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Summary on RoF Technologies, Modulations, and Optical Filters: Review

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ABSTRACT

In order to meet the growing need for bandwidth, this article offers a thorough examination of Radio over Fibre (RoF) technology and its integration with wireless communication networks. It starts out by going over the development of wireless networks and the difficulties they encounter, like spectral congestion and RF spectrum operational constraints. An effective way to handle data traffic is to include optical fibre into wireless networks. A detailed analysis is conducted of the technical features of RoF systems, including modulation approaches such as external and direct modulation. While external modulation provides better performance by getting around constraints, direct modulation uses the RF signal to directly modify the brightness of the light source. It is detailed how optical filters, including Fabry-Perot, Fiber-Bragg Grating, and Tunable filters, are used in a variety of applications. They provide an explanation of their functions and importance in optical communication. In addition, a thorough review of relevant literature is included in the study, along with a summary of the main conclusions, approaches, goals, drawbacks, and achievements of academic studies on optical communication and RoF systems. This analysis focuses on the field's problems and achievements. In summary, RoF technology integration of optical and wireless networks holds enormous potential to satisfy the changing needs of high-capacity, high-speed wireless communication. In order to effectively utilise the potential of RoF systems and progress contemporary wireless networks, additional study and development work is yet required.

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1. INTRODUCTION

The development of wireless communication networks in the modern era requires ongoing capability improvement and the supply of wide benefits. Wireless networks are now widely used in both the military and the civilian worlds, and they are an essential part of our everyday lives. Our lifestyles have undergone tremendous transformation due to the swift progress of technology. The need for more bandwidth has increased due to the spread of communication technologies and the internet's quick development [1].

Wireless network programs like Global System for Mobile (GSM) and General Packet Radio Service (GPRS) were created in the early days of telecommunications with low data rates in mind. But as more and more people adopt next-generation mobile technologies and their need for bandwidth-intensive applications increases [2]. systems that can effectively handle the large information rates expected in future wireless networks become more and more necessary. As a result, practical options such as radio-wave frequencies and optical fibers are being investigated. Even though optical fiber technologies provide much more bandwidth and longer transmission links, using radio-wave frequencies has benefits in the wireless domain and helps to alleviate spectral congestion.[3].

Moreover, it is hard to imagine contemporary living without the creative applications of wireless technology, such artificial intelligence (AI), streaming high-definition video online, and cutting-edge consumer programs like YouTube that demand a lot of bandwidth. All of these applications need a lot of capacity, fast transmission rates, and low latency [4]. Therefore, high transmission speed, wide bandwidth, and dependable mobility have become prerequisites for today's wireless communication systems [5, 6].

Nevertheless, as the operational Radio Frequency (RF) spectrum experiences escalating congestion and maneuvering within the higher frequency band becomes progressively intricate, fulfilling these requirements directly proves challenging [7]. Two strategies have been identified to address these limitations. The first approach uses the idea of Micro/Pico cells, in which the size of the cell is lowered to support a higher number of subscribers [8]. The second option is to operate in a higher frequency band as an alternative to reducing spectral congestion in the lower frequency range [9]. Nevertheless, implementing these ideas comes with a number of difficulties. Reducing the size of a cell to serve more customers means that additional Base Stations (BSs) are needed to cover the whole service area, which raises the total cost [10].

However, choosing to operate at a greater frequency range results in increased costs for equipment, installation, and maintenance. In recent decades, optical fiber communication has become an essential part of communication systems, demonstrating its superiority as a vital transmission mechanism in contemporary telecommunication networks [11, 12].

As a result, choosing optical fiber over copper cables for wireless networks makes it easier to design new locations and greatly eases the actual deployment of equipment. Furthermore, the combination of wireless and optical networks provides benefits including improved physical security and resistance to fading [13]. The large amounts of data traffic, high data speeds, and large bandwidth requirements that are common in today's wireless communication networks can be effectively managed with this strategy. The suggested system architecture reduces system cost and complexity by using optical fiber as the transmission medium and implementing the complicated and expensive procedures at a Central Unit (CU) as opposed to the Base Station (BS)[14].

