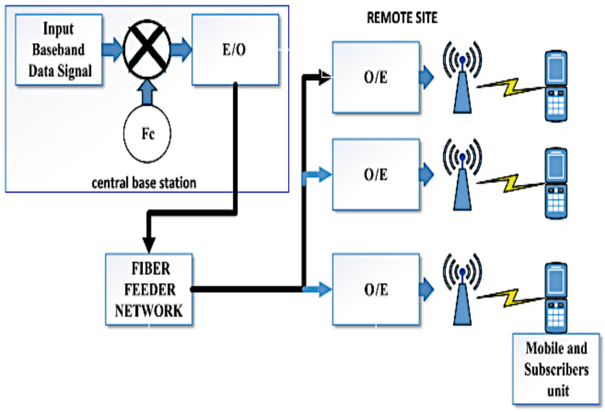

FIGURE 1:BLOCK DIAGRAM OF ROF [14].

As a result, the development of the RoF technology as a hybrid Fiber-Wireless (FI-WI) communication technology can be considered as a promising solution for exponentially increasing bandwidth requirements and is conducted with the objective to deliver the wireless communication to long distances with high QF and low BER [9].

This paper provides a review on several recent ROF systems and makes a comparison among them to provide the readers with the technologies that enhance the performance of the wireless systems in term of BER and QF for long distance communications and the rest of the paper is discussed as follows section 2. Provide a literature review on RoF systems conducted previously. Section 3. Provide the related system methodologies. Section 4. Provide a detailed discussion and compute a comparison among the conducted researches. Finally, section 5. Provide a comprehensive conclusion about the whole review paper.

2. LITRATURE REVIEW

This section provides a comprehensive literature on various recent works about the RoF systems to provide the reader with a background theory and clear vision about these systems.

At the beginning, simple RoF systems were implemented using a single fiber link to deliver low-capacity signal for long distances using single channel. As a result, Abdullah et al. [9] have implemented the design of single channel RoF system to transmit a total of 2 Gbps data rate over 5000 km. Later on, these simple RoF systems used various modulation techniques to provide better signal quality and enhance the overall system capacity. So, Haleema Khalil et al. [5] proposed a single channel RoF system with various modulation formats such as Non-Return-to-Zero (NRZ), Duo-Binary (DB) and Carrier Suppressed Return-to-Zero (CSRZ). Then Jain et al. [18] designed an increased capacity single channel RoF system to transmits a 10 Gbps data rate signal over 25-80 km SMF using different modulation techniques of Return-to-Zero (RZ), NRZ and Gaussian pulse modulator.

After that, the studies have demonstrated that the overall system capacity for long haul communication can be improved by increasing the channel numbers using WDM and DWDM multiplexing technique. As a result, Jain et al. [19] have increased the capacity through using two channel WDM-RoF system to provide the transmission of a signal with 10 Gbps data rate for the distance from 20 to 80 km of SMF. In addition, Namita Kathpal et al. [17] extended to 8 channels by implementing a WDM-RoF system based on a Bessel Filter to transmit a total of 32 Gbps for 120 km of SMF. Furthermore, Suresh Kumar et al. [2] further extended to 16 channels by designing a WDM-RoF system with EDFA and FBG to transmit 16 RF signal's each with a 10 Gbps data rate to make a total of 160 Gbps data rate for the distance of 60 km. For further enhancement in the system capacity, most of the recent works have utilized DWDM instead of WDM because it transmits larger number of channels due to small channel spacing. As a result, Mohsen et al. [20] designed and implemented a DWDM-RoF system to transmit 32 channels of 40 Gbps in order to provide the transmission of a total of 1.28 Tbps data rate using DWDM technique integrated with RoF along with a Dispersion Compensation Fiber (DCF) and Erbium Dopped Fiber Amplifier (EDFA) for the distance of 60,120 and 180 km. In addition, the bidirectional transmission can be provided by these multiplexing techniques such that Abbood et al. [21] demonstrated a bidirectional 4 channel DWDM-RoF system to provide the transmission of 4 channels to provide a total of 80 Gbps for 120 km of distance.

Because RoF is analogue transmission, the signals are susceptible to noise, distortion and dispersion. So, in order to provide a high quality signal at the receiver advanced modulation techniques and dispersion compensation devices such as Fiber Bragg Grating (FBG), EDFA and DCF are used to compensate this effects. Regarding the signal quality improvement using advanced modulation techniques, Ait Ahmed et al. [22] analyzed the transmission performance of N channel WDM-RoF system with a 10 Gbps data rate for each channel using various modulation techniques such as Differential Phase-Shift Keying (DPSK) and QAM. In addition, Bristy et al. [23] proposed the performance analysis and design of 8 channel WDM-RoF system based on the CSRZ and Quadrature Phase-Shift Keying (QPSK) digital modulation techniques to support the transmission of 8 channels each with 20

