System Modelling and Improvement of Radio over Fiber of the Internet of Things through Quantum Entanglement

By

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Declaration

I hereby declare that the contents of this thesis are original and solely the result of my own work and have not been submitted, in whole or in part, for any other degree or professional qualification, except where explicitly stated otherwise in the text. Parts of this work have been published in my own publications listed in the pages below.

Shakir Salman Ahmad

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Abstract

The first part of the contribution that is made by this thesis is to expand on how new paradigms of fire detection in the IoT environment have been created. Clarifying how it had intended the physical distribution of the Remote Antenna Unit (DRAU) architecture. These observations show how the architectures of distributed RAUs protocols of BRAUS in IoT-RoF are expanded to new selection metrics. Under distance two performance measures have been considered and they include number of RAUs and fiber optic attenuation, path loss factor. Following the simulation and numerical analysis of the presented desirable protocols the obtained results indicate that the outage probability minimization of the desirable protocols is less than the work [18]by 65% On the equal basis, bandwidth efficiency of the desirable protocols is found to be higher than recent works 34%. The second contribution of this thesis is the proposed A new quantum MAC protocol has been designed and implemented here in this thesis and named as Quantum Entanglement-based MAC protocol, abbreviated as QE-MAC. Four entangled states are used to form the control packets of MAC classical protocol and the transmitted data on the classical channel. ACK, RTS and CTS control packets are not employed here but state transitions are used instead. This approach has some benefits in that it minimizes the delay and collision issues conventionally associated with control packets and in result boosts the performance of the networks. The delay, duty cycle, and power consumptions of the proposed QE-MAC protocol are defined and calculated as follows: For this reason, all of these reduce the proposed approach delay and power consumption by 35% compared to the related work in the literature. The third contribution of this thesis is the analysis of the performance of the Radio-over Fiber (RoF) with energy harvesting (EH) of cooperative communication technique. The influence of small, large-scale fading, and large-scale fading is analyzed by using mathematical modeling. For the Radio-over Fiber (RoF) with energy harvesting (EH) of cooperative communication technique, we use outage probability as our performance measure. Last but not the least, the results depict that cooperative communication enhances the capacity of the system than the direct traditional communication with energy harvesting by 22%. The fourth contribution brings the ICHC-RoF into the field for the first time. The Outage probability mathematical model is described next: Furthermore, an analysis of the throughput performance of the offers' proposed protocol is also derived mathematically. Theoretical calculations reveal that the proposed ICHC-RoF system has superior performance and enhancements of 35% from simulations.

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List of Abbreviations

5G	5th Generation (Of Wireless Technology)
AF	WireleAmplify-And-Forward
BER	Bit Error Rate
BF	Baseband Frequency
BRAUS	Best Remote Antenna Unit Selection
BS	Base Station
CA-OFDM	Carrier Aggression-Orthogonal Frequency Division Multiplexing
CATV	Cable Television
CS	Central Station
DAS	Distributed Antenna Systems
DRAU	Distribution Of Remote Antenna Units
DWDM	Dense - Wavelength Division Multiplexing
EH	Energy Harvesting
EML	Electro-Absorption Modulated Laser
EVM	Error Vector Magnitude
FDM	Frequency Division Multiplexing
FSO	Free Space Optical
FTTH	Fibre To the Home
HFC	Hybrid Fiber-Coaxial
IF	Intermediate Frequency
IFoF	Intermediate Frequency Over Fiber
IMD	Intermodulation Distortion
IOT	Internet Of Things
LTE	Long-Term Evolution
MAC	Medium Access Control
MN	Master Nodes
mm-wave	Millimeter Wave
MRC	Master Remote Central
MZM	Mach-Zehnder Modulator
NOMA	Non-Orthogonal Multiple Access
OEO	Optoelectronic Oscillation
OFC	Optical Frequency Comb
OFDM	Orthogonal Frequency-Division Multiplexing
OOK	On/Off Keying
OTDM	Orthogonal Time-Division Multiplexing
PAPR	Peak To Average Power Ratio
PoF	Power-Over-Fiber

PON	Passive Optical Network
QE-MAC	Quantum Entanglement- Media Access Control
QPSK	Quadrature Phase Shift Keying
RAU	Remote Antenna Unit
RF	Radio Frequency
RFoF	Radio Frequency Over Fiber
RoF	Radio over Fiber
RoF-IoT	Radio Over Fiber-Internet of Things
Satcom	Satellite Communication
SFDR	Spurious-Free Dynamic Range
S-RAU	Selected Remote Antenna Unit
SMF	Single Mode Fiber
SOA	Semiconductor Optical Amplifiers
SOI	Silicon-On-Insulator
SPOF	Single Point of Failure
VCSEL	Vertical-Cavity Surface-Emitting Laser
WDM	Wavelength Division Multiplexing
WSN	Wireless Sensor Networks
WSS	Wavelength Selective Switch

List of Symbols

Symbol	**Definition**
i, j	Indices representing communication links (e.g., sensor-to-RAU)
$G_{i,j}$ or $'i, j$	Antenna gain over the $i - j$ link (typically set to 3)
R_o	Required transmission rate to bandwidth ratio (typically 0.5)
$d_{i,j}$	Distance over the $i - j$ link (range: 5–50 m)
α	Path-loss factor (range: 2–6)
SNR	Signal-to-Noise Ratio (range: 0–50 dB)
OSNR	Optical Signal-to-Noise Ratio (range: 0–50 dB)
L_{total}	Total length of the optical fiber (range: 0–50 km)
γ	Nonlinearity coefficient (range: 1–2)
B_{OF}	Optical fiber bandwidth (typically 32 GHz)
R	Number of Remote Antenna Units (RAUs) (range: 5–25)
$\rho_{i,j}$	Random variable representing channel gain (exponentially distributed)
$\sigma^2_{i,j}$	Variance, often includes path-loss and distance: $d_{i,j}^{-\alpha}$
P_T	Transmission power
P_N	Noise power
$R_{i,j}$	Transmission rate over link $i - j$
$P_{i,j}^{\text{out}}$	Outage probability over link $i - j$
$P_{i,j}^{s}$	Successful transmission probability over link $i - j$
R_b	Bit rate
B_{ref}	Reference bandwidth for OSNR calculation
β_{thd}	Threshold distance or signal limit
β_{max}	Maximum signal link distance from sensor to RAU
L_{max}	Maximum fiber link length
ω	Ratio $\omega = \frac{L_{\text{total}}}{L_{\text{max}}}$
$P_{\beta_{\text{max}}}(\omega\beta_{\text{thd}})$	Probability of selecting best RAU path
BE_{BRAUS}	Bandwidth Efficiency of the BRAUS protocol