To cater to the burgeoning bandwidth requirements of individual users, the integration of optical and wireless networks is employed through a technique known as radio-over-fiber (RoF). RoF technology is presented as a viable and cost-effective solution to meet the escalating user bandwidth demands and wireless requirements in broadband, interactive, and multimedia wireless services. In RoF, an analog optical connection is utilized to convey information over optical fiber by transmitting modulated radiofrequency (RF) signals from the central station (CS) to the base station (BS) or remote antenna unit (RAU) [15]. The modulation process can take place either directly on the radio transmission or on an intermediary frequency. In simpler terms, RoF entails the conveyance of information through optical fiber by modulating light using a radio signal [16].

RoF can be used to set up a personal area network or high-speed wireless local area network. The particular applications dictate the frequency of radio signals transmitted by RoF systems, which varies greatly and usually falls within the GHz range [2]. Prior to being transmitted across the air in RoF systems, wireless signals are optically transferred between a Central Station (CS) and a group of Base Stations (BSs). The majority of signal processing duties, including as coding, multiplexing, RF generation, and modulation, are handled by the Central Office (CO), which increases the BS's cost-effectiveness. Every base station (BS) is set up to establish a radio link with a minimum of one user's mobile station that is within the BS's radio range. As a result, RoF is set to be a crucial technology in the years to come [17].

An extensive analysis of Radio over Fibre (RoF) technology and its incorporation into wireless networks of communication is presented in this research. It starts out by providing thorough explanations of RoF technology, including its underlying concepts, modulation methods, and technical nuances. This investigation highlights the main issues that modern wireless networks must deal with, namely spectral congestion and RF spectrum constraints. In order to properly manage data traffic, high speeds, and bandwidth requirements, the article suggests integrating optical fibre into wireless systems as a solution to these difficulties.

It explores the technical details of RoF systems in more detail, giving detailed explanations of modulation methods and the importance of optical filters. The study also performs a thorough evaluation and analysis of pertinent academic research, summarising findings, techniques, and advantages and disadvantages. Lastly, it identifies directions for further study and research with the goal of advancing RoF systems and contemporary wireless networks. All things considered, this work makes a substantial contribution to the field of wireless communication research by providing answers, recommendations, and new avenues for investigation into the integration of RoF technology.

2. RADIO OVER FIBER

The first uses of Radio over Fiber (RoF) occurred in mobile and cordless phone services in 1990. This technology differs greatly from the traditional optical fiber communication system in terms of implementation, even if it may be able to address some of the issues with ultra-high-speed wireless systems for mobile communication. Radio over fiber technology has a wide range of possible applications, despite its underutilization [18, 19].

Different roles are involved in the coordination between the Base Station (BS) and the Central Station (CS). The CS is in charge of the creation of signals and modulation methods, using a transmitter that consists of a laser and a data source. Conversely, the BS, which has a receiver that is essentially made up of a photodiode, picks up signals from the Optical Fiber Network (OFN). The electrical signal is transformed into an optical signal inside the CS, which then uses OFN to link to the BSs. The OFN includes remote nodes that use demultiplexing to distribute the amplified optical signal to the base stations. The optical signal is converted back into the electrical domain for end-user delivery via a small antenna device called a remote antenna, which is housed in the base station (BS). The BS receives end-user radio signals, transforms them into the optical domain, and sends the data back to the CS via OFN all at the same time. The goal of this complex procedure is to improve the dispersion of radio frequency (RF) signals between control stations and base stations [20].

Long-distance transmission issues can be resolved by the optically linked system, especially in underserved areas and dead coverage areas like tunnels, where macro base stations frequently fail to provide sufficient coverage. By extending coverage to places where wireless signal transmission is impossible due to wave propagation characteristics, such as hilly terrains, subterranean spaces, tunnels, and isolated regions, the implementation of RoF technology becomes crucial in addressing dead zones [21]. Figure (1) shows Optical Communication Architectures: Exploring Radio-over-Fiber (RoF) Systems for Backhaul, Fronthaul, and Converged Access Networks.