Gbps data rate for the lengths of 200 km using single Mach-Zehender Modulator (MZM). On other hand, Hala M Abdel et al. [24] designed a 2 channel RoF system based on various hybrid electrical modulation techniques such as Pulse Amplitude-Frequency Modulation (PAFM), Quadrature Amplitude-Frequency Modulation (QAFM), differential phase shift keying-Amplitude Modulation (DPSKAM), offset quadrature phase shift keying-Amplitude Modulation (OQPSKAM) and Frequency-Phase modulation (FPM) to provide an enhanced performance RoF system by better quality signal at higher communication distances. While Regarding the dispersion compensation and attenuation mitigation, Mahmood et al [15]. Implemented a 4 channel WDM-RoF system based on an ideal FBG and DPSK digital modulation technique to compensate the dispersion and transmit the a total of 40 Gbps data rate over 50 km of SMF with an EDFA. furthermore, further improvements were observed by integration of these advanced modulation techniques. So, Aadel M. Alatwi et al [25]. designed a 4 channel WDM-RoF system based on hybrid modulation technique OQPSKPM in addition to Minimum Shift Keying (MSK) and hybrid optical source Vertical Cavity Surface Emitting Laser (VCSEL) and MZM to deliver a total of 160 Gbps data rate signal to the length of 120 km as compared to system with traditional modulation techniques of OQPSK and PM. On other hand, V. R. Sudheer et al. [26] implemented a two channel RoF-DPSK based cost effective full-duplex system in order to transmit two channel of 1 Gbps data rate over 95 km of SMF and recovering and reusing the optical carrier frequency using FBG passive optical device for uplink transmission.

Later on, another approach was observed for improving the signal qulaity through integration of multiplexing devices, Passive Optical Network (PON) and Digital Signal Processing (DSP) divices. As a result, Bashar J. Hamza et al. [27] implemented an enhanced performance Subcarrier Multiplexing (SCM)-WDM-RoF system based on 10-Gegabit Passive Optical Network (XGPON) for bidirectional transmission using traditional optical network along with the Square Root Module (SRM) designed by MATLAB at the receiver side to transmit 4 channels with 10 Gbps data rate to the distance of 80 km.

Recently, studies have demonstrated that the capacity and speed of the signal can be also enhanced using high frequency mm-wave specially Q-band around 40 GHz, and V-band around 60 GHz and W-band around 100 GHz that can support 5G and beyond 5 G network technologies. So, Sharma et al. [28] designed a high speed cost effective 4 channel WDM-RoF system to deliver 4 channels of 10 Gbps data rate using 60 GHz mm-wave at the length of 60 km. While Jain et al. [29] implemented the design of high speed 4 channel WDM-RoF system to transmit a total of 40 Gbps data rate for a length of 70 km utilizing high frequency mm wave of 100 GHz. On the other hand, drissa Kamissoko et al. [30] proposed W-MMW based ROF system to transmit a total of 120 Gbps data rate over 30 km and 50 km of SMF using two different optical heterodyning techniques which are the Optical Double Side-Band (ODSB) and Optical Single Side-Band OSSB schemes respectively.

Several studies have depicted that FBG can be used as the wavelength RE-modulation instead of MZM at the receiver side as a cost-effective solution such that Kaur et al. [31] have proposed a full duplex RoF-PON system based on FBG as wavelength RE-modulation and DCF as dispersion compensation in order to provide an overall cost-effective system by making cost effective base station. In the proposed system instead of using another MZM and light sources for upstream signal, FBG is used as wavelength reflector to reflect a specific wavelength for upstream transmission as a cost-effective solution for long distance transmission systems.

3. METHODOLOGIES

This section provides the main methodologies related to the RoF systems in order to provide the reader with a good understanding and a clear vision on RoF systems to be able to build RoF system and enhance their own systems. These methodologies include optical signal generation, System Enhancement Techniques, system limitations, performance measuring parameters and RoF applications.

3.1 OPTICAL SIGNAL GENERATION

It is well acknowledged that in RoF systems, the signal is transmitted in the form of light. Thus, the generated electrical signal should be converted into optical signal at the Central Station (CS) prior to transmission. As a result, the CS is responsible for generation of the optical signal. The generation of the optical signal can be made electrically through RF local oscillators or optically using laser sources either directly or using external modulators.

Recently, most of the researchers prefer the mm-wave as the new operation frequency band. Thus, generation of optical signal electronically is not desired since it is applicable only for low frequencies. While the generation of the optical signal in optical domain using optical generation techniques such as Direct Modulation, External Modulation and Optical Heterodyning conversion became the area of interest. Major optical signal generation techniques are discussed below [32]:

- Direct Intensity Modulation (DIM): It is the simplest and cheapest technique used to generate the optical signal. From its name is clear that this method modulates the laser light intensity with the baseband signal directly to generate the optical signal as shown in figure 2. Similarly, at the BS, the electrical signal can be reconstructed directly with the help of photodetector. Although this technique is simple in configuration but it is applicable only for low frequency signals as the modulating signal is restricted by the laser's bandwidth modulation. As a result, for high frequency signals, this technique tends to create unwanted noise, frequency chirp and exhibit nonlinear characteristics due to light stability [32].

