WDM and DWDM based RoF System in Fiber Optic Communication Systems: A review

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***Abstract*:** The utilization of Fiber Optic (FO) in 5G communication systems has achieved several advantages such as increasing the capacity and the bit rate with a reduction in the total implementation cost. Radio over Fiber (RoF) systems could form the basis for 5G communication networks, due to several reasons related to its ability to provide the required bandwidth for the broadband data transmission to the end-users, other advantages are related with the lower loss in attenuation and higher immunity to RF (Radio Frequency) interference. Particularly, the utilization of Wavelength – Division - Multiplexing (WDM) and Dense - Wavelength - Division - Multiplexing (DWDM) techniques with the RoF system has gained all the attention of researchers in the last few years. As a result, this paper demonstrates a review of the proposed systems, schemes, and methods that contribute in enhancing the WDM and DWDM based RoF systems.

***Keywords*:** WDM, DWDM, RoF, Optic Fiber, Optisystem, BER.

1. Introduction

Recently, because of the nonstop requests of the client's application, the information limit with respect to remote correspondence has been raised reliably from voice and basic messages to sight and sound with future administrations. Radio over Fiber (RoF) frameworks could be the response to numerous critical necessities of the 5G media transmission networks [1]. Because of reasons identified with its capacity to perform with lower misfortune and higher transfer speed. RoF innovation has attracted a lot of interest in upgrading the limit and portability of rapid remote information transmission for the converging of remote access frameworks with optical frameworks [2]. RoF essentially explains the idea where light is balanced with radio recurrence (RF) signals and afterward sent over optical fiber to advance transmission just as remote access. It sends a RF signal between a Central Station (CS) and a Base Station (BS) and from the BS the signal is remotely sent to various clients. RoF systems have an astounding limit, bigger transfer speed, improved inclusion, decreased weakening misfortunes, and better resistance to RF interferences [3].

The huge demand for higher network bandwidth requires an urgent solution, the multiplexing system was the best solution for handling such demand. The most valuable technologies were the Wavelength Division Multiplexing (WDM) and Dense Wavelength Division Multiplexing (DWDM), which have been widely utilized to compensate the increase of the data rate per each channel, the channel number per FO link and will improve the overall transmission capacity. The emerging of FO amplifiers such as Reconfigure-Optical Add/Drop Multiplexing (ROMAN) and Erbium Doped Fiber Amplifier (EDFA) has gained significance in WDM cost-effectiveness, providing flexibility for the management of wavelength and providing transparency and flexibility by enabling the element of ROADM [4].

The WDM is a significant element in the development of optical correspondences. WDM has given greater adaptability to the framework and improved the network plan. It assists with the upgrade of the framework's ability by sending different frequencies over a solitary fiber [5]. An extensive data rate expansion can be offered by WDM based systems that are ignored as a solitary fiber utilizing numerous frequencies, in which a different channel is conveyed at every frequency. In WDM, the optical spectrum is partitioned into smaller sub-channels; thereby each can be utilized for communicating simultaneously [6].

Today, the wireless signal may lose the channel in data transmission level. So it needs to increase the high capacity to the access network of current wireless communication systems [7]. Subsequently, the RoF framework is the ideal decision to expand the high limit and subcarrier recurrence of late remote frameworks. It underpins both optical and remote organizations. In a remote organization, RoF is the cutting edge remote broadband with fast information transmission and an expanded high limit channel of RF balance. So the cutting edge remote framework utilizing RoF is extremely helpful in light of the fact that it has huge numbers of the application to improve RF adjustment, for example, WDM, OFDM ideas [8].

2. Fiber Optic Communication System

This section demonstrates a brief overview for the basic concept of FO system, benefits and applications.

2.1. Overview of Optical Fiber Communication System

FO's can be characterized as a medium used for taking care of the development of data starting with one point then onto the next as a light sign. The optical fiber link that conveys the light and a beneficiary that gets the light sign and converts it back into an electrical sign and consequently the FO's isn't electrical in nature [9]. A fundamental correspondence framework based FO comprises of a sending gadget that changes over an electrical sign into an optical sign. The fundamental outline of such frameworks can be appeared in Figure 1, in which it incorporates a transmitter hardware, light source, FO's link, and locator and beneficiary hardware [10].

FO based systems can be fabricated utilizing a LED or LASER, plastic fiber, a silicon photodetector, and some basic electronic hardware [10]. A bigger portion of the yield force can be coupled into the optical filaments on account of LASERs as they radiate more directional light pillars than LEDs. That is the reason LASERs are more appropriate for high digit rate frameworks. LASERs have limited ghastly width just as quicker reaction time. Subsequently, LASER based frameworks are fit for working at a lot higher regulation

frequencies than LED-based frameworks. Average LEDs have lifetimes more than 107 hours, while LASERs have just 105 hours of lifetime. Something else is that LEDs can begin working at much lower input flows which are impractical for LASERs. As indicated by these prerequisites, either LED or LASER can be used as an optical source [11].

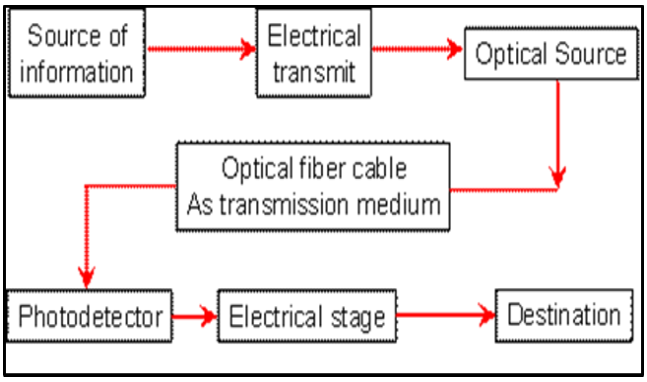

Figure 1. Overview on the Basic diagram of FO communication system

2.2. Benefits of Optical Fiber Communication System

FO-based communication systems have transformed the industry of telecommunication. Recently, FO's have become the dominant choice for Ethernet backbone infrastructure, higher-speed services, and a general structure for data networking [12]. As a result, four main advantages were related with the concept or FO cabling based communication system which are:

1. A secured communication system: FO cabling can be denoted as the higher security strategies for correspondence. The advancement of the cabling makes obstruction of the transmission hailing staggeringly irksome. Any undertakings to invade the glass connection will results a "light spillage" which subsequently will resulted in a distinguishable debasement in trades [13].
2. The Compatibility of Electromagnetic: - FO cabling is impenetrable to gigantic quantities of the outside forces that bad copper cabling. In zones, for instance, mechanical workplaces where colossal motors, controllers, and constrained air frameworks are ceaselessly starting and ending, FO cabling is enthusiastically recommended [14].
3. The transmission speed: - FO cabling is generally faster than standard copper cabling. The little width glass filaments can keep up the trade speed of more than 10-gigabit speeds per strand. While copper cabling can keep up these velocities, it would take massive amounts of huge width gathering 6 associations amassed together to appear at the movements of one fiber strand [15].
4. The transmission distance: - The fiber link is the ideal methodology for a colossal distance, highlight point hardline correspondences. Very far on conventional copper cabling limits gigantic distance correspondence requiring the need of extra stuff to widen the trading of signs. Towards the best reach of copper joins, decreasing will begin to set in causing a slight decay of rates on gigabit transmissions. Fiber joins are far unrivaled and more moderate for basic distance network with the capacity to accomplish more than 10 gigabytes of speed at more than 40 km long [16].

Another general advantages were concerning with the concept of FO communication system, which are summarized and listed below [17].

1. Larger bandwidth to be used.
2. In the transmission medium there is a total electrical isolation
3. The lower impact of transmission loss
4. Significantly reduce the size and weight
5. Provide higher security for signal
6. Higher Immunity to crosstalk and interference effects
7. Lower consumption of power.