Chapter 1

Introduction

1.1 Background and Motivation

As the acceptance of the internet has escalated and mobile technology has developed at a fast pace, individuals are becoming more dependent on online resources and services. With the rising important matter of Internet and the high speed advancement of mobile technology, people have become increasingly reliant on online services. As a result,the modern technological surroundings require more and more high-speed, and high-capacity communication facilities. Fiber optic communication systems offer the greatest data transmission capability, making them a crucial component of modern telecommunications[1]. Because of numerous constraints such as geographical situation, economical equilibrium, provider's tactic, and damage circumstances in the event of a disaster, optical fiber-based high-speed links, like fiber-to-the-home, cannot be deployed at all places[2]. As a result, a radio transmission connection is deemed appropriate for combining huge network traffic, which has advantages in system deployment like flexible layout and ease of installation. To deliver sufficient bandwidth to individual users, optical and wireless networks are combined. This approach is referred to as radio-over-fiber (RoF) technology[3]. The progress of communication technologies and network system development in terms of computational intelligence, Wireless Sensors networks (WSN) and the Internet of Things (IoT) are undergoing steady advancement. In what follows, the integration of Radio over Fiber technology gives vast potential for developing more efficient and effective communication systems. An economically viable and a technically promising method has been the railway of frequency (RoF) technology. Radio-over-Fiber (RoF) is an analog optical transmission that transports the information in the modulated of radio-frequency form. These are delivered to the optical fiber to an antenna unit called Remote Antenna Unit (RAU) or a Base Station (BS) by a Central Office (CO) or Central Station (CS) [4]. Radio-over-Fiber (RoF) concept is an understated concept and extends beyond the mechanical scope of its deployment. It is already the unified amalgamation of intelligence, control and signal-processing Ratios that were initially intended to interpolate and supplement conventional communication Systems. This integration makes both functionalities and flexibility strong. The given configuration is a very close one in comparison with the complexity of the access-node sites that tend to be common in the traditional cellular environments. It is opposite the centralized design or the ones normally related to cloud-supported structures or Central Office (CO) offices. This transformation can be taken as a unified model in which strong operational advantages are attained in a variety of areas. The best of the benefits that were achieved during the convergence of configuration paradigms is the enhancement of ease of management. Organisations also simplify the delivery of the product because by establishing a single configuration framework, they ensure that the process of operations is less complex. This integration further enables integrated view and enforcement of Identity and Access Management (IAM) policies, thus enabling a typical auditing[3]. The need to handle and transfer an increasing amount of data and the desire to rationally distribute the available resources drive the development of 5G networks and the Internet of Things (IoT) and the emergence of other technologies. At the same time these innovations aim at containing operational costs and maintaining continuity of service quality. These systems represent a pioneering technological paradigm shift with the potential to reshape communication technologies and network systems entirely. With a focus on end-users and supervision, these systems demonstrate significant potential in addressing existing and future Quality of Service (QoS) challenges. Emerging communication technologies suggest possible ways to improve QoS through supporting high-quality transmission for a huge population[5]. Moreover, Radio-over-Fiber can improve the privacy and security of end-users. The fiber optic technology enables the transfer of sensitive information in large distances to a centralized point. This ensures that it is minimally dependent on intricate security provisions in the wider communication system thus reducing the risks of data loss, and intrusions of unauthorized parties. Hence, making it important in military WSN circumstances, where data confidentiality is crucial.The convergence of Radio on Fiber (RoF) technology to Wireless Sensor Networks (WSNe) and the Internet of Things (IoT) points to the paradigmatic change and the actual practice of communication in modernity. The synergy facilitates real-time data transfer as well as increases the overall throughput and strengthens system reliability. Besides, it also reinforces end-user security and improves the efficiency of operations.The Internet of Things (IoT) and Wireless Sensor Networks (WSNs) are convergence platforms that are created to encounter the complexities which bedevil the modern communication systems. They bring huge benefits to individual users and greater communities through the combined capabilities to provide reliable and secure and always-on connectivity.[6].

1.2 Problem Statement

The four regions that make up the network topology of WSN or IoT technology in combination with RoF are sensors (IoT devices), remote antenna units (RAUs), optical fiber, and the central office (CO). These parts work together as follows: Data is sent to the RAU via sensors connected to the RAU through a wireless link. The RAU has a DAC converter and is physically linked to the fiber optic network. After that, the data is sent to the CO through a fiber optic link for additional processing and analysis. There are numerous challenges in integrating Radio-over-Fiber (RoF) with WSN and IoT devices. These challenges can be recapped as follows:

1. Communication Protocol: The combination of Wireless Sensor Networks (WSN) and Radio over Fiber (RoF) may be discussed as a new paradigm, and this fact preconditions the rise of issues connected with the enhancement of a sufficient communication layer, able to ensure a stable operation of the network.

2. Communication Regulation: A strictly performed protocol is necessary in to maintain a steadfast existence of sharing information among the sensors and the Remote Antenna Unit (RAU). Such a protocol should be designed to eliminate the impairment of data loss and avert the outages of the links.

3. Bandwidth Efficiency: One of the most critical factors is bandwidth efficiency due to the limited availability of frequency resources. Optimizing bandwidth utilization is essential for achieving high performance in the network.

4. The MAC protocol: Deployment of IEEE 802.11 on Radio-over-Fiber (RoF) network is associated with significant changes, mainly those that relate to medium access control (MAC) protocols. IEEE 802.11 MAC has been

designed with the propagation delays assumptions of less than 1 picosecond, whereas RoF add a delay of about 5 picoseconds per kilometer of optical fiber

5. Delay: Minimizing transmission delays is essential to ensure high data rates and timely delivery. Reducing latency is a critical aspect of RoF networks, particularly for real-time applications.

6. Power Management: Power in the field of wireless sensor networks (WSN) is a scarce resource. Therefore, designing an efficient power management protocol is crucial to the extension of life span of the network and increasing the efficiency.

7. Multi-Source Transmission: Efficiently utilizing channel resources while allowing multiple sensors to transmit data simultaneously requires an optimized transmission strategy. Proper regulation ensures minimal interference and maximizes channel efficiency.

8. Energy Harvesting: Given the restrictions of battery life, most important thing of the WSN-RoF integration is that it enables sensors to gather energy from their surroundings. Therefore, network sustainability can be significantly enhanced by putting the energy-harvesting systems into place.

A new communication scenario and protocol should be devised to tackle the above-mentioned issues while combining WSN with RoF. Therefore, this thesis proposes a novel design paradigm that enables flexible communication between WSN and RoF. For successful transmission to happen between the sensors and RAUs, the suggested paradigm aims to minimize the outage probability. Bandwidth efficiency is also improved by integrating cooperative communication. Furthermore, a novel Quantum MAC protocol is presented to improve duty cycle and power consumption while reducing delay and jitter between WSN and RoF. Subsequently, this thesis suggests two novel protocols for WSN over RoF, one that makes effective use of multi-source transmission and the other that permits sensors to gather energy together.

1.3 Aim and Objectives

This study seeks to improve a new and effective communication architecture for combining WSN with RoF. The ultimate goal is to ensure smooth communication between sensors and RAUs while bypassing the main issues like outage probability, delay, power consumption, bandwidth efficiency, and energy harvesting. To accomplish this target,this thesis will focus on the following interrelated objectives:

Objective 1: Designing new cooperative communication for WSN over RoF (Chapter 3)

- The study under consideration explores the modeling and designing of the innovative cooperative communication structure that can be applicable to Wireless Sensor Networks (WSNs) that are operated via Radio-over-Fiber (RoF) networks. As an example of its use, early fire detection is advanced using the proposed system, which adds to camera sensors or other available suitable sensing technologies.
- In the RoF-IoT environment, the BRAUS1 algorithm was proposed in order to enhance capabilites for the system. The optimisation criterion will involve three variables which include; the total number of Remote Antennae Units (RAU) machines, the existence of master nodes and distances between the communication links necessary.
- The outage probability of the suggested protocol, BRAUS, was lowered by 65% in comparison to recent work after being mathematically modeled and driven.

Objective 2: Designing new MAC Quantum protocol for WSN over RoF (Chapter 4)

- Recently a new architecture of using quantum entanglement in IoT-RoF has been introduced. In this architecture, edge sensors will be gathering environmental data on a continuous basis and these data will be passed to a targeted decision making module to be more thoroughly analyzed so that a suitable course of action may be taken.
- The study proposes an Internet-of-Things (IoT) with Radio over Fiber (RoF) architecture that will combine the use of entanglement-based quantum communications and classical connections. There are two modalities of communication the first one is a classical one used to carry the data and the second one is a quantum-entangled Control information channel utilized in delivering information. procedure. The newly analytically evaluated protocol is a Quantum Entanglement-based MAC protocol (QE-MAC) which was proven to reduce the underlying latency by 35% compared to the current methods.

- The QE-duty MAC protocol and consequent power consumption could be simultaneously reduced by up to 35% compared to previous study results and provide the significant benefit in performance.

Objective 3: Designing new energy harvesting model for WSN over RoF (Chapter 5)

- New cooperative communication techniques for RoF with energy harvesting (EH) are designed.
- Two modes of communication are taken into consideration: cooperative communication and direct communication over the RoF system.
- An extensive mathematical model has been derived for the proposed protocol.

Objective 4: New protocol is designed names as Inter-Cluster Head Cooperation over Radio over Fiber (Chapter 6).

- Inter-Cluster Head Cooperation: Introduced and proposed the concept of Inter-Cluster Head Cooperation over Radio over Fiber (ICHC-RoF) as a novel approach to reduce outage probability.
- Developed a robust mathematical model to analyze and quantify the outage probability within the proposed ICHC-RoF framework.
- A mathematical analysis of throughput for the proposed protocol, providing a quantitative assessment of the system's data transfer capabilities.

Upon thorough validation and evaluation of the proposed communication framework through rigorous testing, mathematical modeling, and comparative analysis with existing solutions, this research aims to provide verifiable evidence of achieving its objectives. The study aspires to make a substantial contribution to the advancement of efficient and reliable Wireless Sensor Networks (WSN) over Radio-over-Fiber (RoF). The proposed framework seeks to effectively address critical challenges such as outage probability, bandwidth efficiency, latency, power consumption, and energy harvesting. Through innovative cooperative communication, quantum-based MAC protocols, and energy-harvesting techniques, this research introduces novel solutions to enhance system performance. Additionally, the development of an Inter-Cluster Head Cooperation (ICHC) protocol is expected to further improve network reliability and efficiency. This study will providing a strong theoretical basis and practical insights for integration WSN with RoF,Leds to future advancements with high-performance, energy-efficient, and scalable communication networks.