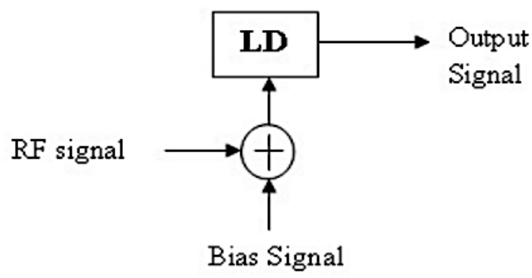

FIGURE 2: BASIC STRUCTURE OF DIM [32].

- Optical Heterodyning: This method depends on the principle of combining two or more optical signals with frequencies w_1 and w_2 to create a beat signal at the photodetector output whose frequency is equal to the frequency difference between two optical signals $w_1 - w_2$ as shown in Figure 3. This technique is useful for generating high frequency signals with higher Carrier to Noise Ratio (CNR) as well as it decreases the system sensitivity towards chromatic dispersion when only one of the two light carriers is modulated with data. In addition, this technique suffers from laser phase noise when the phases of the two optical signals are not correlated. [32].

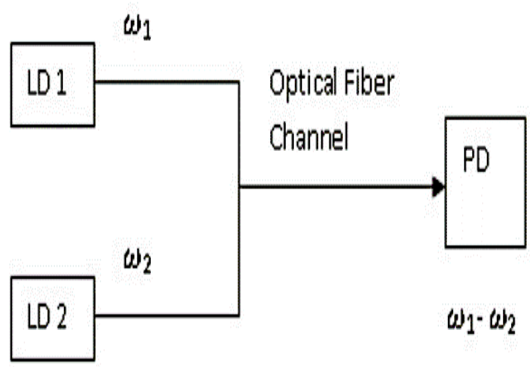

FIGURE 3: BASIC STRUCTURE OF OH [32] .

- External Modulation: It is considered as one of simplest and most preferred modulation technique utilized for high frequency signals across long distance communications. In this technique, the light carrier produced by the laser is modulated with the baseband signal by using an external intensity modulator such as Mach-Zhender Modulator (MZM), Electro Absorption Modulator (EAM) or External Phase Modulator (EPM) to generate high frequency mm-wave signal as depicted in Figure 4. The main working principle for this technique relay on the higher order harmonic generation resulting from the modulator nonlinearities in transmission. This technique is further classified into two types such as External Intensity Modulation (EIM) and External Phase Modulation (EPM) [32].

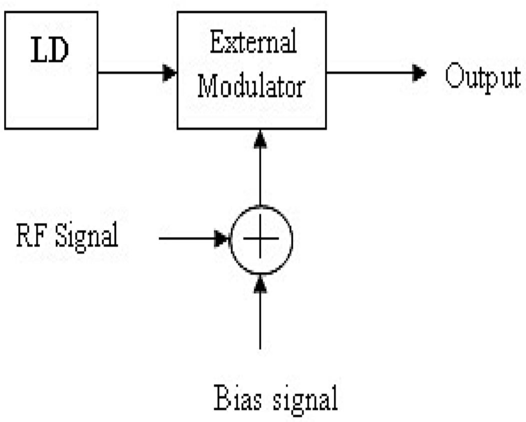

FIGURE 4: BASIC STRUCTURE OF THE EM [32].

A. External Intensity Modulation (EIM): In the EIM technique, the signal intensity that is twice of the signal amplitude is modulated as with the baseband signal and this can be implemented using either EAM or MZM. This technique eliminates the need for complex circuitry and it provides the long-haul transmission and large bandwidth without the usage of any amplifier. Further, there are three different approaches to this method employing MZM or EAM: Optical Single Sideband (OSSB) modulation, Optical Double Sideband (ODSB) modulation and Optical Carrier Suppression (OCS) Modulation as discussed in following sub sections.

B. External Phase Modulation (EPM): In this technique, the phase of the carrier signal is modulated with the light signal using phase modulators. Another advantage of this modulation technique over MZM modulator is that they do not need dc biasing due to which they are free from bias drifting problem and thus provides a stable output.

3.2 SYSTEM ENHANCEMENT TECHNIQUES

It is well-known that an increase in the system providing distance tends to decrease the system performance due to noise and distortion. In order to enhance the system performance with increasing distance several performance enhancement techniques can be used faithfully. These enhancement techniques are categorized upon the type of the enhancement such as Signal Quality Enhancement and System Capacity Enhancement.