2.3. Applications of Optical Fiber Communication System

1. Medical: - FO Used as light guides, imaging based tools, and also as lasers for performing surgeries operations [18].
2. Defense/Government: - Used as hydrophones SONAR and seismic waves and, like in aircraft, in submarines, and other vehicles and for field networking [17].
3. Data Storage: - Used for the transmission of data between different units [17].
4. Telecommunications: - Fiber is laid and used for transmitting and receiving purpose. [17].
5. Networking: - Used to connect both the clients and servers in a wide field of network settings and help raise both the speed and accuracy of data transmitted over the network [17].
6. Industrial/Commercial:- Used for imaging in difficult to arrive at zones, as wiring where Electromagnetic – Interference (EMI) is an important issue, as tactile gadgets to make the temperature, pressure, and different estimations, and as wiring in vehicles and mechanical settings [19].
7. Broadcast/CATV: - Broadcast/link organizations are utilizing FO links for wiring CATV, High Definition TV, web, video - on - Request, and wide range of applications [20].
8. Lighting and Imaging: - FO links are utilized for lighting and imaging and as sensors to gauge and screen a tremendous scope of factors. It is likewise utilized in examination, improvement, and testing in the clinical, innovative, and mechanical fields [20].

3. Methodology of WDM Based RoF System

The methodology would be clarified in details by illustrating the concept of each element as below:

3.1. Radio over Fiber (RoF) system

3.1.1 RoF Overview

ROF is ordinarily a simple optical connection that communicates regulated RF signals. RoF innovation utilizes optical fiber connects to disseminate RF signals from a focal area to the Remote Antenna Units (RAUS). It communicates RF signal downlink and uplink. It communicates an RF sign to the Central station (CS) from the base station (BS) and the other way around [21]. The interest for network data transfer capacity is enormous because of the development in rush hour gridlock, for example, video on interest, web uses, and voice over IP, web-based video, and voice. This can be given by the

RoF framework in view of its focal points as, huge transfer speed, insusceptibility to radio recurrence impedance, diminished power consumption, multi-administrator, and multi-administration activity, dynamic asset distribution, and so on Consequently, it is more ideal contrasted with RF signal preparing. The principle necessities of RoF connect engineering are duplex activity (downlink-uplink), sensible length, and elite optical segments [22].

The demonstration of RoF based system can be seen in Figure 2, in which the Control Station is used for the generation of the signal. In this, the RF signal is transmitted with the help of an optical fiber link. At the Control office modulation and signal processing is used to build the baseband signal. There is negligible Attenuation loss in this transmitted signal then, this transmitted signal is detected at the BS. At the Base Station Unit (BSU) the operations of both conversion the electrically to optically (E/O) and optically to electrically (O/E) take place [11]. The signal transmission between the Wireless Terminal Unit (WTU), BSU, and the user takes place with the help of an antenna which is placed at the base station unit. Communication between BSU and CS takes place with the help of an optical signal. Therefore the cost of transmission equipment such as antennas, amplifiers is getting reduced. Hence, the RoF system looks like a more efficient system than conventional wireless networks [23].

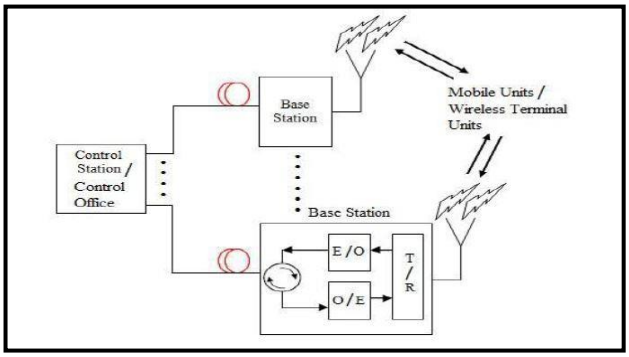

Figure 2. Basic diagram of RoF system [11]

3.1.2 Mack Zander Modulator (MZM)

In optical transmission systems, communications traffic is conveyed by optical carriers. The intensity of carriers is modulated by the communications traffic. The optical carriers can be Amplitude Modulated (AM) or Phase Modulated (PM). The technique of modulation is the most major process in the RoF based system where the RF electrical signal is enforced to modulate the optical carrier signals. And such modulation methods is categorized into two groups that are either integrated with MZ interferometers or Electro Absorption Modulator (EAM) [24].

There are two main types of modulation which are [25]:-

1- Direct Modulation (DM): - DM based technique which is also denote as the Intensity Modulation (IM), directly modulates the amplitude of the laser beam based on the input RF Signal.

2- External Modulation: - In the EM based method, a dedicated devices such as MZM is utilized to modulate the phase of the optical carrier. EM is preferred because DM is ideal for inexpensive transmitters, but it resulted in an undesirable chirp for the wavelength, which results an excessive Chromatic Dispersion (CD) at high speeds.

In optical communication systems, the most interesting modulator is the Lithium Niobate (LiNbO3) model based MZM. MZM can be categorized as single drive SD-MZM and dual-drive DD-MZM. The optical wave entrance is the input pin and then splits equally into its two other pins. The structure of the DD-MZM has two arms and electrodes. MZM is utilized to control the optical-waves amplitude. Input waveguide splits into two waveguide interferometer arms and bias is applied to these two arms, a phase shift is induced in the wave passing through the arm, due to the applied voltage. The optical signal would transfer through both two arms of the interferometer are recombined at the output of MZM and the phase difference between the two waves is converted to an amplitude modulated signal. The layout of MZM can be clarified in Figure 3 [11].

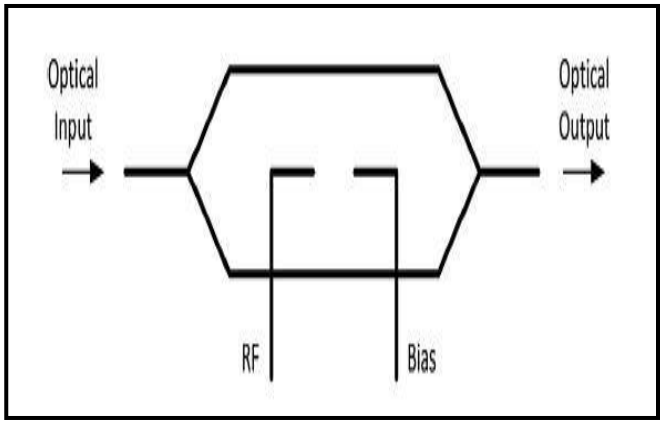

Figure 3. The layout of MZM [11]

3.1.3 RoF advantages

The ability to concentrate the majority of the costly, high-recurrence gear at a concentrated area is the principle preferred position of RoF systems, in this manner making it conceivable to utilize easier distant locales. Moreover, RoF innovation empowers the bringing together of portability capacities, for example, full-scale variety for consistent handover. There are numerous advantages of having straightforward far off destinations. The main preferred position would be recorded beneath [26]:

1. Large Bandwidth:

The optical fiber has unlimited band-width. The increase in information being transferred over the optical fiber medium is ensured due to the high frequency carrier. Most of the optical systems which are run at the bit rate 10 Gbps. We observe that there is big room for improving the system bandwidth. There are two main technologies to increase the system bandwidth: (a) Wavelength Division Multiplexing (WDM) (b) Optical Time Division Multiplexing (OTDM)[27].

2. Low Attenuation Loss:

In RoF system optical fiber is used between the CO and BS which has several advantages over free space and copper cable transmission media. The optical fibers available in the market have very low attenuation, thus they can be used to serve the purpose of reducing the losses between CO and CS which are separated far apart.[28].