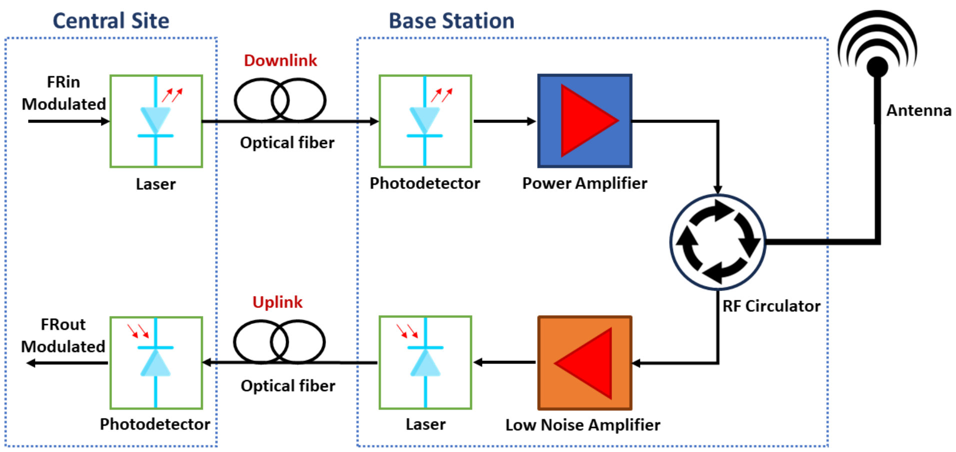

Figure 1. shows A typical RoF system.[22].

When taking into account the baseband-to-modulated RF format function, the conversion of electrical signals to optical signals simplifies the integration and upgrading of signals with RoF. Even while copper coaxial and other conventional transmission media might not completely replace optical fiber, it is by far the most effective and useful option in situations where factors like system transparency, RF power loss, and future improvements are crucial. Even though RoF has a lot of potential, further research in this area is necessary before it can be used widely [23].

Direct modulation and external modulation are the two main types of modulation that are often used in RoF systems. The RF signal directly fluctuates in the direct modulation format in accordance with the semiconductor laser diode's bias current. Conversely, external modulators that are fitted with Mach-Zehnder or electro-absorption interferometers are integrated for modulation functions [24].

3. MODULATION IN OPTICAL SYSTEM

In the fields of electronics and telecommunication, modulation is the process of changing one or more properties of cyclic waveforms by another signal, known as the modulation signal, is a standard procedure.

Effective information conveying frequently uses this modulation strategy. It's important to remember that, as shown in Figure (2), the carrier frequency must be at least twice that of the modulation signal. The figure shows several types of modulation.

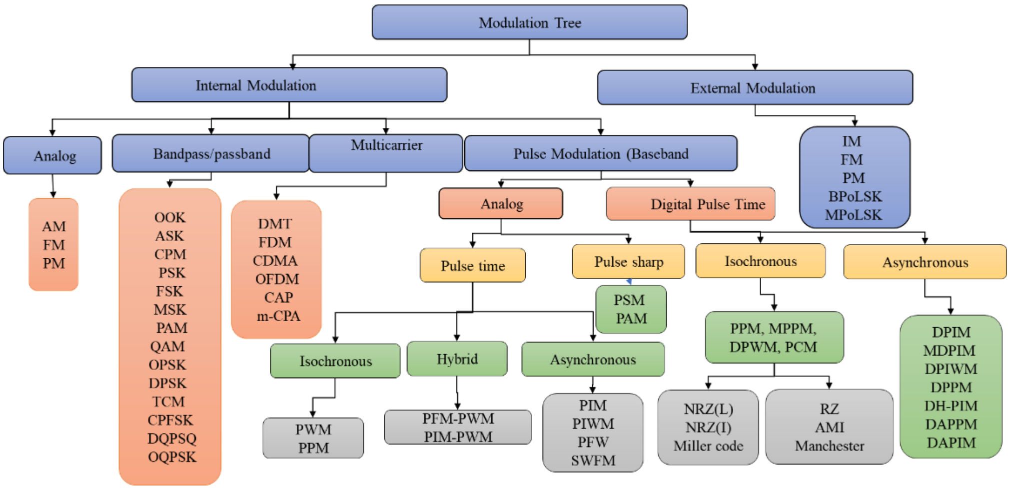

Figure 2. Modulation tree[25].