3.2.1 SIGNAL QUALITY ENHANCEMENT

In the RoF Systems, improving the signal quality is considered as one of the best enhancement methods because enhancing the signal quality provide the enhancement of the overall system distance, BER of the system, QF and eye-diagram opening. Through which these parameters are the most important parameters that determine the quality of the system. Some of the most significant signal quality enhancement techniques are Encoding Techniques, Modulation Techniques, Advanced Modulation Techniques and MM-wave.

- **Encoding Techniques:** Recently encoding techniques are becoming vital in communication generally and wireless communication specifically, through which it can be used in various applications such as data rate improvement and security enhancement. One of the main stages of the RoF system is encoding stage. Encoding is the process of coding the binary data generated by the Pseudo Random Bit

Sequence Generator (PRBSG) from one format to another format and generate the baseband signal which can be later modulated by modulation techniques. Encoding techniques are used to provide more reliable and faster data rate transmission as well as better quality signal at the receiver side [33]. That means more secure, more reliable and better-quality signal can be received by using encoding technique.

There are several encoding techniques which are mostly used such as Non-Return-to-Zero (NRZ), Return-to-Zero (RZ), Modified Return-to-Zero (MDRZ), Manchester encoding, Gaussian Pulse (GP), Alternate Mark Inversion (AMI), Duo Binary Return-to-Zero (DBRZ), etc. The most preferred encoding technique to provide a RoF system that support long-distance communication is NRZ encoding techniques. Recently, most of the researchers prefer RZ encoding technique for systems that are with distance around 50 km. while for RoF systems that provide communication above 50 km, the NRZ and GP are more preferred [5, 33, 34].

- **Modulation Techniques:** It is obvious that the second stage of the RoF system is Modulation Stage. Through which this stage is used to generate a robust and soliton-like signal which can be received with minimum error and distortion. In order to perform modulation process and obtain a higher signal quality at the BS, several modulation techniques are used in the CS to create a robust signal prior optical transmission because these modulators have a strong and effective impact on the communication systems. These modulation techniques are Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), Phase Shift Keying (PSK), Differential Phase-Shift Keying (DPSK), Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), Quadrature Amplitude modulation (QAM), etc. The most preferred Modulation technique to provide a RoF system that support long-distance communication with a high quality signal is DPSK [22].
- **Advanced Modulation Techniques:** Furthermore, for extension of the coverage distance of the wireless system through using RoF systems, the above mentioned modulation techniques can be combined to generate novel hybrid modulation techniques that provides higher effects than conventional modulation methods, such that combination of QPSK and AM results in OQPSKAM. as well as DPSKA is obtained from integrating the DPSK and AM. In addition, combination of FM with PM generates an FPM. While, merging QAM with FM results in QAFM, as well as integration of PAM with FM results in PAFM [24].
- **MM-wave:** Recently, most of the researchers prefer the millimeter-wave (mm-wave) in general as the new frequency band of operation which is an optical frequency band from 30 GHz to 300 GHz usually used instead of modulation techniques at the CS as alternative carrier signal. nowadays, these frequency bands are most preferred because they provide larger distances, higher communication bandwidth and faster data transmission with minimum BER and Highest QF. In addition, this frequency band is categorized into three abundantly used low attenuation bands of Q-band (around 40 GHz), V-band (around 60 GHz) and W-band (around 100 GHz) [35, 36].

Further enhancements in the signal quality can be done using several passive optical devices that are used to compensate the impairments like dispersion, attenuation and nonlinear effects which are resulted from signal losses and errors that are accumulated through transmitting signal for long distances such as FBG, DCF, EDFA, Optical Amplifier (OA), channel spacing and linewidth (LD). these optical devices are mentioned in the RoF Limitation sub-section in detail.

3.2.2 SYSTEM CAPACITY ENHANCEMENT

Due to the rapidly increasing number of next generation mobile users and their huge demand on the bandwidth intensive applications, today's Wireless communication require higher system capacity. Enhancing the system capacity provide higher number of user and faster communication that leads to enhancing the overall system cost. One of the most important system capacity enhancement technique is Multiplexing Techniques [12]:

- **Multiplexing Techniques:** Generally, RoF system has limited capacity and can transmit the information only in one direction. In order to provide a bidirectional (full duplex) communication, RoF system should use two optical fiber links. In order to further increase the system capacity and bandwidth, several advanced optical multiplexing techniques are used such as SCM, WDM, DWDM, FDM, OFDM, etc. The most utilized multiplexing techniques in recent RoF systems are SCM, WDM and FDM since they provide the delivery of signals with high QF, Low BER and low signal attenuation and distortion [12]:
  - SCM: It is a multiplexing technique through which multiple signals are multiplexed in the wireless domain and sent on a single wavelength. An important advantage of the SCM is that microwave devices are more mature than optical devices.
  - WDM: It is a passive optical device that merge the light signals having various wavelengths from various fiber links into a single fiber link. They include DWDM devices that utilize the optical (analog) multiplexing techniques to enhance the system capacity beyond levels which can be provided by Time Division Multiplexing (TDM).
  - Optical Frequency Multiplication (OFM): It is a cost-effective technique that allow multiple functionalities wich are required to support the wireless systems. The key advantage of this technique is that it can provide several functionalities with a single laser source and low frequency electronics at the CS. These functionalities include Increased cell capacity allocation, remote LO delivery, remote antenna controlling multi-standard support and in-band control channel for dynamic radio link adaptation.