3. Easy installation and Maintenance-

In RoF systems remote antenna units are made simpler. Most RoF methods eliminate the requirement for a LO and related gear at the RAU. In these cases a photograph indicator, a RF intensifier, and a radio wire make up the RAU. Balance and exchanging gear is kept in the headed and it is shared by a few RAUs. This framework prompts more modest and lighter RAUs, adequately decreasing framework establishment and upkeep costs. This course of action makes the establishment and upkeep cost to be diminished at an apparent level [29].

4. Immunity to RF interference-
Protection to Electromagnetic Interference is a very important property of optical Fiber communications. It provides security and privacy for microwave transmission. This is because of the signals are transferred in light form through the Fiber [30]. Since the RF signal is transmitted over the optical fiber, there is not any chance for electromagnetic interference. The quality and integrity of the information are preserved in optical communication.

5. Dynamic Resource Allocation & Operational flexibility - It allows to allocating the capacity because of it uses new modulation equipment's and the switching at the CS. It is possible to allocate more capacity to a certain areas in peak time while reducing the capacity allocation in off-peak. The allocation of channels to different users can be made dynamically to guarantee the efficient management of resources as it would be a resources wastage to allocate the capacity in the unpopulated area. [31].

6. Low Power Consumption-
Complex equipment's are kept at the CS, to reduce the power consumption. For this reason, the BS which are not active at one point of time can be changed to passive mode. It may be a possibility of nonlinear effects as well as dispersion in optical fiber. We can minimize these types challenges present in RoF system by developing some modulation techniques as a proposed solution. Research is also going on to the different kind of modulation techniques which are capable, to minimize the nonlinear effect and dispersion. RoF is a consistent system for users which provides communication with negligible degradation of wireless range [32].

3.1.4 RoF applications

There are numerous utilizations of RoF innovation which would be listed as below:

1. Video Distribution Systems (VDSs):- The large bandwidth provided by the RoF system is a key factor to VDs. The Common-Antenna Television (CATV) network that has used in electrical communication techniques is a good example of it. The replacement of low bandwidth coaxial cables by optical fiber provides better quality of service in terms of the number of users. For example, the coaxial cable bandwidth cannot exceed 1GHz but this value can exceed in the case of optical fiber easily [33]. The utilization of FO in VDS can be seen in Figure 4.

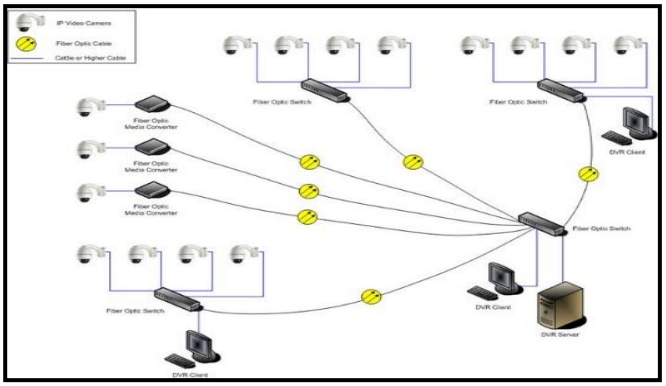

Figure 4. The utilization of FO link in VDS [33].

2. Satellite Control: - Such control can be performed by the remote antenna located at a satellite earth station which can be controlled via optical fiber. To support numerous distant satellite earth stations, the CO/CS can be incorporated at a particular area. The decision of sending the optical fiber between the CO/CS and the satellite earth station is the most ideal decision since the satellite earth stations require high data transfer capacity to deal with the proficient working of the satellites. This is a practical strategy [33]. Figure 5 exhibit the idea RoF for satellite correspondence.

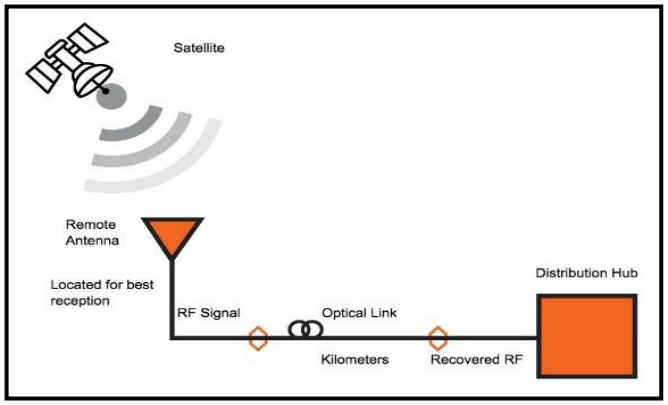

Figure 5. The utilization of RoF for satellite communication [33]

3 Cellular Networks: - They have become more attractive nowadays and all service based mobile network providers are deploying their resources to cope with the increase in capacity requirements. For capacity, we automatically understand that the RoF system is the best option since the optical fiber relayed between CO/CS and BS has a large capacity. Therefore with an increase in capacity, more services can be provided in the broadband network [34]. The utilization of FO in cellular networks can be demonstrated in Figure 6.

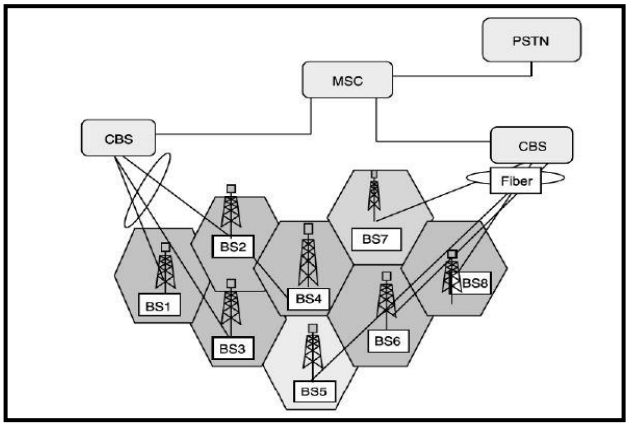

Figure 6. Optical utilization in cellular based network [34]

4. Vehicle Communication: - the RoF system can be utilized to control the traffic of vehicles by deploying various BSs along the dedicated roads.

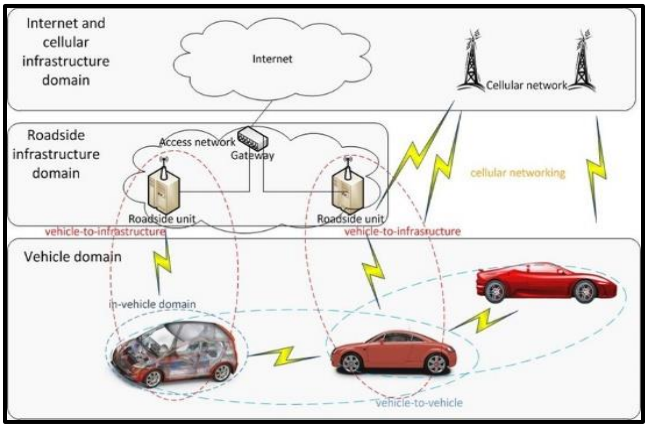

Figure 7. Vehicle communication scenario with RoF system [35].

These BSs communicate with the vehicles moving in the road through the microwave signal while the BSs are connected to the CO/CS. Higher-frequency signal is a necessity for the tracking of fast-moving vehicles. Thus the RoF system is considered as the most reliable system for this purpose [35]. The simple idea of vehicle communication can be seen in Figure 7.

5. Mobile Broadband Services: - due to the large growth in the mobile broadband based services, it requires large bandwidth. For example, the 4G services use the bit rate in several MBs. Thus, the RoF system is the optimum choice to deal with the need for higher bandwidth to reach more clients. The RoF will help to provide a good quality signal as the losses, reflections, and other impairments are minimized. The utilization of RoF in Mobile broadband services can be seen in Figure 8. [36].