1.4 Summery of Contributions

The following main contributions are outlined in this study:

1. The thesis presented a new paradigm design on early fire detection based on camera sensors with additional sensor technology as the RoF-IoT system.As part of the suggested design, sensors detected information concerning the environment they were in and relayed that information to a particular area in order to elicit an ideal response.An optimal remote antenna unit selection (BRAUS) cooperative protocol has been suggested, wherein the distance over different connections in RoF-IoT networks, the master nodes' number, and the quantity of RAUs are considered in the selection process.Analyzing the outage probability of BRAUS, the mathematical model put forward in the recent work proposes that the probability reduces to 65% below the probability of outages as calculated by the recently proposed protocol.The bandwidth efficiency has also been mathematically modeled and analyzed based on the proposed protocol BRAUS, and it is estimated that the efficiency of the suggested protocol is 34% higher than that of the current work.

2. According to the proposed configuration IoT-RoF quantum entanglement has a total of two paths, where one is a classical path for the purpose of data transmission and the other is the quantum entanglement link over which the MAC control packets are transmitted. To add, the latency in QE-MAC, the proposed protocol, has been modeled mathematically and reduced by 35% in contrast to previous research.In addition, the QE-duty MAC cycle and power consumption have been theoretically suggested and controlled, and it has been found that they are 35% less than those of previously worked studies.

3. The capability of the Radio over Fiber with Energy Harvesting to the cooperative communication system is examined in this work for the first time. Two modes of operating communication are taken into considerations; cooperative communication mode and the direct communication mode. The

analysis of the performance is performed through outage probability calculations, and the outage probabilities of both paradigms are evaluated.

4. Cooperative communication over RoF has been proposed to improve the energy efficiency of the whole system. In addition, a new communication scenario is proposed using a double source and double destination to forward data efficiently for remote antenna units. The proposed system shows better energy efficiency.

1.5 Research Methodology

The present study's research methodology is centred around the resolution of the propagation latency concern within the MAC protocol of RoF. The considered key issue is the high impact of the propagation latency on the network performance. This latency leads to high collisions, as well as spurious retransmissions and reduces the efficiency of the network in general.There are limiting the conventional MAC performance and offer the quantum entanglement as the remedial methodology framework. Specifically, the work develops one new Quantum Entanglement interpreted mechanism of MAC (QE-MAC), whose implementation is centered on the creation of entangled states that are shared over the multi-user network .Quantum teleportation plays a very important role in that case where there is a need to transport a quantum bit over a long distance in circumstances of latency, that is, the propagation of photons. Data is transferred using regular channels to designate the control packet inside the typical MAC protocol. The system uses four discrete base states of deliverance of data. The latency, duty cycle, and power consumption are developed and collected performance indicators relative to the QE-MAC protocol in study.A descriptive analysis of the metrics of the low-power IoT devices has been carried out with a heavy focus on power consumption, duty cycle, and latency. Having qualified these metrics by empirical measurement, the study is effective in outlining how to design, choose as well as deploy such devices. According to the results the suggested MAC protocol outperformed the conventional RoF MAC protocol. It showed a significant outcome of 35 % decrease in power consumption and latency.This demonstrates how well the suggested solution to the propagation delay issue that RoF MAC systems face works. The work to be discussed is the creation of a new communication system named as Radio-over-Fiber (RoF) network combining wireless and fiber optic technologies. The RoF network aims at offering highly-bandwidth and reliable connection between clouds of sensors in the Wireless Sensor Networks (WSNs) and the central office in a specified area. It carries out the research in a disciplined manner, starting with new paradigm design on fire detection in the (IoT). The current study is a continuation of the steps developed in the past surveys as it fixed the design of Distributed Remote Antenna Units (DRAU). It goes forward to ascertain the best placement of Remote Antenna Units (RAUs) in an IoT-RoF system that is facilitated by DRAU. This mission is fulfilled by the determination of new selection criteria designed to maximise the efficiency of the protocols.This study uses a broad mathematical model to investigate outage probability as well as bandwidth efficiency. Some key design parameters, thus delivered, include link distance, amount of Remote Antenna Units (RAUs), fiber-optic attenuation, and path-loss components, in particular, wavelength-dependent separation between RAUs or beamformers and the reference norm. The integrated type of assessment will provide a more accurate assessment of network performance under changing conditions of network operation. Simulation and numerical analysis show that the proposed scheme can reduce the outage probability by 65% and increase the bandwidth efficiency by 34%, demonstrating an impressive improvement over state-of-the-art schemes in facilitating IoT communication. Here we focus on a study of energy harvesting for remotely sited sensors to allow the sensors to collect energy for themselves without any physical connection. The study additionally brings a first-of-its-kind performance analysis of Radio-over Fibre (RoF) and energy harvesting (EH) in a collaborative communication framework. The research encompasses a detailed mathematical modeling of the impact of small- and large-scale fading phenomena. As a performance metric, the study focuses on outage probability for the Radio-over Fiber (RoF) system incorporating energy harvesting through cooperative communication.Analysis of the system shows that there exists a significant improvement of the performance of the system when contrasted with direct conventional communication architectures that also use energy harvesting. These outcomes underscore the potential values of implementing this kind of novel paradigm in the future communication networks.

1.6 Thesis Outlines

The thesis is structured as follows in its chapters.

Chapter 1: A comprehensive exposition of the research is presented, encompassing its rationale, goals, objectives, contributions, research methodology, and a synopsis of the thesis architecture.

Chapter 2: provides an in-depth analysis of the pertinent literature concerning Radio over Fiber (RoF), including its architectural designs, associated research, and a discourse on prospective avenues and obstacles.

Chapter 3: explores how the Distributed Remote Antenna Unit can perform better using Selection-based RoF-IoT Paradigm, with sections on communication structure, propagation modeling, and construction of BRAUS-based protocol, bandwidth efficiency, and results.

Chapter 4: investigates the delay in the MAC protocol of RoF, with a focus on Quantum Entanglement-based MAC, analyzing delays and power consumption, and presenting results.

Chapter 5: delves into energy harvesting for RoF, detailing the proposed system, outage probability, and results.

Chapter 6: explores the energy efficiency of cooperative communication over RoF, discussing the communication structure, energy efficiency in double sensor node cooperative communication, and presenting results.

Chapter 7: offers a conclusion and outlines potential future work, while the References section cites the sources used throughout the thesis.

1.7 Published Research Works

[1] S. S. Ahmad, H. Al-Raweshidy, and A. Alkhayyat, "Distributed remote antenna unit with selection-based of (RoF-IoT) paradigm: Performance improvement," *IET Communications*, Oct. 2022, Art no. cmu2.12524.
DOI: 10.1049/cmu2.12524, ISSN: 1751-8628, 1751-8636.

Available: https://ietresearch.onlinelibrary. wiley.com/doi/10.1049/cmu2.12524

[2] S. S. Ahmad, H. Al-Raweshidy, and R. Nilavalan, "Investigating delay of the media access control protocols for IoT-RoF using quantum entanglement," *IET Networks*, vol. 13, no. 4, pp. 324–337, Jul. 2024.
DOI: 10.1049/ntw2.12117, ISSN: 2047-4954, 2047-4962.

Available: https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/ntw2.12117

[3] S. S. Ahmad and H. Al-Raweshidy, "Energy harvesting with network coding technique of Radio over Fiber: Toward minimizing of outage probability," in *Lecture Notes in Networks and Systems: Proceedings of the Third International Conference on Computing and Communication Networks*, Singapore: Springer

Nature, 2024, pp. 433–442.
First Online: 22 Oct. 2024. DOI: 10.1007/978-981-97-2671-4_33

[4] S. S. Ahmad, H. Al-Raweshidy, and R. Nilavalan, "Inter-Cluster Head Co-operation over Radio over Fiber (ICHC-RoF): Reduction in power efficiency," acceptance at The First International Conference on Applications of Artificial Intelligence in Industry, Education, Health, and Sustainable Development 2025 (ICAAIIEHS 2025).