In order to provide the reader with a clear vision and good understanding about the multiplexing techniques, a brief comparison is made between these multiplexing techniques as shown in table 1.

TABLE 1:COMPARISON AMONG SCM, WDM AND OFM.

Parameter	SCM	WDM	OFM
Attenuation	Moderate	Low	Low
Scattering	SBS	SBS & FWM	SBS
Dispersion	Chromatic & PMD	Chromatic	Chromatic
BER	Less	More	More
CNR	Less	More	More

3.3 ROF LIMITATIONS

Since the RoF is Generally an analogue transmission system in nature, the main limitations can be caused by noise, attenuation and distortion effects that limits the two important wireless transmission parameters such as dynamic range and noise figure [5]. In which these limitation effects results from the linear and nonlinear impairments of the optical transmission medium [3]. The linear impairments are the limitations related to the fiber itself such as CD, fiber losses, PMD and intermodal and intra-modal dispersions [3]. Through which these linear impairments can limits the available distance and bandwidth [13]. As a result, to compensate the linear impairments like dispersion and attenuation and enhance the system performance in term of BER and QF, there are several cost-effective optical fiber devices and techniques which can be used to mitigate these linear impairments such as:

- Fiber Bragg Grating (FBG): It is a distributed reflector implemented in a small piece of fiber link which is utilized reflect some desired wavelength of light and pass the other wavelengths for specific condition such as filtration and dispersion compensation as shown in figure 5 [15].

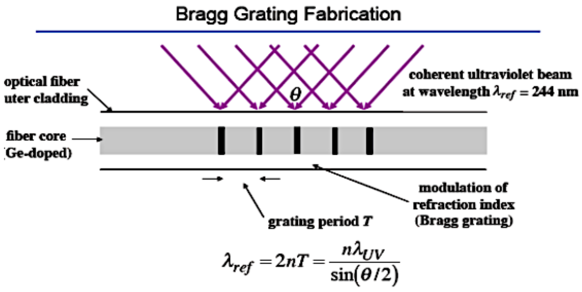

FIGURE 5: FIBER BRAGG GRATING [37].

- Dispersion Compensating Fiber (DCF): It is a simple and effective technique used to compensate the dispersion available in the system using a piece of fiber that has negative Group Velocity Dispersion (GVD) around -90 ps/nm.km in order to mitigate the resulted dispersion of the Single Mode Fiber (SMF) that have positive GVD at the laser source of wavelength 1.55 µm as shown in figure 6 [38, 39].

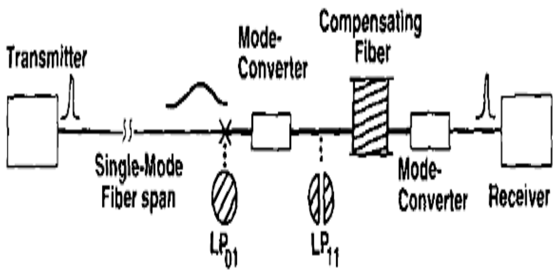

FIGURE 6: DISPERSION COMPENSATION FIBER [40].

- Channel Spacing: This is an approach used for radio frequency planning in RoF systems. It evaluates the frequency difference between adjacent allocations in a frequency plan [15].
- Erbium Doped Fiber Amplifier (EDFA): It is an optical amplifier that utilize a doped optical fiber as a gain medium to amplify the attenuated signal amplitude at large distances and overcome the fiber loss [37]. In the EDFA, the signal that is required to be amplified and the pump laser are multiplexed into the doped fiber and the signal is amplified by interacting with the doping ions. As shown in figure 7[41]

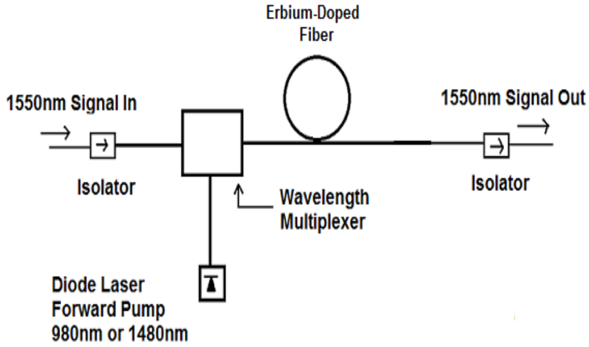

FIGURE 7: ERBIUM DOPED FIBER AMPLIFIER.