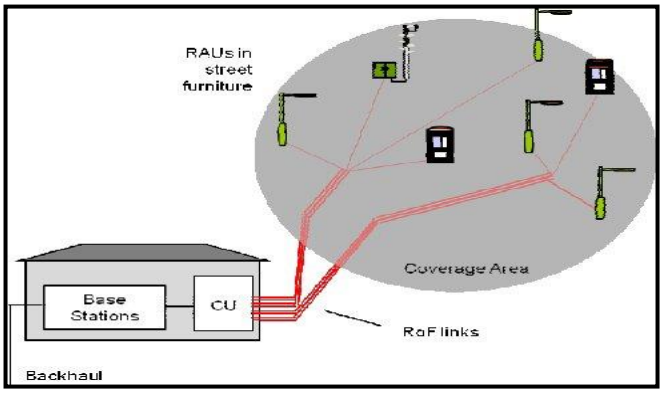

Figure 8. The utilization of RoF in Mobile broadband services [36].

3.1.5 Multiplexing techniques in RoF

It represents the multiplexing process of the wavelength with different frequency channels onto a single fiber. In this process, each cable would have the ability to handle several signals subsequently. Notwithstanding that, the RoF multiplexing uses the frequencies to send information in equal or sequential, which builds the limit of the fiber by allotting approaching optical signs to a particular recurrence inside the assigned recurrence band.

3.2. Wavelength Division Multiplexing (WDM)

3.2.1 WDM overview

WDM could be defined as a type of Frequency Division Multiplexing (FDM) based technique in which the optical signal with various wavelengths would be combined, transferred, and then separated at the end of the transmission side. Such a technique is required in the case of the availability of several channels.

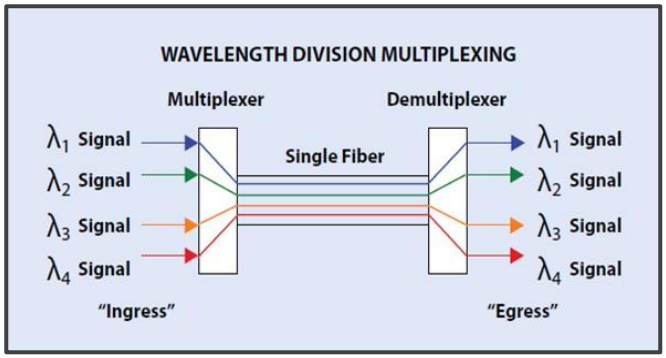

Figure 9. WDM concept [37]

Hence, the system capacity would be increased in a significant manner [11]. The WDM could also be denoted as a passive device that performs the main task of combining and recombining different wavelengths over a single fiber cable. WDM could provide an effective way to optimize the capacity of the RoF system and improve the total number of BS that was powered by a single CO. [37]. The basic concept of WDM technology can be illustrated as in Figure 9.

Recently, the distribution of the RoF system based WDM technique has gained significant attention in which, it can achieve a capacity of 1 Tbps. Furthermore, in such systems, it is possible to diminish the frequency spacing of the channel to 50 GHz or 20 GHz, which may increase the chance to utilize a larger number of channels. However, increasing the spacing would increase the difficulty related to the system upgrading especially when considering a high value of bit rate (equal to 40 Gbps). Such difficulties would be resulted due to the effects of the nonlinear phenomenon. The diagram in Figure 10 clarifies the RoF system-based WDM technique [37].

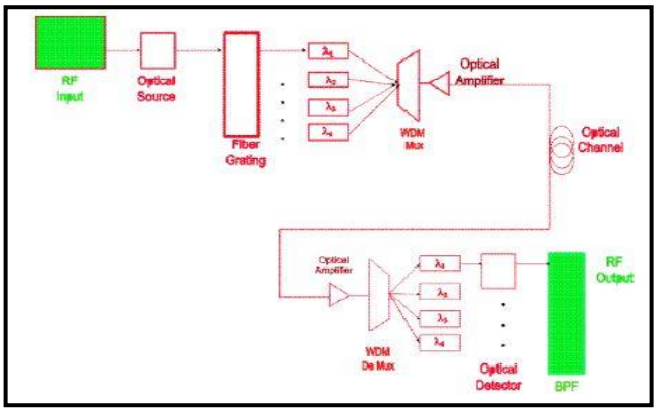

Figure 10. Diagram of RoF system based WDM technique [37].

3.2.2 WDM types

There are two types of WDM which have been defined by the International Telecommunication Union (ITU):

1- Coarse Wavelength Division Multiplexing (CWDM):- in this type, a lower number of the channel would be utilized represented by four or eight for example along with wider channel spacing of 20 nm. The selected wavelength range for this type is between (1310-1610) nm. The selected bit rate must be in the range of (1-1.3125) Gbps. Such type has a sign in the metropolitan area only and has not been considered to be suitable for the cases of Fiber-To-The-Home (FTTH) [11].

2- Dense Wavelength Division Multiplexing (DWDM):-in this type it would be performed for longer distances with larger data capacities, which would make them preferable. DWDM utilized a large number of channels, and a small channel spacing ranging between (12.5-100) GHz. The obtained bit rate would higher than 100 Gbps. In several cases, the Time Division Multiplexing (TDM) could be considered as an alternative to WDM in which different channels would be separated based on the arrival time [11].

Furthermore, WDM has a unique facility of adding flexibility to the complex communication system, where different data can be injected at different locations in the system. Meanwhile, other channels can be extracted for such operation, in which the Add-Drop Multiplexer (ADM) could be used to add and drop data channels based on their wavelengths [11]. Figure 11 clarify the spectrum concept of both CWDM and DWDM.

3.2.3 DWDM

It is the most famous WDM innovation with broadcast communications and link organizations on account of its capacity to deal with so much information. It assists with growing the limit of current FO spines and prepare it for 5G deployments. It consolidates and communicates numerous signals of various frequencies at the same time on a similar fiber. Presently, DWDM, the continuous growth in data rate values to reach the Tera bit per second (Terabps) [38].

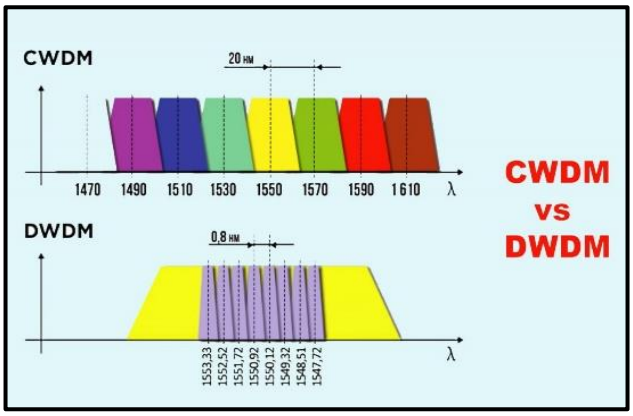

Figure 11. The spectrum concept of both CWDM and DWDM [11].

3.2.4 Key difference between CWDM and DWDM

Several parameters could be demonstrated as a key difference between the two techniques. One of these is the wavelength spacing and the number of channels, where DWDM would have a higher number as compared to CWDM. Another major parameter is the distance of transmission, in which the CWDM has a capability of transmission in a distance up to 160 km [39]. While DWDM could be used for long haul distances. The power requirements are another factor to be highlighted, where CWDM uses an uncooled distributed-feedback laser. Meanwhile, DWDM uses the uncooled distributed- feedback laser. As a result, DWDM would consume more power than CWDM. Finally, the system costs are the last factor to be considered between them where DWDM are commonly higher than CWDM by four to five times [38]. It is worth to mention, that in CWDM channels 20 nm of space channel is allocated per each channel, while in DWDM it utilizes either 50, 100 or 200 GHz spacing. Thereby, it allows large number of wavelengths to be formed within the same fiber. The common utilized number of channels in CWDM are between (8 to 18), while DWDM can reach up to 32 channels [38]. A summarized comparison between the two mentioned above types can be listed as seen in Table 1.