These modulation methods can be categorized into two main groups:

3.1 Direct Modulation

Using this technique, the RF signal directly modulates the light source's brightness. The RF signal is then recovered by direct detection at the photodetector (PD). Known as intensity modulation direct detection (IMDD), this method is acknowledged as the most basic and economical way to optically transmit radio frequency signals. It is important to properly alter the RF signal before transmission. The photocurrent that is produced is a precise duplicate of the RF signal that is modulating; it is immediately obtained in the first phase following its passage through the fiber and its direct detection on a photodetector [26]. The optical signal received is subsequently transformed into an RF signal through the combined action of the photodetector (PD) and a band-pass amplifier located at the distant antenna position (as depicted in Figures 3). This method offers significant advantages as it is straightforward, robust, and cost-effective. Furthermore, when a low-dispersion fiber is employed alongside an external modulator, the system achieves linearity. Although the transmitter architecture is remarkably uncomplicated and economical, its performance is notably affected by shortcomings in laser modulation. In commercially available Radio-over-Fiber (RoF) systems, a laser diode undergoes direct microwave intensity modulation, catering to restricted RFs (typically up to 2 GHz), suitable for wireless services like Global System for Mobile Communication (GSM) and Universal Mobile Telecommunications System (UMTS). As such, one significant limitation of this technology is that it cannot operate efficiently at higher microwave frequencies. This limitation results from fading in the modulation sidebands caused by the laser diode's limited modulation bandwidth and the effect of fiber dispersion. To overcome this obstacle, sophisticated ultra-high-frequency optical analogue transmitters and receivers must be used in conjunction with accurate fiber dispersion compensation techniques (Figure 3) [27]

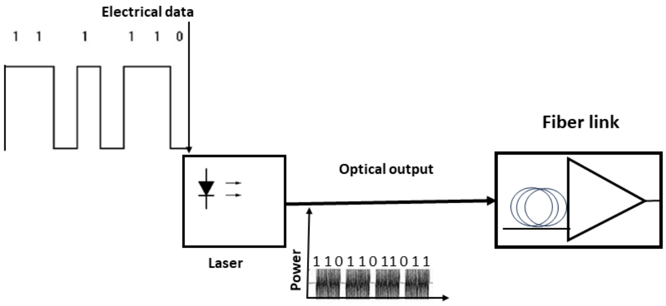

Figure 3. Direct Modulation[28].

3.2 External Modulation

Out of all systems, optical external modulation (Figure 4) is a superb option for producing optical mm-wave signals with outstanding spectrum purity since it is a straightforward method of getting around the drawbacks of direct modulation. High radio frequency frequencies (over 10 GHz) are often used for external modulation. An external modulator modifies the laser light with an intermediate frequency (IF) or, in the most basic arrangement, a mm-wave tone, after a continuous wave (CW) laser [29]. While direct modulation is advantageous for cost-effective transmitters, it introduces challenges such as excessive chromatic dispersions and undesirable wavelength chirping, particularly at high speeds. Consequently, external modulation is favored. The Mach-Zehnder Modulator (MZM) is a preferred modulator, often referred to as an electrical-to-optical (EO) converter. Recent research in the MZM domain indicates its versatility beyond being a simple EO converter. It has the potential to serve purposes such as linearization and compensation for dispersion introduced as the signal traverses an optical path. Specially designed MZMs have emerged as solutions capable of addressing both of these issues simultaneously [30]. The limited switching speed and amplitude noise of the laser source.

For this kind of modulation, the best strategy to reduce unwanted effects is to move the modulation process away from the laser source and towards an interferometer-based arrangement, like the Mach-Zehnder interferometer (MZI). The MZI operates like a switch; signals with a value of 1 are accepted while those with a value of 0 are rejected. Choosing external modulation allows larger data rates than choosing intensity modulation. Furthermore, additional improvements can be achieved by adjusting the optical carrier's phase and amplitude [31].

Before being transmitted, the laser source's optical signal must be modified by adding signal information. Visual alteration is the term used to describe this process most often. The two primary types of systems that use this technology are external modulation systems and direct modulation systems. A digital signal with a bit range of up to one gigabit per second is directly correlated with the adjustment of an optical signal [32].

The refractive index difference can be adjusted to match the high optical frequencies used in lasers. However, there's a chance that this modification will cause variations in the output mode and frequency. The operational current in the architectural designs needs to be kept as low as possible in order to exceed the chirp frequency. But minimizing the chirp frequency also lowers the extinction rate of the modulator, which lowers the signal-to-noise ratio [33].