While the nonlinear impairments arise when fiber is used as the transmission medium due to higher capacity, higher data rate and larger length of the modern RoF systems. These nonlinearity effects are one of the most unwanted phenomena in the modern RoF systems, because they results in intermodulation distortion, adjacent channel interference phase distortion and harmonic distortion etc, that leads to reduction of the signal quality even for short lengths [42]. Optical fiber nonlinearities are generally divided into two categories. The first category relates to the refractive index of the fiber link which includes the nonlinearities that take place due to intensity-based disparities in the fiber refractive index and are generally called as “Kerr effect”. The second category is related to scattering nonlinearities that take place due to inflexible stimulated scattering that is further divided into SRS and SBS [2].

I. KERR EFFECTS

Due to intensity-based disparities in the refractive index of the fiber core, several nonlinearities appear, these nonlinear effects are called Kerr effect. The Kerr effect is further classified into various non-linearity’s such as SPM, XPM and FWM [42].

- SPM is generally the self-induced phase shift that is observed when the light signal pass across the fiber link such that the signal phase changes due to interaction between the transmission medium and the transmitted signal. The changes in the amplitude of the signal during the transmission of the signal inside the fiber link leads to variations in the core refractive index which in turn changes the signal phase. As a result, a shift in frequency occurs Due to this nonlinear effect named as frequency chirping. In which this chirping tends to pulse broadening after interaction with dispersion in the fiber. This effect depends on the input power directly; this implies that broadening of the pulse increases with an increase in input power.

- In XPM, the wavelength of a signal affects the phase of another signal. which means that in this nonlinearity, the refractive index of a signal is not only affected by its own intensity, but also it is affected by other signal's intensity that propagate in the same fiber. This effect results in the translation of power modifications from one wavelength channel to phase variation of another channel.
- In FWM, several wavelengths of the light propagate in a same fiber and are close to each other in wavelength due to comparatively less channel spacing. These wavelengths that propagate through fiber simultaneously interact with each other to create new wavelength called as "idler" because of FWM nonlinearity.

II. SCATTERING EFFECTS

- SRS play an essential role in WDM based optical communication system. In which the optical signal photons interact with the fiber molecular liberation and also interact with other signal photons while using similar fiber core for propagation of the light. As a result, scattered light generation occurs. In addition, the resultant signal wavelength is longer than other optical signals [42].
- SBS is the scattering of the light in backward direction. In order to decrease the SBS effect, the input power can be kept below threshold value of SBS or the spectral line width of the source itself can be increased [42].

As a result, to minimize the linear effects and improve the dynamic range of the system, one of the above-mentioned techniques should be properly applied through which these methods considerably enhance the transmission capacity and decrease the overall system cost. However, for compensation of the nonlinear effects, nonlinearity mitigation techniques are preferred in order to accomplish significant gains in the system performance. these techniques are performed to enhance and optimize the performance of communication system [42].

Nowadays, compensation of nonlinear effect in the optical fiber is an attractive research area to improve the system performance and meet the capacity requirement for next generation mobile communication system. Non-Linear Compensation (NLC) techniques are very useful to improve the data rate of the next generation mobile communication system. NLC techniques can be implemented in both digital and optical form or as integration of these two forms. These techniques can be located at the transmitting end, fiber channel or even at the receiving end. In addition, the integration of several NLC techniques can provide better performances and are called hybrid NLC [42]. Several NLC techniques are discussed below:

- Digital Back Propagation (DBP) is a digital NLC method that is implemented at both transmitter and receiver in order to compensate intra-subcarrier nonlinear effect. This technique is significantly efficient and most utilized NLC technique that have the principle of Split-Step Fourier Method to provide the solution of Manakov equation that is generally known as NLSE in single polarization transmission system.
- Volterra Based Nonlinear Equalizer (VNLE**)** is a digital NLC method which can be accomplished at both transmitting end and receiving end to

compensate intra-subcarrier nonlinearity. In this method, Volterra Series Transfer Function (VSTF) is utilized in order to provide the solution for Manakov equation.

- Phase Conjugation (PC) is a hybrid NLC method that is utilized in both optical and digital domains. In addition, this technique can be implemented at receiver or at fiber medium to compensate the nonlinear phase.
- Optical Phase Conjugation (OPC) is used in optical domain and it inverts the spectrum of the input signal in the middle of the fiber link. In this method, the nonlinear phase variations generated at the beginning of the fiber link are compensated by nonlinearities created at the end of the fiber link. In addition, this technique demands detailed positioning and a symmetrical link.
- Digital Phase Conjugated Twin Waves (PCTW) is based on a digital signal processing that can be performed at the receiving end. PCTW is made up of transmission of the wanted signal on one polarization and its conjugate on another polarization. In addition, PCTW can be used on the subcarrier frequency rather than polarization in OFDM systems. In this technique, half spectral efficiency is lost because of transmission of the signal conjugation.
- Machine learning-based NLC is a technique that can be used to reduce the fiber nonlinearity effect. Training process determines the distribution of the possible noisy calculation points.