Table 1. Comparison between the CWDM and DWDM based techniques [39]

Types	CWDM	DWDM
Channel Spacing	20nm	0.4nm or 0.8nm
Wavelength Range	1311~1611nm	C-band: 1529nm~1561nm L-band: 1570nm~1603nm
Transmission Capacity	16 * 2.5Gb/s = 40G	160 * 10Gb/s = 1600G
Laser	Uncooled Laser	Cooled Laser
Cost	30%	expensive
Application	100km	4000km

3.2.5 WDM for 5G Networks

The improvement of 5G networks beginning in 2019 is commonly accepted to bring changes not restricted to individuals' day by day life. It will uphold the advancement of Internet from versatile web to astute web, which will impact the modern environment profoundly. The organization of international standard which is denoted by (3GPP) defined the 3 main application scenarios of 5G: the first was the eMBB (Enhanced Mobile Broadband), the second was the uRLLC (Ultra - Reliable Low Latency Communications), and the third was the mMTC (Massive Machine Type Communication) and as seen in figure 12 [40]. The aim of each application can be summarized as below.

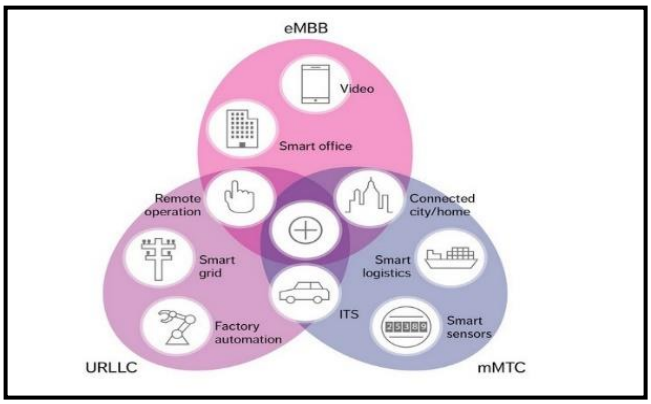

Figure 12. Three application scenarios of 5G networks [41]

1-With eMBB, the IMT-2020 means to help applications and administrations that require [41]:

- High information rates or traffic densities, for example, top download accelerates to 20 Gbps, client experience information rate up to 100 Mbps with just 4 ms inactivity.
- In various assistance zones, for example, indoor/outside, metropolitan and rustic regions, office and home just as nearby and wide zones availability.
- In exceptional organizations zones, for example, monstrous get-togethers, communicated, private, and fast vehicles.
- Vivid applications that need quick video downloads, ultra superior quality screens and expanded and augmented reality.

2- URLLC is needed for strategic and time-touchy applications, for example, self-sufficient vehicles, far off medical services, crisis reactions and industry robotization. URLLC model applications and administrations for industry mechanization include [41]:

- Robotized far off driving - which empowers a distant driver or a V2X application to work a far off vehicle with no driver or a far off vehicle situated in a perilous climate.
- Robotized rail interchanges (for example railroad, rail-bound mass travel) - with URLLC, train activity can be completely robotized with profoundly dependable correspondence with moderate latencies at extremely high speeds of up to 500 km/h.
- Robotized measures for receptive streams at processing plants and water dissemination organizations.
- Robotization for power dispersion (primarily medium and high voltage).

- Robotization of the street-side remote foundation supporting road-based traffic, associating distinctive framework units, for example, side of the road units with traffic direction frameworks.

3- mMTC test applications and administrations include:[41]

- Smart cities - 5G is an empowering innovation for IoT, and as brilliant urban areas basically depend on IoT to work, 5G will assume a basic part in permitting data assembled through sensors to be communicated continuously to focal observing areas.
- Smart metering - Smart metering empowers savvy frameworks to interface with water, gas, oil, and electric utilities. Utilities and buyers can get continuous information on water quality, temperature, pressure, pace of utilization, and extra information gathered by means of sensors and shared through 5G organization .
- Smart logistics – several logistics services providers (LSPs) are now utilizing IoT gadgets to follow the area of shipments utilizing a mix of GPS and remote network. 5G will take this to the following level, as low inactivity would empower nonstop, up-to-the-second following of precisely where the products are.

The interconnection between the nodes of 5G network is realized through the utilization of optical transceiver modules and optical fibers. The interconnection between the wireless base station and DU is defined as front-haul. The interconnection between DU and CU is defined as mid-haul. The interconnection between CU and the metro core network is defined as back-haul. The three interconnection types can be clarify in Figure 13. The front-haul distance is usually <10/20km and the bit rate of the data interface is 10/25/100Gbps. The mid-haul distance is usually < 40km and the bit rate is 25/50/100Gbps. The back-haul distance is usually 40-80 km and the bit rate is usually 100/N×100Gbps. The transmitting span of the trans-provincial backbone network is usually hundreds of kilometers and the bit rate is N×100/200/400Gbps [40]

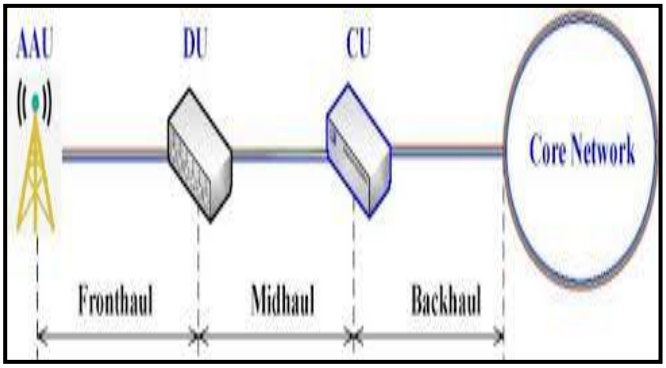

Figure 13. The interconnection of front-haul, mid-haul and back-haul [40].

Optical fiber transmission is generally utilized in telecom spine organization and server farms, to improve bandwidth, WDM techniques are ordinarily utilized. In any case, the solid transmission advancements are assorted confronting diverse application situations. The primary variables affecting the decision are power misfortune and chromatic scattering of the fiber interface. The laser sources (with modulators included) and photon indicators (PDs) are significant for the expense of the transmission framework [40].

As it's known to all, WDM-PON (Wavelength Division Multiplexing-Passive Optical Network) joins WDM innovation with PON technology structure that permits administrators to convey high data transmission to various endpoints over significant distances. It incorporates a few advancements, including drab ONU innovation, Auxiliary Management and Control Channel (AMCC), optical modules, OAM, and insurance exchanging. With these key advances, WDM-PON is viewed as an ideal arrangement which can meet the 5G necessities and has pulled in incredible consideration these days [42].

The design of WDM-PON 5G front-pull organization can be demonstrated as seen in Figure 14. A few RRUs and a DU are associated through a WDM-PON highlight multipoint geography. The WDM-PON OLT is associated with the DU, CU, and ONU. ONU is likewise associated with RRUs. This OLT stage conveys the front-pull traffic between the DU and RRUs just as the center take traffic between the DU and CU. Regarding the front-pull transmission or the association among RRUs and DU, WDM-PON transmission interfaces assume a critical job that empowers the straightforward client information transmission between them. Also, the arrangement of applying WDM-PON to convey 5G is particularly reasonable for those administrators who need to give both remote and wireline administrations in a greenfield situation [42].