Chapter 2

Literature Review

2.1 Introduction

Lately, Internet users across the globe have been increasing at a fast rate.These two phenomena, a growing number of user bases interested in multimedia content on the one hand and a simultaneous increase in bandwidth requirements on the other, have put a considerable pressure on the existing networks infrastructure. Therefore, this has motivated service providers to come up with updated and efficient access network architectures. The spread of wireless devices: personal digital assistants (PDAs) and mobile phones, and laptops that have been developing steadily, but has been especially accelerated in the case of latency-dependent applications like real-time communication and streaming media. These trends have triggered a steep rise in the use of wireless telecommunications thus prompting a new strong demand of a higher wireless capacity with high latency and throughput. [7]. The promising solution is Radio over fiber (RoF), where data transmitted over wireless channel to RAU which allow data to flow over fiber optic to particular Central office(CO). Reconfigurable optics (RoF) is a model of the mixing of fiber optic with wireless network at the physical level.Radio-over-Fiber (RoF) integration Radio-frequency In Radio-over-Fiber (RoF) integration, optical fiber is used as an analog transmission medium to convey radio-frequency (RF) signals between a Central Office (CO) and a Remote Antenna Unit (RAU), or in the case of a Multi-Segment Unit (MSU), several Remote Antenna Units tied together. This sort of an architecture allows managing the network infrastructure centrally, the CO carries out access control to both optical and wireless communication realm[8]. The Radio-over-Fiber (RoF) systems form a category of optical networks, which permit wireless access by employing radio signals on an optical carrier. RoF architectures can be simply divided into two types depending on radio signal's frequency range post conversion: RF-over-Fiber (RFoF) and Intermediate Frequency-over-Fiber (IFoF). RFoF is used in the transmission of the high-frequency radio, usually more than 10 GHz and IFoF is applied in the transmission of intermediate frequency, which is usually less than 10 GHz. RF or IF signal can be directly modulated onto an optical carrier such as in both architectures or cascaded externally modulated onto an optical signal.Anitable distinctions of the two is signal processing in the base stations: In RFoF a signal is processed over the base station without conversion to the radio frequency, whereas in IFoF it is necessary to up transform the signal into the RF signal in the base station before transmission over the air.[9].

2.2 RoF Architecture

Radio-over-Fiber (RoF) networks primarily consist of three key components: The optical backhaul, the (RAU) with the wireless front end are these components.Stitching together of the architectural components of construction of a multi-tier radio-frequency over-the-air network would form the basis of its integration and interconnection.[10].Radio-over-Fiber (RoF) or the combination of optical and radio networks well discussed in the scientific literature. Some of the RoF architectures have appeared with each portraying unique advantage in regard to performance, scalability, and use of resources across the whole system.This review is a survey striking up the main architectures of Radio-over-Fiber (RoF). Especial attention is paid to their being used in Internet of Things (IoT) and Wireless Sensor Network (WSN) ecosystems.The explanation of the next section is the summary of the relative advantages and drawbacks of various architectural structures, thus describing their effectiveness in various deployments.The following inquiry, pursues the objective of systematically comparing the representative RoF architectures, to the extent of the advantages and shortcomings of each architecture and also their applicability to diverse deployment environments[11].

2.2.1 Radio over Free Space optical (RF/ FSO)

The FSO is characterized by one of the essential benefits an optimal performance of the system specified by the situation when it is used. The systems are capable

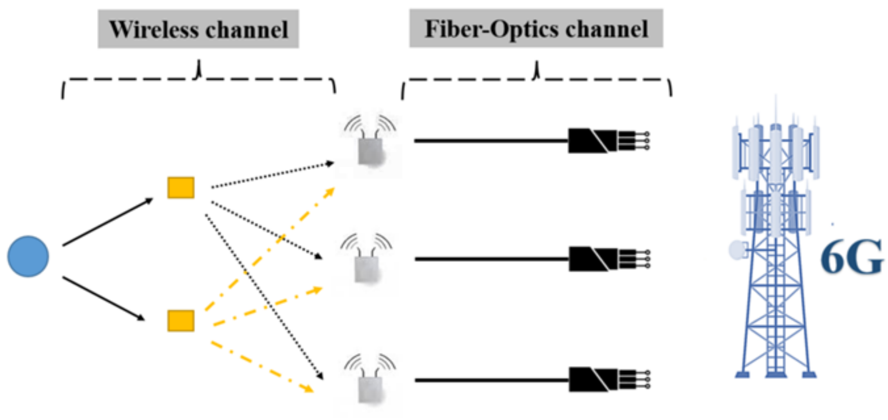

Figure 2.1: Radio over Free Space optical (RF/ FSO).

of operating in a location where the use of physical infrastructure like the optical fiber cables is impractical.This constraint can be affected by technology shortcoming or lack of logistical ability in some sites. As a result, FSO would be especially appealing in the deployment in rural or remote areas where no off the shelf fiber exists. Due to enormous advantages, free space optics (FSO) communication now stands as a viable contender of high-capacity broadband connection.A number of benefits are associated with the use of these systems; these are the ability to support high bit rates and facilitate full-duplex communications. They do not require licensing as well, and this makes it easy to comply with regulations. Also, they offer safe data transmission and an ability to be deployed easily. On the whole, all these attributes make FSO capable of supporting next-generation cellular systems with escalating bandwidth needs of multi-service and multi-application situations at a relatively low cost. Moreover, FSO has a feasible and cost effective solution of aspects like metropolitan area network (MAN) extensions, fronthaul, and backhaul in the wireless cellular networks [12]. The architecture of the RF/ FSO can be summarized as follow, the source (transmitter) may contain several Rdio Frequency users that are integrated with antennas. In the middle, the receive is RAUs which able of receiving RF signal sent from RF source. The received single converted to be conventional and suitable to be transmitted over FSO, the FSO device transmit optical signal to the received FSO deceive. Then, the signal down to the central office for further processing, as shown in the figure(2.1). Free Space Optics (FSO) systems form a mode of communications that offer large capacity, high speed transmission to long distances. They are however prone to local weather changes. Turbulence in the atmosphere, which is represented by the effects, including scintillation and beam wander, has the potential to damage the stability of the link along with its performance. The turbulence in the atmosphere is caused by a spatial variation In the air's refractive index in the path of optical transmission which generates random intensity fluctuation and consequently affects stability and reliability of the communication link[13].Along with the fading caused by turbulence, any imperfect alignment between the transmitter and the receiver may result in beam vibration, e.g. by building sway. This Intropic ends up in the form of pointing errors that consequently affect the effectiveness of the communication connection. Consequentially, these aspects lead to the lower reliability of the optical wireless technology as opposed to regular optical fiber technology. Also, these constraints detract the success of using Free Space Optics (FSO) as a single solution to fronthaul. Therefore a tendency of FSO being more appropriate when mixed with other technologies. [14].

2.2.2 Radio Frequency over Optical Fiber (RF/OF)

Optical fiber technology is highly suitable for various communication applications due to its superior reliability, high bandwidth capacity, and immunity to environmental factors. Unlike Free Space Optics (FSO), which is affected by atmospheric turbulence, weather conditions, and misalignment issues, optical fiber ensures stable and uninterrupted communication. It supports significantly higher data rates, making it ideal for high-speed internet, telecommunications, and data center networking. Additionally, optical fiber experiences minimal signal degradation over long distances, Deals with ultra-low latency and high reliability cannot be neglected with regard applicable to real time scenarios such as in the case of 5G networks. and financial transactions[15]. Unlike FSO, which suffers from beam wander and pointing errors caused by building sway, optical fiber maintains a secure physical connection, eliminating alignment issues. Its resistance to electromagnetic interference and eavesdropping further enhances its security, making it preferable for military, financial, and critical infrastructure communications. Moreover, optical fiber's ability to transmit data over vast distances without significant signal loss makes it the preferred choice for backbone networks, undersea cables, and long-haul communication links. The architecture of the RF/ OF can be summarized as follow, the source (transmitter) may contain several RF terminals that are integrated with antennas. Source transmit signal to RUA that is connected to converter, the converter convert signal from electrical signal to optical signal.Fiber-optic communication network is described as a network where the light waves move within a composite optical fiber with an aim of transferring information between two points.The CO manages all the signal processing and control see figure2.2. While optical fiber in (RoF) networks provides high bandwidth and reliability, it has several constraints compared to Free Space Optics (FSO). The high deployment cost of fiber, requiring extensive

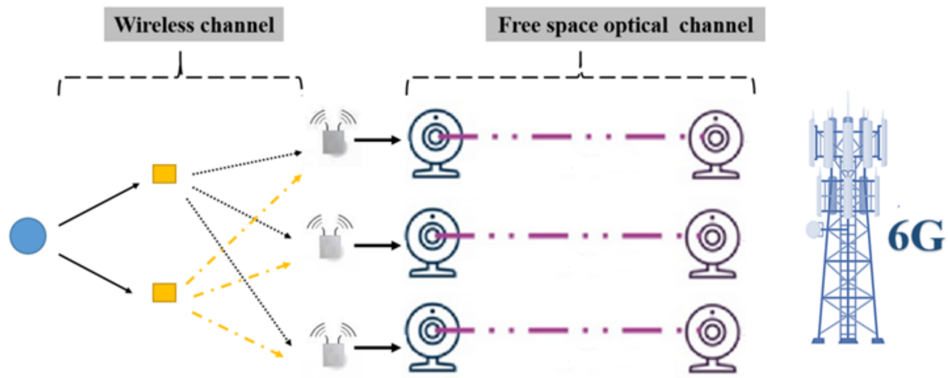

Figure 2.2: Radio Frequency over Optical Fiber (RF/OF).