3.4 MEASUREMENTS OF ROF SYSTEM

In order to determine whether an RoF system is working correctly or not, the performance of the systems is measured using several performance analyzing parameters and factor which such as [29]:

A. Signal to Noise Ratio (SNR) is determined as ratio of the average signal power to the average noise power. It estimates the system performance in a noisy medium. SNR is expressed in decibels:

$$\textbf{SNR (DB)} = 10 \times \boldsymbol{log_{10}}\left(\frac{\textit{Average signal power}}{\textit{Average noise power}}\right) \quad (1)$$

B. Optical Signal to Noise Ratio (OSNR) is determined as the ratio of the optical signal power to the optical noise power in a fiber link. OSNR in dB is expressed as

$$\textbf{OSNR (dB)} = 10 \times \boldsymbol{log_{10}}\left(\frac{\text{Optical signal power}}{\text{Optical noise power}}\right) \quad (2)$$

C. Noise Figure (NF) is utilized to compute the figure of the receiver merit such that the higher the value of NF the lower system performance and vice versa. NF is also described as the ratio of the input SNR at to the output SNR. NF is expressed in decibels:

$$\textbf{NF (DB)} = 10 \times \boldsymbol{log_{10}}\left(\frac{SNR_i}{SNR_O}\right) \quad (3)$$

D. Bit Error Rate (BER) is the ratio of the number of bits that are altered due to noisy channel (error bits) to the total number of transmitted bits during the bit interval. BER calculated as:

$$\textbf{BER} = \frac{\textit{Number of error bits}}{\textit{Total number of transmitted bits}} \quad (4)$$

E. Eye Diagram is also known as eye pattern in telecommunication, through which it is an intuitive graphical representation of optical signals. It is called so, because the pattern represented on this display looks like a series of eye between a pair of rails. The eye opening corresponds to the amount of distortion. In which, the signal quality of the system along with the Inter Symbol Interference (ISI) can be analyzed from the opening of the eye [43]. The eye opening is computed by the following equation:

$$E_{eye} = I_1(min) - I_0(max) \quad (5)$$

F. Quality Factor (QF) is a measurement unit that is used to measure the received signal quality.in which the signal quality is determined in term of eye opening. The QF is determined using the following equation.

$$\text{QF} = \frac{E_{eye}}{\sqrt{\sigma_0{}^2 - \sigma_1{}^2}} \quad (6)$$

G. BER and QF are related as follow:

$$\text{BER}=\frac{1}{2}erfc\ (\frac{Q}{\sqrt{2}}) \quad (7)$$

H. BER and OSNR are related as follows:

$$Log_{10}(BER) = 10.7 - 1.45 \times [OSNR] \quad (8)$$

3.4 ROF APPLICATIONS

Due to the huge advantages provided by the RoF system, it can be considered as a fundamental technology for the provision of the unrestricted access to broad band wireless communication in several applications. Three main RoF applications are described below [32]:

- Fiber to the Antenna (FTTA) is an RoF application that use a direct optical fiber link between the control unit and the antenna, that helps in gaining immunity against lightning strikes as well as electric discharges, and it decreases the link losses that provide in decreasing the BS complexity through directly connecting fiber link to the electrical converter then to the antenna unit.
- Dead Area Access: RoF provides the wireless access to the dead zones and to the areas that is impossible to provide it with the backhaul connection such as mountain sites, jungles, underpasses and building areas.
- Communication purpose: RoF can provide several communication applications such as Cable Television (CATV) signal transmission, L-band frequency signals (950-2150 MHz) satellite communication transmission and transmission of mobile radio signals for wireless access (3G, 4G, 5G, WI-FI).

4. DISCUSSION

It is clear that radio signals cannot be transmitted for long distances due to atmospheric noise and distortion. So, RoF is a promising technology for providing the recipient of these signals to long distances since it modulates the radio signals on optical carrier signals using laser sources and transmit them across fiber optic link. However, for long distances higher than 50 km, an external modulator such as EAM or MZM is required as in [9, 18, 20, 44]. According to the currently existing researches the most preferred and abundantly used external modulator is MZM since it can transmit the signals for larger distances with better signal quality.

However, with an increase in the distance, the signal quality tends to decrease and BER tends to increase. In order to enhance the signal quality and decrease the BER at long distances, various encoding formats can be used in the CS such as NRZ, RZ, GP, DB, CSRZ and AMI as in [5, 18, 34, 45]. Through which NRZ is the most preferred encoding techniques since it provides the lowest BER and highest QF at long distances. Beside encoding techniques various modulation techniques are also used to enhance the signal quality such as PAM, DPSK, QPSK and QAM as in [22, 23, 26]. Through which DPSK is the most preferred among them since it provides the best QF and BER. for further signal quality enhancement these modulation techniques are combined to make the hybrid modulation techniques such as PAFM, DPSKAM and OQPSKAM. In which these techniques provide better system performance as in [24].