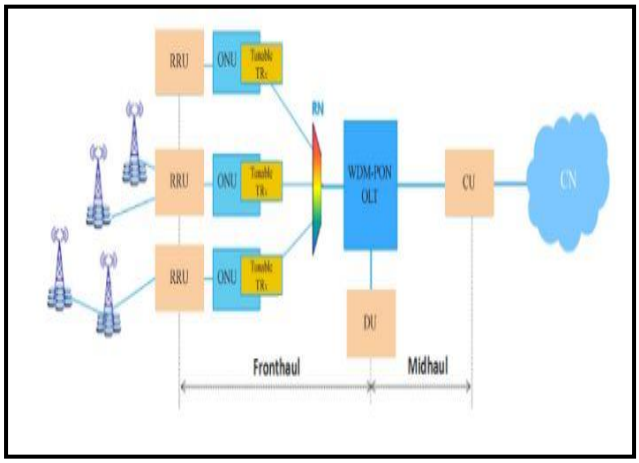

Figure 14. The structure of WDM-PON network [42]

4. Related Works

This section will highlight the related works in the field of WDM and DWDM based RoF system

In [43] authors designed and analyzed the performance of a RoF system by using Optisystem software and based on several parameters such as Q-factor, Eye height, and Min Bit Error Rate (BER). Results were based on the two modulation techniques of Non-Return to Zero (NRZ) and Return to Zero (RZ). Such results have indicated that NRZ has suffered from considerable nonlinearities, while RZ may suffer from considerable effects of dispersion due to the shorter width of the generated pulses. Furthermore, results indicate that using RZ coding could achieve better performance as compared to NRZ coding.

In [44], the authors presented two architectures for RoF based system in a wireless accessing network. These architectures are all-band RoF and band-mapped 60-GHz RoF that would be integrated into WDM Passive Optical Network (PON). The results of analyzing these systems have reported providing cost-effectiveness and several solutions for the next generation of multi-service networks. Besides, by mapping

several signals into the 60 GHz sub-bands, the proposed architecture could achieve higher efficiency and lower power consumption.

In [45], researchers investigated the spectrum based on sliced DWDM PON by considering the power efficacy and cost-effectiveness solution for the access network. The proposed DWDM system was with 32 channels a data rate reaches up to 3 Gbps and by using both the NRZ and RZ modulation format. Results obtained indicate that the performance with NRZ format is better as compared to RZ with a Min BER value achieved of 10-12. In order, to make RZ achieve the same BER values as compared to NRZ, it has been found that extra power of 4 dBm is required for such an issue. As a result, the proposed system based DWDM PON with NRZ format could be considered as cost-effectiveness and better suited for FTTH based network.

In [46] authors, presented the process of generation signal of optical carriers suppressed for RoF based system. The modulation of this signal would be performed by using the Dual Drive MZM (DDMZM). The entire scenario has been carried out by using Optisystem software. In this work, it has been utilizing a single RF with a frequency of 2100 MHz and a data rate of 1 Gbps and modulated at 1550.12 nm frequency. Results obtained indicate that optical carrier suppression could improve the overall performance of RoF systems such as the noise figure and gain.

In [47] authors studies the overall performance of the RoF system by using MZM and based on several parameters of bias voltage, RF bias, and the ratio of extinction to overcome the dispersion losses and minimize the signal degradation, which causes due to the fading of power. Their proposed system has considered an extinction ratio of 30 dB and a switching bias voltage of 4 volts. Results obtained concluded that setting the typical bais and extinction ratio could achieve the optimum results for the RoF system.

In [48] authors designed and implemented a scheme for a DWDM system with 320 Gbps of data rate and a distance of 70 km. Moreover, 32 channels were set for the proposed scheme with a bandwidth range between (1527-1552) nm. Simulation results indicate that the output power was 21.5 dBm for a fiber length of 5 m. This study has specified the optimum results of gain, BER, and Q-factor based on the selection of input power, pump power, and the length of EDF.

Meanwhile, in [49] researchers proposed architecture for both wired and wireless signal transmission with the capability of delivering 25 Gbps of data rate. A full-duplex based RoF system by using both WDM and Optical Add Drop Multiplexer (OADM) has been performed by using optisystem software. The investigation was based on two modulation techniques of NRZ and RZ and the parameters of the eye diagram, Q-factor and Min BER. The distance investigated was between (10-100) km with an input power of 0.1 dBm and the input bit rate was 5 Gbps. Results obtained indicate that RZ is better in overall performance in handling the high bitrate with longer transmission-based applications.

In [50], the authors designed a scheme for the WDM-PON network, where two cases have been investigated in this work. The first was with a static value of the distance of 50 km and varied values of bitrate (108, 109, and 1010) Gbps. While for the second case the bit rate value would be static at 109 and the distance would be varied (20, 50, and 80) km. Results, obtained would be on the analysis parameters of Q-factor, Min BER, and eye diagram. Such results indicate a reversal relation between the bitrate and both the Q-factor and eye height. Meanwhile, the BER would have a direct correlation with the bit rate.

In [51], the authors designed a RoF system that consists of two RF channels using MZM which have been simulated by using Optisystem software. The characteristics of MZM would be studied based on the different modulation schemes. The parapets of Q-factor, Min BER would be observed as performance analysis of their work and along with different fiber lengths. Results obtained showed that values that Q-factor values for channel 1 were 21.23, 16.77, 16.33, 15.65, and 15.49 for the distances of (10, 20, 30, 40, and 50) km respectively. While, for channel 2 were 18.07, 15.07, 15.9, 13.60, and 11.15 for the same set of investigated distances. Furthermore, the obtained values of BER were in the range of (10-100 – 10-54) and (10-73 – 10-5) for channels 1 and 2 respectively.

In [52], the authors proposed a WDM- Based RoF system with a capability to transmit a 1 Gbps of input data rate in both uplink and downlink along with an optical link of 25 km distance. Their proposed system has shown significant results and good signal quality.

In addition to that, another investigation was carried out in [53] for the Bidirectional WDM-PON system, the modulated signal was transmitted over 25 km of SMF link, while for the demodulation it has been used the Reflective Semiconductor Optical Amplifier (RSOA). Results obtained from the proposed system could achieve a bit rate of 10 Gbps without considering a small amount of dispersion.

Furthermore, in [54] authors proposed a designed a bidirectional 8 channel WDM-PON system with various modulation techniques of (NRZ, RZ, CSRZ, and MDRZ) and based on the use of optisystem software 14.1. Results obtained showed that the proposed system has shown better performance with the using of MDRZ rather than using other methods with the total investigated distance of 120 km, a power of 1 dBm, and frequency spacing of 200 GHz. With such a format the requirements for an amplifier, DCF, and repeaters would be unnecessary to be utilized. Thereby, the results of eye height when applying the MDRZ were 2.01e-5, 2.05e-5, 2.03e-5, and 2.18e-5 over the distance of (90, 100, 110, and 120) km respectively.

In [55], the authors proposed a 16 channel RF system with the use of subcarrier multiplexing (SCM) which will be integrated along with the WDM for RoF system implementation. The later integration aims to provide a higher data rate and mobility for broadband-based communication. Moreover, the work also investigated the performance of EDFA for an optical link with a length of 200km. Results obtained demonstrate a significance in signal quality when utilizing the EDFA for 100 and 150 km of SMF cable for the SCM-WDM-based RoF system. Furthermore, an increase in power with decreasing losses has been shown. As a result, it has been concluded that the proposed system could boost the performance of the optical system.

In [37], researchers proposed a model for the RoF system based on two cases of with and without the use of Optical Orthogonal Frequency Division Multiplexing (OOFDM). The proposed model has considered a multi-channel scenario through the process of combining both techniques of WDM and SCM. Performance analysis was based on the different Quadrature Amplitude Modulation (QAM) schemes and with 20 km of distance. In addition, three data rates were included along with the investigation which is (5, 7, and 10) Gbps. The overall results showed a significant manner when utilizing

WDM along with the proposed scheme.

In [56] authors proposed an investigation for a RoF based system with various length of (5, 20, and 60) km of fiber cable and various cases of channel spacing. The system consists of four transmitters with a first selected frequency of 1552.50 nm and a channel spacing of 0.4 nm between the other three channels. The bandwidth selected was 10 GHz, and the input bit rate was 1 Gbps. The parameter of the eye diagram, Q-factor, and Min BER would be analyzed by using optisystem software. Furthermore, a methodology for enhancing the quality of the received signal for the proposed system by utilizing the optical amplifier after the transmission of the case of 60 km distance. Such optimization has increased the efficiency of the proposed system.