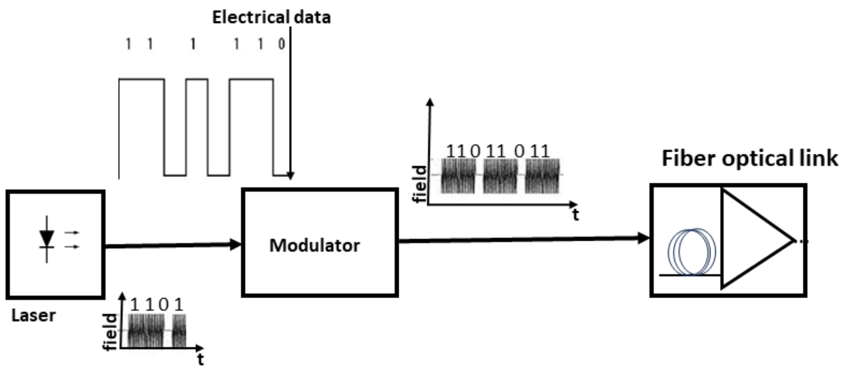

Figure 4. External Modulation[28].

4. OPTICAL FILTERS

An extensive summary of the different optical filters used in various applications may be found in the Table (1). The components, uses, and functionalities of each filter type are explained. In the domains of scientific study, imaging, and telecommunications, where exact control over light wavelengths is critical, an understanding of these many optical filters is vital. Fabry-Perot, Fiber-Bragg Grating, Tunable, Absorptive, Band Pass, Infrared, Ultraviolet, and Dichroic filters are among the filters that are covered. The purpose of this compilation is to provide experts and hobbyists in the fields of optics and allied fields with a reference manual.

Table 1. Different optical filters

Filter Type	Description
Fabry-Perot Filter	Also known as a "Thin-film filter," it consists of two flat highly reflective mirrors spaced some distance apart, forming a Fabry-Perot interferometer. A light signal is incident on the left part of the interferometer. Some light passes through the cavity, some exits the cavity, and the remaining light is reflected[34].
Fiber-Bragg Grating Filter	An element of WDM systems, the Fiber Bragg Grating performs multiplexing and demultiplexing functions. When light passes through a grating, certain wavelengths interfere effectively, while others are destructively interfered with[35].
Tunable Filter	Utilizes two main technologies: MEMS and Bragg grating. Various types include liquid-crystal tunable filter, acousto-optics tunable filter, and linear variable filter. Applied in drug discovery, microplate readers, gemology, and other fields[36].
Absorptive Filter	Typically constructed from glass with added inorganic or organic compounds. These compounds absorb specific wavelengths of light and transmit others. Plastic can also be used to create a gel filter, which is lighter and more cost-effective than glass-based filters[37].
Band Pass Filter	Allows certain wavelengths to pass through while blocking others. The width of the band pass filter in the wavelength range is less than an angstrom and a few hundred nanometers. Combines LP and SP filter characteristics to block noise and optimize receiver sensitivity in single optical channel applications[38].
Infrared Filter	Infrared light covers a broader range of wavelengths than visible light, from 300 GHz to 430 THz. Used in infrared photography, metrology, thermography, and heating applications. Infrared is divided into near-infrared and far-infrared.
Ultraviolet Filter	Ultraviolet wavelengths range from 400 nm to 100 nm, subdivided into Ultraviolet A (400-315 nm), B (315-280 nm), and C (280-100 nm). UV filters, with RED, GREEN, and BLUE layers, are employed in diverse applications. Ultraviolet light is shorter than visible light but longer than X-rays[39].
Dichroic Filter	Transmits light based on wavelength; it allows light within a specific wavelength range to pass through while blocking light outside that range. Used for long pass and short pass applications, providing selective transmission of light[40].

5. ROF'S CHALLENGE IN 6G COMMUNICATION

The application of Sub-THz technology presents potential and challenges for 6G communication. Even though Sub-THz frequencies offer enormous data-rate transmission capacities, establishing dependable mobile user communication in deployment settings is fraught with difficulties. The propagation characteristics of Sub-THz signals present a significant difficulty since they are characterised by specular and sparse channels with dominant multipaths coming from reflections or line-of-sight (LOS). These difficulties are made even worse by diffraction and penetration losses. Although they are limited by existing technology restrictions, increasing broadcast power or improving receiver sensitivity are viable alternatives to guarantee sufficient signal-to-noise ratio (SNR) for Sub-THz communication [41].