trenching and infrastructure investment, makes it less feasible in remote or underdeveloped areas where FSO can be deployed more affordably[16]. Fiber networks also lack flexibility and scalability, as they require physical connections, making rapid expansion or reconfiguration difficult, whereas FSO can be easily adjusted. Urban deployment faces challenges such as right-of-way issues, underground congestion, and potential damage from construction or natural disasters, leading to costly repairs and service disruptions. Additionally, while optical fiber supports long-distance transmission, it requires repeaters or amplifiers for ultra-long-haul links, increasing complexity and power consumption. Unlike FSO, which can be quickly deployed for temporary or emergency links, optical fiber installations demand precise planning and fixed pathways, making them unsuitable for dynamic environments. Furthermore, active components like amplifiers and network management systems contribute to ongoing operational and maintenance costs.As much as optical fiber is still the foundation of large-capacity communication networks, Free Space Optics (FSO) is a viable and economical alternative where it would not be possible to physically implement fiber cable.[17].

2.2.3 Radio Frequency over Free Space and Optical Fiber (RF/ FSO/OF)

With the increasing demand for high-speed, reliable, and cost-effective communication systems, hybrid architectures that combine different transmission technologies have gained significant attention.One of the most interesting solutions is mixing Radio Frequency (RF) over Free Space Optics (FSO) and Optical Fiber technology. This architecture has been able to combine optical fiber,

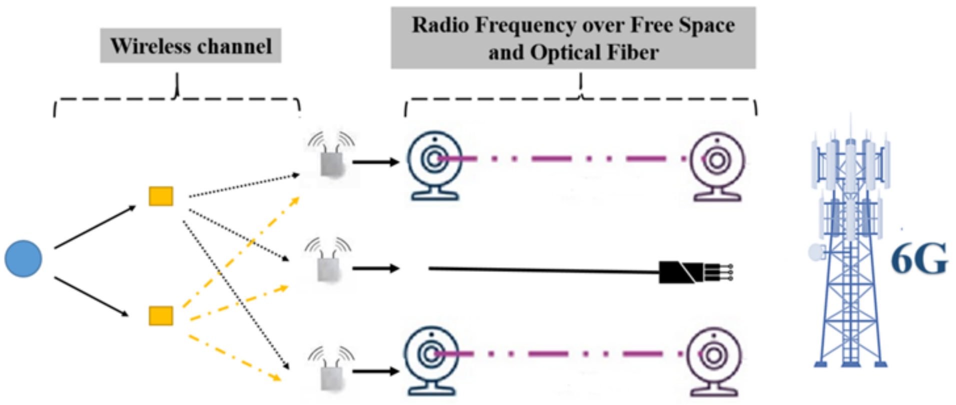

Figure 2.3: Radio Frequency over Free Space and Optical Fiber (RF/ FSO/OF).

FSO and RF, to connect to various environments without fault in the operations. .This has led to hybrid networks where parts of one type of network technology are incorporated in other, useful aspects of the other type and the drawbacks of each are kept at the barest minimum, which makes hybrid networks very resilient and efficient in sending data[18].In telecommunications the source (transmitter) is a device whereby numerous radio-frequency (RF) users, each bearing an antenna, radiate wireless transmission.Remote Antenna Unit (RAU) first receives RF signals and relays the signals to a signal converter.A converter is supposed to modulate and convert a signal in radio-frequency (RF) to optical signal.After the optical signal has been put over a fiber optic connection, the signal is directed to the Central Office (CO). In the CO, there is signal operations, routing and administration of the network.Under modern network design Free Space Optics (FSO) connections are presented so as to increase the flexibility of the systems and deal with the fixed-fiber deployment limitations. Connection between two nodes of a network that require FSO is normally triggered by the inability or the costs incurred and are too high to enable installation of dedicated fiber ducts physically.After signal processing in the Central Office (CO), the optical signal which has been created is then sent via Free Space Optics (FSO) link either to an intermediate destination plant or to the final destination. At arrival, the optical signal is also re-modulated into a Radio Frequency (RF) signal hence making it to be wireless [19].The adaptive mechanism used by the system under consideration switches between fiber-optic and free-space optical (FSO) mode of transmission according to the current conditions in the network. Such dynamic method maintains a steady and smooth flow of data throughout the network see figure2.3.

2.2.4 Advantages, Challenges and Applications of RoF

Radio signal transmission over optical fiber (RoF) technology is a hybrid of wireless with optical network where RF signal is sent by using fiber optic cable.The principle applied through this strategy provides a set of valueable benefits as regards to network performance and another valueable as regards to network reliability. Top among these is a significantly low signal attenuation complemented by a large bandwidth capacity and strong immunity against electromagnetic interferences.The Remote Operating Framework (RoF) enables central control and management of the network hence simplifying the process and also cutting on costs.The modern technological development requires more and more systems that can deal with high-frequency signals. (RoF)system which integrates wireless with optical networks by transmitting radio frequency signals over fiber optic cables, offers numerous advantages for modern communication systems[20]. However,multiple challenges should be addressed to enhance its performance:

- Fiber Nonlinearities: High-power RF signals can induce nonlinear effects on optical fibers, such as phase modulation and four wavesc combining, leads to signal distortion and degradation. These impairments can compromise the integrity of the transmitted signal, especially over long distances [21].

- Wirless MAC protocol integration to RoF:One of the major constraint comes about when Radio-over-Fiber (RoF) is used in deploying IEEE 802.11. IEEE 802.11 MAC protocol is built toward propagation delays lower than 1 microsecond and RoF systems incorporate an extra propagation load of 5 microseconds per Kilometer of optical fiber.This is a main problem which considerably reduces the entire network performance and in other instances, it can result to failure of the entire system. This is mostly achieved by an increment in number of collisions or acknowledgement (ACK) timeouts. These problems are especially evident in cases whereby the standard IEEE 802.11 MAC protocol is used.IEEE 802.11 protocol was initially to serve radio-based wireless network. Its functionality is based on the (negligenable) delay of propagation over the wireless channel; then, when implemented in a Radio-over-Fiber(RoF) system, some additional propagation delays are unavoidable due to presence of an optical-fiber propagation channel. It is, therefore, necessary to reconfigure the protocol to support this newly introduced temporal limitation in order to ensure that the efficiency is preserved and the latency making advantages of such RoF environments are reaped [22].

- Chromatic Dispersion: The varying propagation speeds of different light wavelengths cause chromatic dispersion, resulting in signal spreading and distortion. This effect is particularly detrimental for high-frequency signals, as it can lead to inter-symbol interference and reduced system performance [23].
- Rayleigh Backscattering: In RoF systems, Rayleigh backscattering can cause interference between forward and backward propagating signals, leading to nonlinear distortion. This phenomenon is especially problematic in radioastronomic applications, where signal fidelity is paramount [24].
- Integration with Millimeter-Wave Technologies: RoF systems are increasingly incorporating millimeter-wave frequencies to achieve more data rates. However, millimeter-wave signals experience significant propagation losses and require precise photonic components for effective transmission, posing design and implementation challenges[25].