Recently, another work proposed in [57] with two-channel has been designed for the RoF system by using MZM as an external modulator. Besides, it has been selected the Q-factor as an evaluation metric for their proposed system and based on different distances of (10, 20, and 30) km. Furthermore, the evaluation has been carried out by considering different extinction ratios ranges between (10-30) dB with a spacing of 5 dB. Results obtained showed a direct correlation between the extinction ratio and Q-factor, while a reverse relation has been found between the Q-factor and the distance. The optimum results were achieved for the case of using 30 dB and 30km of extinction ratio and distance respectively.

In [58] it has been proposed a scheme for four-channel DWDM based on the use of the Free Space Optical (FSO) channel. Results obtained would take into consideration different weather conditions with a distance length of up to 5 km. The effectiveness of their system was for a distance of up to 2 km, while for a long distance the Q-factor would be significantly reduced until reach zero.

Moreover, in [59] authors demonstrated an investigation for the DWDM system using Roman Optical Amplifier (ROA), where 80 channels were included with the investigation. The Min BER and Q-factor were the basis of their investigation and with various channel spacing ranging from 20 GHz to 100 GHz. results have concluded that utilizing the100 GHz of channel spacing has achieved the best overall performance and results.

In [60] researchers designed and evaluated a scheme based on full-duplex communication between four BS and one CO. Their proposed system works for 5Gbps data transmission and a distance of 90 km. The proposed scheme has achieved a Q-factor of 30.8. However, such a scheme has achieved a lower bit rate which needs to be enhanced to meet the requirement for 5G systems.

5. Conclusions

This paper presents a brief discussion to the literature review that is related to the utilization of WDM techniques along to the RoF system. First, the general description about the fiber optic communication system and its related advantages along with dedicated applications were listed. Then, the techniques of RoF along with its advantages would be discussed and clarified in consistent manner. Finally, the WDM based techniques and its types according to ITU has been demonstrated. From the overall demonstration in this work, it can be concluded that during the past ten years WDM has been widely used as a major method for handling higher capacity and transmitting bit rates. Also, it was integrated with different other techniques to enhance the efficiency of the proposed systems. Furthermore, using WDM for RoF based system provides the required mobility. It is worth to mention that the WDM performance has been effected by the nonlinearity characteristics within the fiber cable, which may consider as a main limitation for WDM systems.

References

[1] Wey, J. S., & Zhang, J. “Passive optical networks for 5G transport: technology and standards,” Journal of Lightwave Technology, Vol. 37, No. 12, pp. 2830-2837, 2018.

[2] Y. Xiao and J. Yu, “A novel WDM-ROF-PON architecture based on 16QAM-OFDM modulation for bidirectional accessnetworks,” Opt. Commun., Vol. 295, pp. 99–103, May 2013.

[3] J. Johny and S. Shashidharan, “Design and simulation of a Radio Over Fiber system and its performance analysis,” in 2012 IV International Congress on Ultra-Modern Telecommunications and Control Systems, pp. 636– 639, 2012.

[4] Shakir, A., Alsaqour, R., Abdelhaq, M., Alhussan, A., Othman, M., & Mahdi, A.. “Novel Method of Improving Quality of Service for Voice over Internet Protocol Traffic in Mobile Ad Hoc Networks,” International Journal of Communication Networks and Information Security, Vol.11, No. 3, pp.331-341, 2019.

[5] Jalil, M.A. AL-Samarrie, A.K. “Radio-over-Fibersystem Capacity Improvements by using Wavelength Division Multiplexing and Subcarrier Multiplexing Techniques,” Eng. Technol. J., Vol. 33, pp. 1416–1428, 2015.

[6] Basa, A. Talukder, M.Z. Islam, M.R. “ Performance analysis and comparison between coarse WDM and dense WDM,” Glob. J. Res. Eng., Vol. 13, pp.45–52, 2013.

[7] Sethi, R. K., and Aditya Goel. “Performance analysis of optical communication systems using OFDM by employing QPSK modulation,” International Journal on Recent and Innovation Trends in Computing and Communication, Vol. 3, No. 1, pp. 226-237, 2015.

[8] Chen, You-Wei, et al. “Key Enabling Technologies for the Post-5G Era: Fully Adaptive ,” All-Spectra Coordinated Radio Access Network with Function Decoupling. IEEE Communications Magazine, Vol. 58, No. 9 ,pp. 60-66, 2020.

[9] Fan Wei, Hanyi Zhang, and Bingkun Zhou Tsinghua, “Carrier Phase and Amplitude Manipulation for Linearization and Dispersion compensation in Radio-over-Fiber Systems Using Mach-Zehnder Modulator,” Progress in Electromagnetic Research Symposium Abstracts, Electromagnetics Research Symposium Proceedings, Stockholm, Sweden, Aug., pp.12-15, 2013.

[10] Pradeep R. and Vijayakumar N., “Performance Analysis of RoF link using Mach-Zehnder Modulator in radio over fiber systems,” International Journal of Advanced Research in Engineering and Technology (IJARET). ISSN Print: 0976-6480 and ISSN Online: 0976-6499 Vol. 7, No. 5, pp. 45–52, September-October 2016 Article ID: IJARET_07_05_006 ISSN Print: 0976-6480 and ISSN Online: 0976-6499© IAEME Publication

[11] Singh, Rajbir, Manoj Ahlawat, and Deepak Sharma. “A Review on Radio over Fiber communication System,” International Journal of Enhanced Research in Management & Computer Applications , Vol. 6, No.4, pp. 23-29, 2017.

[12] Website,https://www.antaira.com/Blog-Four-Advantages-of-Fiber-Optic-Communications Accessed 20-12-2020.

[13] Willner, Alan.“ Optical fiber telecommunications ,” Academic Press, Vol. 11. 2019.

[14] Velasco, Luis, et al. “Monitoring and data analytics for optical networking: benefits, architectures, and use cases,” IEEE Network, Vol. 33, No. 6 pp. 100-108, 2019.