Furthermore, in order to monitor prevailing propagation patterns, it becomes imperative to deploy high-gain and beam-steerable antennas at both the transmitter (Tx) and receiver (Rx) ends. However, obstacles like the lack of commercially available RoF units at Sub-THz frequencies and the difficulty of achieving phase coherence in measurements prevent the use of Radio over Fibre (RoF) schemes, which could address issues like long-range communication and frequency extension. These difficulties highlight how difficult it is to put RoF solutions for Sub-THz communication in 6G networks into practice [42].

6. RELATED WORKS

Table (2) summarizes key findings, methodologies, objectives/problems, weaknesses, and strengths from various scholarly works related to Radio over Fiber (RoF) systems and optical communication. Each row represents a specific study conducted by different authors, offering insights into diverse aspects of optical communication technology. The organized information allows for a comprehensive overview of the state of research in this field, highlighting both challenges and advancements. This table serves as a valuable resource for individuals interested in understanding the nuances of RoF systems, modulation techniques, and the impact of various factors on system performance.

Table 2. Related Works Analysis

Author	Key Findings	Methodology	Objectives/Problems	Weaknesses	Strengths
Hussein Ahmed Mahmood (2019) [43]	FBG improves performance	SCM/ASK, FBG	Chromatic dispersion impact	Specific fiber length of 10 km	Better performance observed
Musaddak M. Abdul Zahra (2022) [44]	128 QAM susceptibility	RoF-MMW, 50 Gb/s, 128 QAM	Ultra-high-capacity transmission	BER not favorable for 128 QAM	Successful long transmission
Oratilwe Jothi (2022) [45]	256-QAM outperforms 16-QAM	SCM-OFDM at 10 Gbps	Enhance system capacities	Lower performance for 16-QAM, 64-QAM	Useful combination of SCM and RoF
AbdulNasser A. Abbood (2018) [46]	Dispersion limits high bit rate	OFDM with 16-QAM	High bit rate over long haul	Dispersion problem limits bit rate	Successful 20 Gbps transmission
Muhammad Usman Hadi (2019) [47]	D-RoF cost-effective	Bandpass sampling for 20 MHz LTE	Mitigate impairments in A-RoF	Cost of deploying D-RoF system	Supports transmission up to 70 km
Namita Kathpal (2018) [48]	MDRZ & CSRZ reduce signal degradation	Integrated alternate mark inversion modulation	Non-linear distortion in optical system	Rapid Q-factor decrease for MDRZ & CSRZ	Enhances data transmission up to 100 Gbps
Humam Hussien (2021) [49]	ISI in fiber due to non-linearities	DFSK with NRZ modulation	Growing demand for high data rates	ISI in previous architecture	Good results for different signals
Paramjot Singh (2018) [50]	CSRZ modulation technique at 3.2 attenuation	FSO based ROF-WDM system	High Q factor with low BER	CSRZ modulation at 3.2 attenuation	Suitable for topographical areas
Hussein Ahmed Mahmood (2018) [35]	Distortion with increased fiber length	RoF with DPSK modulation, WDM, ideal dispersion FBG	Efficient technique for baseband signal detection	Distortion with increased fiber length	Best performance with ideal dispersion FBG
Dr. Adnan Hussein Ali (2020) [51]	Limited dynamic range in optical-OFDM systems	ODSB modulation with 16-DWDM-ROF link	Non-linear effects in optical communication fibers	Limited dynamic range in optical-OFDM systems	Better performance with ODSB modulation
Marwah M. Kareem (2021) [22]	BER increases with fiber length	OFDM-RoF with 16-QAM modulation	Identifying minimum BER for 16-QAM modulation	BER increases with fiber length	Achieves fiber length of about 100 km
Honglin Ji (2020) [52]	D-RoF vs. A-RoF spectral efficiency	Theoretical analysis and experimental confirmation	Comparison of spectral efficiency between D-RoF and A-RoF	D-RoF considered low spectral efficiency	D-RoF offers exponential improvement in SNR
Badiaa Ait Ahmed (2019) [53]	Constraints on wavelength channel spacing	WDM RoF with FBG, EDFA, DPSK	Resolution of nonlinearity effects, signal loss, dispersion	Constraints on wavelength channel spacing	Good enhancement with DPSK in WDM RoF
Haoyu Yu (2022) [54]	NLIs and PAPRIs in RoF-based CN	Full-duplex RoF-based CN with WDM	Minimization of NLIs and PAPRIs	Prominent factors minimized	NLIs and PAPRIs minimized in model
Umar Farooq (2021) [55]	Chromatic dispersion affecting OFDM subcarriers	A-RoF 5G mm-wave system with LMS equalization	Equalization for OFDM subcarriers affected by chromatic dispersion	Chromatic dispersion affecting OFDM subcarriers	Equalization achieved communication distances
Namita Kathpal (2020) [56]	Non-linear effects in RoF system	8/32 RoF-BF with Bessel Filter	Reduction of FWM effect with Bessel Filter	Non-linear effects, specifically FWM	FWM sideband power decreased by 4 dBm
Drissa Kamissoko (2020) [57]	ODSB scheme limited to 30 km fiber length	Optical heterodyning with ODSB and OSSB schemes	Power fading effect due to interference and fiber CD	ODSB limited to 30 km fiber length	Supports up to 120 Gbps data rates over long distance
Rawa Muayad Mahmood (2022) [58]	Phase noise effect on DWDM-RoF system	DWDM-RoF architecture with varying phases	Effect of phase noise on mm-wave signal	Phase noise effect on DWDM-RoF system	Controlled phase imbalance reduces phase noise
Haleema Khalil (2021) [59]	BER at large distances approaches 1	ROF with NRZ, DB, CSRZ modulation	Choosing efficient modulation format for data transfer	BER at large distances approaches 1	NRZ performs well with high quality factors
Fabio Barros de Sousa (2021) [60]	Long-distance RoF communication	RoF DP-MZM system with NRZ, RZ, Gaussian	Design and investigation of RoF system	Long-distance RoF communication	Excellent BER and Q-factor values