2.3 Related work

2.3.1 Outage probability over RoF

The growing architecture model of (IoT) networks is the proposal to directly link IoT equipments to the wired network of optical fiber.This study will focus on the ways of correcting the inefficiencies that are normally encountered within a wireless network. Among the proposed measures, a specific mention should be made of Passive Optical Networks (PONs) due to their wide scope and a very large data-transmission rate.Some of the devices in the so-called Internet of Things (IoT) require electrical-to-optical signal conversion. It is an operation that demands a lot of energy and is expensive in terms of cost hence providing more challenges to the implementation and performance of the system [26]. As well, it is possible that most Internet of Things (IoT) applications have data rate demands that cannot be well served with conventional physical layer (PHY) connections. Consequently, there would be the need to alleviate the shortcomings of low data rates on long distances. This would be performed by incorporation of passive optical systems that are more efficient in transmission and scalable[27]. A test bed is under design and implementation as part of the H2020 FUTEBOL project implementing the architecture principles of the Radio-over-Fiber (RoF) paradigm. A testbed is an isolated environment and it will be used to test the Internet of Things (IoT) applications to monitor the environment. It can facilitate physical test of upcoming wireless technologies since it replicates conditions that occur in the real world[28], more details is shown in Table2.1. Furthermore, a new method which is based on real-life scenarios is used to measure the effects of RoF on the network system performance. In[29], a fiber-Wireless (Fiber wireless) LTE enhanced HetNets with multi-access computing (MEC) assistance is proposed and built.This allows traditional (remote) cloud with Multi-access Edge Computing servers to be deployed at the same location.To bridge this divide between the increase in need of creating 5G applications and the requirement of delay-sensitive and computation-intense operations.In order to elaborate on the energy-delay of the system, the analytical methodology that shall be employed in this paper shall be put across beforehand. A distributed cooperative offloading is then provided according to which it is supposed to shorten the average time of responding to mobile users. To achieve long distance reachability upstream over low data rate optical lines; dark fibers are used and more details can be seen in Table 2.2.In [30]An investigation into a market for Internet of Things over fiber (IoToF) fully based on passive optical keys.A fiber Bragg grating (FBG) based prototype physical layer (PHY) connection with low-cost optic modulation has been suggested and developed. In this study design, implementation, and functionality qualities of the prototype are evaluated.The architected system promises better data rates and extended range on individual applications but in comparison to already existing technologies like Sigfox and LoRa.[31]. examines and introduces two Radio over Fiber techniques: Intermediate Frequency over Fiber (IFoF) and Radio Frequency over Fiber (RFoF). The current transmission strategies have become very convenient in accommodating the rising need of broadband services which need more capacity and effectiveness. The strategies are used to promote the next-generation integrated optical-wireless networks, especially, the satellite communications (Satcom) and 5G systems. New capabilities have been incorporated into the Remote Antenna Units (RAUs) by incorporation of microelectronic instruments thus optimizing their physical size.The direction of the establishment of IoT on the path 5G-6G, and the capability of optical fiber and RoF technologies, themselves are revived and analyzed in[32].The rapidly expanding radio over fiber industry is also discussed, along with technology related to the convergence of IoT and RoF. Not to mention, current great research in a variety of fields is discussed. They then talked about the difficulties that would face 6G IoT systems that are backed by RoF in the future as well as new technological advancements. Power-over-fiber (PoF), which uses radio signals to power future 6G and 5G networks, is thought to be a modern and cutting-edge technology. It is presented and examined in[18]. An experimental purpose continues with the implementation of an identified broadcasting system consisting of radio-over-fiber (RoF) over single-mode fiber (SMF) links. The distances of transmission span are between 100 meters and 10 kilometers according to practice application scenarios. To determine the system functionality of the performance under realistic operational condition, power-over-Fiber (PoF) signals are injected into the system, whose maximum allowable power is 2 watts. In addition to IoT solutions that depend on RoF connectivity, PoF methods can optically forward power to distant devices or systems. The outage likelihood in the RoF-IoT paradigm has not been thoroughly examined, analyzed, or stated in many publications to date. In [33],an analytical presentation of a mixed fiber and FSO employing AF backhauling techniques is made. The impacts of pointing errors, co-channel RF interference, and modulator nonlinearities are shown and analyzed. A limit formula is obtained for the cumulative distribution function of the connection capacity, the asymptotic probability of outages, and the mean bit-error rate. According to the results, utilizing mm-Wave led to a 50% increase in capacity when compared to previous research. In [34] a multiuser mixed RF/FSO relays approach is described as a workable way to improve the strict criteria while taking the small-cell system design into consideration. Additionally, the influence of pointing errors in the FSO connections is taken into consideration while analyzing the outage probability of the link for the hybrid RF/FSO strategy. The outcomes demonstrate how hybrid RF/FSO techniques can improve communication systems in a real-world. A hybrid's mm-Wave-RoF performance with AF techniques is examined in [18]. The study looks into serious performance-restrictive aspects. Specifically, the fiber nonlinearity effects , of the optical modulator are taken into consideration and the effect of the RF co-channel interference discussed as well. They are researched on the basis of these factors and that is the impact on performance of mixed millimeter-wave (mm-wave) role-of-function paradigm. Simple closed form equations are used to statistically model and express the outage probability and average bit error rate of the entire network. Researchers have been paying close attention to the RoF network lately. Nevertheless, very few studies have examined distributed antenna scenarios in conjunction with wireless sensor networks, as well as distributed remote antenna scenarios in the Internet of Things,A state-of-the-art comparison has been presented in the table.2.3, Table2.4and Table2.5. The following is an explanation of the shortcomings of the suggested protocols in[33] ,[34]and [18]:

1. The notion of single point of failure (SPOF) almost emerged since all efforts in the literature used one fiber optics for data transmission from the RAU to central office.

2. As demonstrated in [33] ,[34], using a single antenna unit to support a large number of connections will result in serious interference problems.

3. All of the RoF-IoT communication scenarios that were suggested were based on distributed sensor systems rather than cluster-based systems.

4. Lastly, bandwidth efficiency, one of the crucial metrics, has not been examined and studied in the literature.

Table 2.1: Packet-Level Performance Metrics in RoF-IoT Systems.

Ref. No.	**Study Focus**	**Packet Success Ratio**	**Average Packet Delay**	**RSSI**
[28] (2018)	RoF tech validation in green IoT (H2020 Futebol)	Not explicitly stated (Improved)	Reduced packet delay observed	Improved

Table 2.2: Offloading and Edge Computing Metrics.

Ref. No.	**Architecture**	**Offloading Probability**	**Avg. Server Response Time**	**Energy Consumption**
[29] (2019)	MEC-enabled Fiber-Wireless LTE HetNets	Adaptive, distributed	Decreased	Optimized

Table 2.3: Error Rate and Signal Integrity Metrics.

Ref. No.	**Architecture**	**Bit Error Rate (BER)**	**EVM**
[30] (2019)	FBG-based acousto-optic + RoF	Moderate BER tested	-
[99] (2021)	Power-over-Fiber (PoF)	-	Measured EVM, sensitive to system tuning
[33] (2017)	Fiber-Aided FSO Backhaul	BER affected by scintillation & interference	-
[18] (2018)	mmWave + RoF AF Systems	BER calculated with nonlinearities	-

2.3.2 MAC protocol over RoF

IEEE 802.11 WLAN is a highly widely used and versatile form of wireless network. High-End Antennas or RoF based remote WLAN provides low-cost coverage for

Table 2.4: Outage Probability Findings for Different Architectures

Ref. No.	Architecture	Outage Probability Analysis.
[33] (2017)	Fiber relay FSO Backhaul	Impacted by channel interference and pointing error
[34] (2017)	Hybrid RF/FSO dual-hop	Increased due to pointing errors in FSO links
[18] (2018)	mmWave RoF with AF	Combined effects from optical/RF nonlinearities

Table 2.5: Architecture and Protocol Overview.

Ref. No.	Methods/Protocols	Year	Focus
[28]	RSSI, Packet success, delay	2018	Green IoT + RoF
[29]	MEC, offloading	2019	Delay/energy in HetNets
[30]	FBG modulation for RoF	2019	Low-cost modulation for IoT
[31]	IFoF vs RFoF	2020	Review
[32]	6G RoF IoT challenges	2021	Roadmap Review
[99]	Power-over-Fiber, EVM	2021	Signal quality assessment
[33]	FSO + fiber backhaul	2017	Interference handling
[34]	Hybrid RF/FSO relay	2017	Pointing error impact
[18]	mmWave + RoF AF	2018	Nonlinearities in BER/outage