[15] Leal-Junior, Arnaldo G., et al. "Polymer optical fiber sensors in healthcare applications: A comprehensive review," Sensors, Vol.19, No.14, p. 3156, 2019.
[16] Chang, Gee-Kung, and You-Wei Chen. "Key fiber wireless integrated radio access technologies for 5G and beyond", 24th OptoElectronics and Communications Conference (OECC) and 2019 International Conference on Photonics in Switching and Computing (PSC). IEEE, 2019.
[17] Alieldin, Ahmed. "Report on Optical Fiber Fundamentals, properties and advantages", LiverpoolUniversity,URL:https://factco.-co.uk/wp-content/uploads/2019/08/Report-on-Optical-Fibre-.pdf , 2019.
[18] Li, Min, et al. "A wearable fiber-optic sensor for monitoring human elbow and wrist joint motion, " Advanced Robotics, pp.1-13, 2020.
[19] Dileep, G. "A survey on smart grid technologies and applications," Renewable Energy , Vol.146, pp. 2589-2625, 2020.
[20] Mowbray, Shannon E., and Amir M. Amiri. "A brief overview of medical fiber optic biosensors and techniques in the modification for enhanced sensing ability," Diagnostics, Vol.9, No.1, p. 23, 2019.
[21] Yu, Hongsheng, et al. "Application of optical fiber nanotechnology in power communication transmission," Alexandria Engineering Journal, 2020.
[22] Singh, Rajbir, Manoj Ahlawat, and Deepak Sharma. "Study and performance evaluation of Radio over Fiber using Mach Zehnder Modulator," International Journal of Advanced Research in Computer Science, Vol. 8, No. 5, 2017.
[23] Balinder Singh and Davender Singh, "A Review on Advantages and Applications of Radio over Fiber System," International Journal of Current Engineering and Technology E-ISSN 2277 – 4106, P-ISSN 2347 – 5161
[24] Singh, Rajbir, Manoj Ahlawat, and Deepak Sharma. "Study and performance evaluation of Radio over Fiber using Mach Zehnder Modulator," International Journal of Advanced Research in Computer Science, Vol. 8, No.5, 2017.
[25] Zhu, Ming, et al. "Radio-over-fiber access architecture for integrated broadband wireless services," Journal of Lightwave Technology, Vol. 31, No. 23, pp. 3614-3620, 2013.
[26] Wong, Sie Woo. "Development of OFDM in WDM-radio over fiber access network," Diss. Universiti Tun Hussein Onn Malaysia, 2012.
[27] Mohamed, L. N., and A. G. H. U. Dewmini. " Capacity expansion of fibre optic network in Sri Lanka," 2019.
[28] Sharma, Nitika, Arpan Garg, and Nitin Mittal. "A Comprehensive Survey on OFDM Based Radio over Fiber Modulation System," 2020.
[29] Islam, Saveed, et al. "An Overview of Radio over Fiber (RoF) Technology," 2nd International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT), Vol. 1, IEEE, 2019.
[30] Liu, Guanchen, et al. "Electromagnetic Immunity Performance of Intelligent Electronic Equipment in Smart Substation's Electromagnetic Environment," Energies , Vol.13, No.5, p.1130, 2020.
[31] Goścień, Róża. "On the Efficient Dynamic Routing in Spectrally-Spatially Flexible Optical Networks," 11th International Workshop on Resilient Networks Design and Modeling (RNDM). IEEE, 2019.
[32] Liu, Zigeng, et al. "Low-power-consumption fiber-optic anemometer based on long-period grating with SWCNT coating," IEEE Sensors Journal , Vol.19, No.7, pp. 2592-2597, 2019.
[33] Zarca, Alejandro Molina, et al. "Security management architecture for NFV/SDN-aware IoT systems," IEEE Internet of Things Journal, Vol.6, No.5, pp.8005-8020, 2019.
[34] Chen, Yun, et al. "Pervasive intelligent endogenous 6G wireless systems: Prospects, theories and key technologies," Digital Communications and Networks, Vol.6, No.3, pp.312-320, 2020.
[35] Babir, Md Rafeeun Noby, Shamsul Arefeen Al Mahmud, and Tasnim Mostary. "Efficient M-QAM Digital Radio over Fiber System for Vehicular ad-hoc Network," 2019 International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST). IEEE, 2019.
[36] Kim, Joonyoung, et al. "MIMO-Supporting Radio-Over-Fiber System and its Application in mmWave-Based Indoor 5G Mobile Network," Journal of Lightwave Technology, Vol. 38, No.1, pp.101-111, 2019.
[37] Mohammed Ali, F., E. Al-Hilo, and M. Gamil Tarbul. "Performance analysis of radio over optical fiber system with OFDM using multiplexing techniques," Int J Appl Eng Res, Vol. 13, pp. 10831-44, 2018.
[38] Hyc official website ,Online website available at https://hycsystem.medium.com/how-to-use-dwdm-for-fiber-optic-capacity-expansion-c2276b385f4 Accessed 12-12-2020
[39] Vitex official website for- fiber optic solution, available at https://vitextech.com/cwdm-and-dwdm-networks-which-is-best-for-you/ accessed 27-11-2020
[40] Offical website of HYC company for fiber optic components available at https://optical-passive.com/2020/09/15/wdm-technologies-for-5g-carrying-network/amp/ , accessed 12-12-2020.
[41] https://tecknexus.com/5g/ accessed 15-12-2020
[42] https://medium.com/@ivyhtfuture/wdm-pon-network-an-efficient-solution-for-5g-deployment-e67099fca071, accessed 15-12-2020
[43] Johny, Jincy, and Sreenesh Shashidharan. "Design and simulation of a Radio Over Fiber system and its performance analysis," IV International Congress on Ultra Modern Telecommunications and Control Systems. IEEE, 2012.
[44] Zhu, Ming, et al. "Radio-over-fiber access architecture for integrated broadband wireless services," Journal of Lightwave Technology, Vol.31, No. 23, pp. 3614-3620, 2013.
[45] Husein, Abdel Hakeim M., and Fady I. El Nahal. "Optimal design of 32 channels spectrum slicing WDM for optical fiber access network system," Optik, Vol. 125, No.18, pp. 5141-5143, 2014.
[46] Htet, Sai Naing Min. "Generation of Optical Carrier Suppressed Signal for Radio-over-Fiber (RoF) System Using Dual-Drive Mach-Zehnder Modulator," International Journal of Scientific and Research Publications, Vol.4, No.9 pp. 2250-3153, 2014.
[47] Bhatiaa, Kamaljit Singh, and Sandeep Singh. "Performance Analysis of RoF link using Mach-Zehnder Modulator and its parameters," An International Journal of Engineering Sciences, Special Issue ICTMS-15 , pp.29-30, 2015.
[48] Bhumika Patel , Shankersinh Vaghela Bapu Ankit et al, "Performance Analysis of Optical Link Using EDFA, " International Journal for Scientific Research and Development, Vol.3, No. 3, 2015
[49] Mohan, Arya, and A. P. Anisha. "Full Duplex Transmission in RoF System using WDM and OADM Technology," IJERT , Vol.4, pp. 513-516, 2015.
[50] Hussain, Nahla Abdulrahman. "Wavelength Division Multiplexing Passive Optical Network modeling Using Optical System Simulator," Al-Khwarizmi Engineering Journal, Vol.11, No.3, pp. 61-71, 2015.
[51] Singh, Rajbir, Manoj Ahlawat, and Deepak Sharma. "Study and performance evaluation of Radio over Fiber using Mach Zehnder Modulator," International Journal of Advanced Research in Computer Science, Vol. 8, No.5, 2017.
[52] Sharma, Savita Rana Abhishek, and Savita Rana. "Comprehensive study of radio over fiber with different modulation techniques–a review," International Journal of Computer Applications, Vol. 170, No. 4 , pp. 22-25, 2017.
[53] El-Nahal, Fady I. "A WDM-PON with DPSK modulated downstream and OOK modulated upstream signals based on symmetric 10 Gbit/s wavelength reused bidirectional reflective SOA," Optoelectronics letters, Vol. 13, No. 1 pp. 67-69, 2017.

[54] Rani, Nisha. "Design and Implementation of Various Advanced Modulation format over 8-WDM Bidirectional PON," 2017.
[55] Marwanto, Arief, Sevia M. Idrus, and A. Sahmah Mohd. "Performance analysis of EDFA for SCM/WDM radio over fiber communication link," Supa'at Photonic Technology Centre, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Vol. 209, p. 12.
[56] Ali, Adnan Hussein, and Alaa Desher Farhood. "Design and performance analysis of the WDM schemes for radio over fiber system with different fiber propagation losses," Fibers, Vol. 7 No. 3, p. 19, 2019.
[57] Kumar, Suresh, Deepak Sharma, and Rajbir Singh. "Performance Analysis of Radio Over Fiber Link Using MZM External Modulator," First International Conference on Sustainable Technologies for Computational Intelligence. Springer, Singapore, 2020.
[58] Khan, Muhammad Faisal Nadeem, et al. "FSO Communication: Benefits, Challenges and Its Analysis in DWDM Communication System," Sir Syed University Research Journal of Engineering & Technology, 2020.
[59] Kumar, Ghanendra, and Sandeep Kumar. "Effect of different channel spacings for DWDM system using optical amplifiers," National Academy Science Letters, pp. 1-4, 2020.
[60] Qureshi, Khurram Karim, et al. "Radio-over-fiber front-haul link design using optisystem," Journal of Optical Communications 1.ahead-of-print 2020.