Deepak S (2020) [61]	UESING EDFA each 10 km	OSSB modulation with unequal channel spacing	Minimization of ASE, nonlinearity, modulation effects	Eliminating ASE at 10 km distance	Lowest BER with OSSB modulation
Duc-Tan Tran (2021) [62]	QPSK for longer distance but low datarate	Simulated RoF link with QPSK, 16-QAM, 32-QAM, 64-QAM	Designing fronthaul link for cellular systems	QPSK for longer distance but low datarate	Various modulation schemes simulated

An examination of related studies in Radio over Fibre (RoF) technology demonstrates a wide variety of conclusions, approaches, advantages, and disadvantages. Principal discoveries encompass enhancements in efficacy via methodologies such as Fibre Bragg Grating (FBG), observations of modulation susceptibility like 128 QAM, and juxtapositions of modulation schemes like 256-QAM and 16-QAM. Methodologies encompassing topics including signal modulation, dispersion, and signal processing techniques span from theoretical analyses to experimental confirmations. While improvements in modulation efficiency, cost-effectiveness, and transmission capacity are among these studies' strong points, their drawbacks frequently centre on restrictions on system performance or particular modulation techniques. All things considered, these studies offer insightful information about how to best optimise RoF systems for different applications, underscoring the significance of further study in this area to solve current problems and enhance network capabilities.

7. CONCLUSIONS

This study explores the complex field of Radio over Fibre (RoF) technology and how it is essential to contemporary wireless networks. It starts by explaining the growing needs of our technologically advanced society for bandwidth and dependable mobility. RF spectrum restrictions and spectral congestion provide issues that can be addressed by the development of RoF technology. The discussion includes modulation strategies used in optical systems, highlighting the differences between external and direct modulation approaches, each of which has pros and cons of its own. Moreover, the importance of optical filters in regulating light wavelengths is emphasised, providing an understanding of their various uses in the fields of science, imaging, and telecommunication. After that, the story changes to focus on how 6G connectivity is developing and emphasises the advantages and disadvantages of Sub-THz technology. Last but not least, the synthesis of related works offers a thorough summary of significant discoveries and methodology in the field, opening the door to additional research and development in optical communication and RoF systems. Radio over Fibre (RoF) technology can be made even more advanced in the future by incorporating it into wireless communication networks, implementing sophisticated signal processing in the optical domain, integrating it with 6G communication systems, reducing the size of RoF transceivers, improving security and energy efficiency, and supporting standardisation initiatives for smooth integration with wireless standards.

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