large areas in rural areas. The CSMA/CA protocol is used at the Access Point (AP) and data transmission is controlled according to this protocol and also access control. The scheme reduces the risk of collision of data transmitted between devices by organizing the transmission among them. This is done via a standard Station (STA) linked by high gain WLAN antennas with the AP and STA physically separate. The Wireless Local Area Networks (WLANs) usage forms an affordable plan to provide wide area connectivity especially in remote areas. By use of this methodology, remote accessibility is granted and coverage area of the networks is extended to other areas that do not enjoy good telecommunication services[35]. Continuous use of Access Points (APs) and Stations (STAs) in a Wireless Local Area Network (WLAN) may compromise efficiency of access and create some operational anomalies. This corruption can be mainly ascribed to the increased likelihood of the random collision due to the long periods of time. This study gives a short summary of the problems caused by propagation delay in WLAN medium access control (MAC) protocols. The study suggest a (MAC) protocol to cope with the loss caused by delay and the difference between uplink and downlink in WLANs.To avoid collisions caused by delay, it increases the NAV period of the CTS frame to block the ACK frame before the AP can send its own data in agreement.The research also present an estimation of the proposed method according to Bianchi model.The simulation and numerical study of the propagation models prove that the considered strategy produces a significant increase in link performance with its downlink throughput performance which significantly outperforms the current approaches to it. As a result, the total system throughput is in effect doubled.[36]. This study examines the poor performance due to limitations at the medium access control layer when single-mode fiber (SMF) is utilized to expand the coverage of IEEE 802.11 networks. The study shows that increasing the fiber length leads to a reduction in the previous data. As the analysis has revealed, the network experiences long unavailability due to delays achieved by Medium Access Control (MAC) protocol. Such escarpments happen prior to the physical layer throttling mechanism being activated and, therefore, they increase the overall latency. Also consider packet communication using UDP and TCP. The current study initiates by developing and conducting an empirical research that will entail generation of primary data, after which proper frameworks will be set that can be used to make future comparisons. After the experimental stage is fulfilled, the outcomes are confirmed and, consequently, made more accurate by referring to OPNET simulators. Finally, a predictive analysis of these results is provided, allowing developers of Radio over Fiber (RoF) technologies to rapidly and confidently extrapolate historical data specifically based on their networks. Our work is the first of its kind focusing on fiber optic links [37]. Radio-over-Fiber (RoF) systems: These are designed to support transparent conveyance of radio signals between the spread out access points and distant antenna units through the optical fiber distributions, thereby making a paramount part of the next-period radio infrastructure. This architecture can support high capacity, low-latency communication and this is an important characteristic which can not be neglected in future wireless applications. The architecture facilitates the cost-effective provision of the wireless communication over long ranges and combating the problem of signal degradation[38]. The Radio-over-Fiber (RoF) networks allow the integration of mobility, flexibility of wireless communications and the bandwidth and scalability properties of optical-fiber systems. This kind of integration leverages on relative advantages of the two domains, which enhance better resilience and efficiency of the overall network. On this basis, RoF architectures provide a powering platform in the modern broadband access network implementation[39].The recently published IEEE 802.11n standard includes new location and message control (MAC) technologies to improve access. Here study focus on how IEEE 802.11n works in RoF design. Radio-over-Fiber (RoF) systems can overcome the problem presented by optical fiber propagation delay by using aggregation capability of the IEEE 802.11n standard. The strategy in question allows relaying several data frames in one transmission cycle and hence countering latency. This kind of strategy increases the overall performance of the system under varied network environments, such as network environments that use optical signal media in which transmission delays are inherent. Thus it proves to be resistant to the restraining features of the optical communication channel.To preserve efficiency,the study also discovered that the tunnel parameter values must be adjusted in RoF networks for IEEE 802.11n frame aggregation [40]. This study examines the operation of IEEE 802.11 MAC in the deployment context when the physical layer is deployed in the cloud, utilizing the SDR platform. To evaluate the transmission, the test model determines the probable delay of the ACK arriving at a non-zero time. In the traditional DCF and the most recent IEEE 802.11 specifications, the proposed model is employed to characterize the evolution of block ACK. The data indicates that the performance loss resulting from the alteration of network latency in the DC model can be mitigated by enabling Block ACK[41]. In this work a proposed MAC protocol for RoF-based WLANs that work with standard CSMA/CA-based WLANs. APs and stations engage in long-distance communication in RoF-based WLANs (STAs). Legacy WLANs that employ the CSMA/CA protocol are not required to integrate with RoF-based WLANs, as propagation delays may result in superfluous collisions. The proposed method enables the integration of RoF-based WLANs and legacy WLANs by reducing the number of frame collisions. The proposed protocol only requires changes to the access points (APs) in RoF-based WLANs (RoF APs), thus eliminating need to change STAs.Frames are transmitted continuously by the

RoF AP of the proposed protocol during transmission and receiving in the conventional WLAN to avoid collisions.This confirms that the frames sent by the AP reach the intended STA within a SIFS period after the channel is silenced. Since collisions between poles rarely occur due to the scheduling strategy, the deployment of RoF-based WLANs is improved.Additionally, the proposed method enable fair access to the wireless channel legacy WLANs and RoF-based WLANs by permitting modifications to transmission capacity.The proposed method is studied for IEEE 802.11a/b/g WLAN.Both simulation results and numerical analysis confirm that the proposed RoF-based WLAN TCP outperforms the traditional WLAN. The proposed method is investigated for 802.11a/b/g WLAN.Both simulation results and numerical analysis confirm that the proposed RoF-based WLAN TCP outperforms the traditional WLAN[42]. To control the channel access in the wireless systems, including the ones based on IEEE 802, a combined strategy that considers the TDMA and CSMA/CA can be implemented.This study leds to a new CSMA/CA-TDMA hybrid protocol implementation which increases the capacity of a standard MAC system by a significant level, especially in the highly populated networks.The design that is being proposed does not compromise on scaling, which is a critical necessity in wide-area deployments.In order to do so, two architectural designs, distributed and centralized, as well as transport framework based on MDP further optimises the performance of network. These models aim to optimize network performance by ensuring conflict-free and non-conflict periods, thereby maximizing efficiency and minimizing potential collisions[43]. If the flow rate falls down the channel's maximum capacity, the model will use the situation as a congestion indicator. By generalizing the model can account for the signal attenuation that concealed nodes experience because of channel attenuation.Simulation results show that MDP-based decentralized channel access technology outperforms the time-consuming traditional CSMA/CA method.Centralized methods are better than decentralized methods but require access to all information in the network[44].

Chapter 3

Distributed Remote Antenna Unit with Selection-Based of (RoF-IoT) Paradigm: Performance Improvement

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3.1 Introduction

The fiber-wireless (FiWi) Network, also kown as Hybrid optical-wireless or wireless-optical broadband access network is a major development in broadband network. It has joined the optical fiber capability of carrying large capacities to transmit, and this is also wireless and does not have to be limited to wires. This interconnection is the milestone of the development of the next-generation communication systems. It was created as a new and economically feasible solution to the unending issue of the user end access path[45]..The main purpose of Fiber-Wireless (FiWi) networks is to bring close to perfection the integration of both outstanding capacity of optical-fiber infrastructures and versatile access of wireless communication systems. With such integration, effective connectivity link can be provided between core network nodes and premises of end-users. The architecture improves traffic as well as access to broadband provision[46]. This composite architecture combines both high bandwidth delivery power of optic networks and scalability and convenience of wireless access that deliver access capabilities.During the last 20 years scholars have focused a lot on fiber-wireless

(FiWi) networks. This has instigated much research with a lot of technological development in the field.These networks have experienced a massive expansion and diversification of their uses. The distributed counselling systems, as depicted in the literature, have been implemented in multiple fields, especially the multimedia communication, telepresence technologies, and emergency response systems. Such systems are essential in disaster relief procedures as they ensure reliable and timely messages are passed to other people[47][48]. Consequently, FiWi networks are among the high-profile research concerns. The way they combine performance effectiveness, cost-effectiveness, and flexibility makes them quite apt to meet the changing nature of modern communication system.[49].Advanced technology of the Internet of Things (IoT) has created much buzz among the scholarly and business fraternities.Deploying the Internet of Things (IoT) technologies will essentially rely on present wireless communications infrastructures.There have been many attempts to support the new IoT applications to most of the existing wireless technologies. There is also a trend that new mobile communication systems will be developed to meet the expected needs of the Industry. [50].Mobile apps continue to place great pressure on data networks, and this can be mitigated with the tactical convergence of the wireless and fiber optic networks. This type of hybrid set-up takes advantage of the complementary features of each of the platforms to maintain high volume as well as highly efficient data transfer.Up to today, there has never been any single standard that has been found to be capable of satisfying all the various needs of the IoT applications[51]. Several requirements have to be met by the modern communication systems: complexity of the system, cost efficiency, power efficiency, and the transmission rate. The needs presented in these aspects are crucial when it comes to development and efficient design of modern-day communication systems. Such a challenge is especially prominent in major implementation such as Smart City infrastructures.In the modern Internet of Things (IoT) world, a new networking paradigm is being developed and directly combines optical fiber based networks with the IoT devices[52]. The model has potential in reducing the limitations normally found in wireless systems viz.: signal interference and limitation of bandwidth. It is believed that the double-paradigm will perform better and have an increased applicability in most IoT use cases, detecting the robust capabilities and soundness of optical fiber. This strategy brings up increased reliability, bandwidth and scalability. Specifically, the passive optical networks (PONs) with their long-reach and large data loading capacity offer a valid framework of such an integration.However, deploying optical fiber connectivity directly to IoT devices introduces certain challenges.Notably, the electrical-to-optical conversion processes inherent in optical systems typically entail significant power consumption and cost implications, potentially exceeding the resource constraints of many IoT devices [53]. Practical research findings show that numerous high-performance physical-layer (PHY) connectivity systems, as a matter of course, are far more than required to serve typical internet-of-things (IoT) applications when it comes to bandwidth and data rates. Accordingly, in this way, they create excessive complexity and costs of implementation when they are put in place. This mismatch explains why it is essential to design infrastructure to deal with the specific needs of IoT application to ensure operational efficiency and cost-effectiveness. This is thus leading to an increased need to bridge the gap that already exists by developing passive optical systems which would accommodate low data rate applications over huge distances. These systems should be customized towards low data transmission needs and limited resources that feature applications of IoT. It is this requirement that must be addressed in order to support efficient and scaleable deployment of IoT[54]. The contribution to this chapter can be defined as:

1. This study provides, to the best of our knowledge, a design of the Radio over Fiber-Internet of Things (RoF-IoT) paradigm of early fire detection. The design has camera sensors as well as other possible environmental sensors to check the surrounding conditions. Here, the sensors gather the information in the environment and relay the information to a specified control unit where suitable responsive measures are then trigged.