The traditional RoF systems is a low capacity unidirectional system since it uses a single optical fiber link that support only a single channel as a one-way communication. In order to increase the system capacity and provide a bidirectional transmission that support upstream and downstream several multiplexing techniques are used such as SCM, FDM, OFDM, WDM and DWDM as in [4, 20, 22, 44]. However, the WDM and DWDM are the most preferred multiplexing technique since it provides highest quality signal and minimum BER at long distance communication. For further increasing the system capacity these multiplexing techniques are combined as in [10, 27]. Recently, the RoF systems use the mm-wave specially Q, V and W band as the frequency of operation to provide higher data rate and higher capacity system since this frequency band higher bandwidth and low attenuation as compared to other frequency bands as in [19, 29, 46].

However, with an increase in the system capacity and distance, the dispersion and fiber nonlinearities increase. The nonlinear effects and dispersion are the main limiting factors since they tend to increase BER and decrease the QF. In order to mitigate the dispersion effect, several dispersion compensation techniques are used such as channel spacing, DCF and FBG as in[2, 20, 37, 39, 45]. Although some nonlinear effects can be mitigated by these dispersion compensation techniques such as FWM as in [17]. but other nonlinear effects can be mitigated by NLC as in [42]. In order to provide clear vision about the RoF systems and their applications, the following table provides a detailed comparison among the currently existing systems in term of distance, capacity, BER and QF.

TABLE 2: DETAILED COMPARISON AMONG CURRENTLY EXISTING ROF SYSTEMS.

References	Multiplexing Technique	Modulation and Encoding Technique	Channel Number	Total Capacity (Gbps)	Distance(km)	QF (dB)	BER
[9]	RoF	PAM-RZ	1	2	5000	12.669	4.3×10^{-37}
[36]	RoF	QPSK	1	14	200	-	3.8×10^{-3}
[47]	RoF	Raised Cosine	1	40	150	13.749	1.82×10^{-43}
[5]	RoF	NRZ	1	10	140	8.5	1×10^{-35}
[31]	RoF	NRZ	1	1	100	-	1×10^{-19}
[48]	RoF	NRZ	1	10	80	7.426	5.52838×10^{-14}
[18]	RoF	PAM-NRZ	1	10	80	9.8143	4.657×10^{-23}
[26]	RoF	DPSK	2	2	95	0	1×10^{-20}
[19]	WDM-RoF	NRZ	2	20	80	8.6	3.3×10^{-12}
[25]	WDM-RoF	OQPSKPM-NRZ	4	150	130	30.2	43.6×10^{-20}
[49]	WDM-RoF	NRZ	4	5	90	9	1×10^{-12}
[27]	SCM-WDM-RoF	AM-NRZ	4	40	80	6.0	1×10^{-12}
[29]	WDM-RoF	NRZ	4	40	70	5.5	1.48×10^{-8}
[15]	WDM-RoF	DPSK	4	40	50	25.229	9.4860×10^{-141}
[23]	WDM-RoF	QDPSK -CSRZ	8	160	200	10.0	-
[39]	WDM-RoF	DPSK-NRZ	8	320	160	7.0	1.0×10^{-12}
[17]	WDM-RoF	NRZ	8	32	120	46.83	0
[2]	WDM-RoF	RZ	16	160	60	12.21	1×10^{-34}
[20]	DWDM-RoF	NRZ	32	1.28 Tbps	180	13.709	2.35×10^{-43}
[45]	DWDM-RoF	MDRZ	64	640	1200	13.2	7.1×10^{-40}

5. CONCLUSION

It is well-known that Wireless Communication signals cannot be transmitted for long distances due to the noise and atmospheric distortion. So, RoF is a promising solution for providing the recipient of these signals to long distances since it provides the modulation of the radio signals on optical carrier signals using laser sources and transmit them across the fiber optic link. this paper provides a review on the most recent RoF systems for long distance communications and makes a comprehensive comparison among them to provide the reader with the good knowledge about building a RoF system and enhancing an already existing system. From the comparison it is clear that to build a system that has the ability to transmit the signal for long distance up to 50 km with a high BER and QF, an external modulator should be used. However, for distances higher than 50 km, the signal quality tends to decrease. As a result, signal quality enhancement techniques should be used to enhance the BER and QF of the system such as encoding technique, modulation techniques, MM-wave or passive optical devices. However, for improved system capacity, multiplexing techniques should be used. According to the comparison made in this paper, authors have concluded that regarding the signal quality, NRZ is the simplest and most preferred encoding technique as well as DPSK is the best modulation technique that provides the QF up to 45 and BER around $\mathbf{9.4860\times 10^{-141}}$ respectively. While regarding the system capacity, WDM and DWDM are the most preferred multiplexing technique since they provide highest system capacity up to 160 Gbps and 1.28 Tbps respectively with highest QF up to 13.5 and minimum BER around $\mathbf{7.1\times 10^{-40}}$ for long distances around 1000 km.

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