2. One of the potential cooperative protocols is proposed along with the Best Remote Antenna Unit Selection implemented mechanism (BRAUS). A number of criteria that include number of Remote Antenna Units (RAUs), the number of master nodes, distances between different links connecting the RoF-IoT network, control the selection process.This strategy aims at ensuring improved communication efficiency and maximization of system performance in the distributed network environment.

3. The proposed protocol BRAUS probability of outage has been modeled analytically in order to determine its performance. This analytical analysis furnishes the details in terms of reliability of the protocol in different network conditions.The outcomes reveal that the protocol has the potential in delivering considerable decrease in the probability of outage. Particularly, it proves to be 65% superior to other recent related studies.

4. Moreover, and to the first time, bandwidth efficiency of the proposed BRAUS protocol has also been explored mathematically and analytically. It is observed in the analysis that bandwidth efficiency has been improved significantly. In particular, the new presented protocol will enhance by 34%that of existing methods in recent years.

3.2 Proposed Modeling and System Structure

3.2.1 Radio over Fiber with IoT

One issue with early fire detection in forests and dangerous areas (such as power plants and energy distribution zones) is that the areas are difficult to install or access because of their natural features[55]. We therefore take the early-fire detection system into consideration in our design.

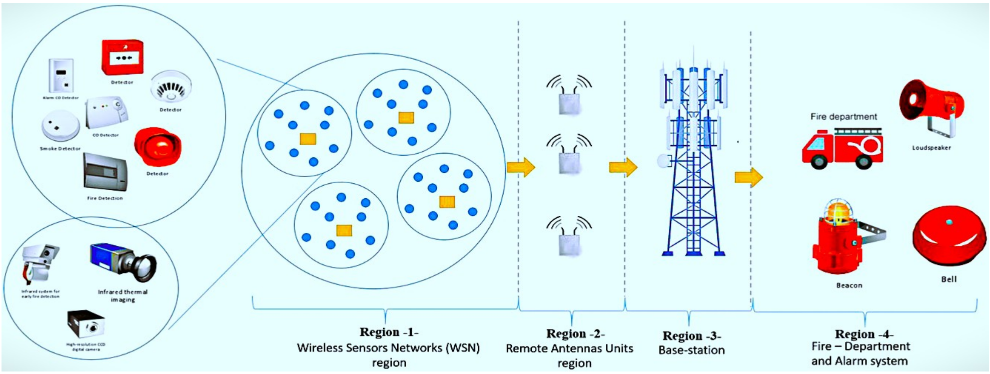

Figure 3.1: Distributed RAU of the RoF in IoT paradigm.

In a RoF network, RAUs are distributed across multiple radio stations known as Distributed Antenna Systems (DAS). In our framework, which has compact Master Nodes (MNs) distributed over mountainous or rocky area to supply wide signals in an area, sensors are given two connectivity attributes: direct connection to RAU and another host node through RAU[56]. In this work, to achieve higher bandwidth, higher coverage, higher signal quality, and higher security for transmitted data,It is suggested distributed RAUs in IoT paradigms using RoF technology. The proposed paradigms are illustrated in Figure(3.1); they consist of four regions, each of which performs a distinct function and is an integral component of the IoT system. A fire detection and remediation system for early detection is considered in this workThe paradigm suggested can be briefly summarised as followed:

1. Cameras, electronic devices, carbon dioxide detectors, etc. Early electronic devices such as sensors are placed randomly or out of order (even if very difficult or oversized) in a special area 1. After the sensor receives the data, it is passed on to the owner of the tunnel or other RAU according to the rules explained in the next section. Compared with ordinary sensors, host nodes have better performance, larger batteries and larger physical models.

The special case of data collection is that the master node sends the message from the sensor to the RAU after receiving it.

2. In the second Regin, The RAU is responsible for transforming the radio signal into an optical signal, which is then sent via fiber optics.

3. This data is received by the base station or super master node in region 3, which is connected to the power modulated optical cable. The super master node then sends the data to zone 4. Its primary responsibilities include processing documents and deciding which department to send them to the decision.

4. Data received is analyzed In Region 4, prompting specific departments (fire department, beacon system, etc.) to take appropriate action.

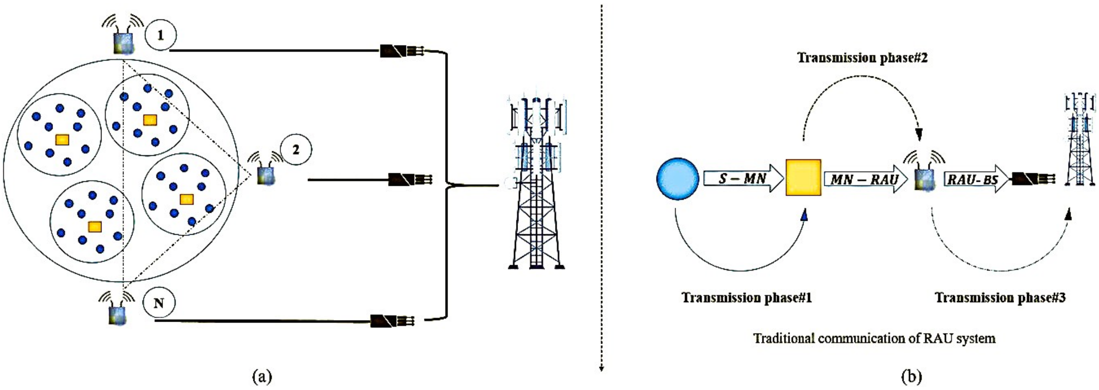

Figure 3.2: Communication structure of traditional RoF.

3.2.2 Proposed RoF Communication Structure in the IoT System

What follows is an analysis and examination of the offered alternatives and substance of the communication style. According to [33][34], this is how the conventional RoF process communicates in an IoT setting: There are three steps to the conventional method of communication:

1. In phase 1, in the designated region, sensors gather data, which is subsequently transmitted to the master controller.

2. The phase 2, which one RAU was assigned in this investigation after the host node transmitted sensor data to it across a radio channel.

3. In the last step the final shows the power transmission on fiber optic from RAU to base station, which is the RCO. Another type of radio communication system, that is the conventional fiber-based radio communication is depicted in Figure 3.2.

The architectural design under consideration comprises three discrete phases and a multitude of RAUs that are arranged in a consistent triangular pattern. Sensors and the preponderance of master nodes can achieve the triangular RAU distribution, as depicted in Figure 3.1 The scenario pertaining to communication is as follows:

1. Phase one involved the collection of data (either routine or critical) from the immediate vicinity at regular intervals (the utmost area that the sensors can cover in this thesis is 10 meters). The gathered data was subsequently transmitted via wireless medium and could be of two types:

   - Primary approach, the first path: collecting data, forwarding it to the close RAU using the chosen metric that takes into account wireless medium and optical fiber. The subsequent step is for the selected RAU to transmit the data to the central office or the base station unit via the most appropriate fiber optic line.

   - Second alternative, second path: If the ideal RAU is beyond the sensor's range, the data captured will take an alternate path. Next, the data is transmitted by the sensor to the primary node in the transmission zone. Following sensor data transmission, the control node notifies the RAUs.

2. Phase 2 of the structure involves data transmission from the closest host node to a selection of RAUs. Next, choose an external antenna device to transfer the data to the MRC. This is step three. The next step is to transmit more signals to the distant center's base station.

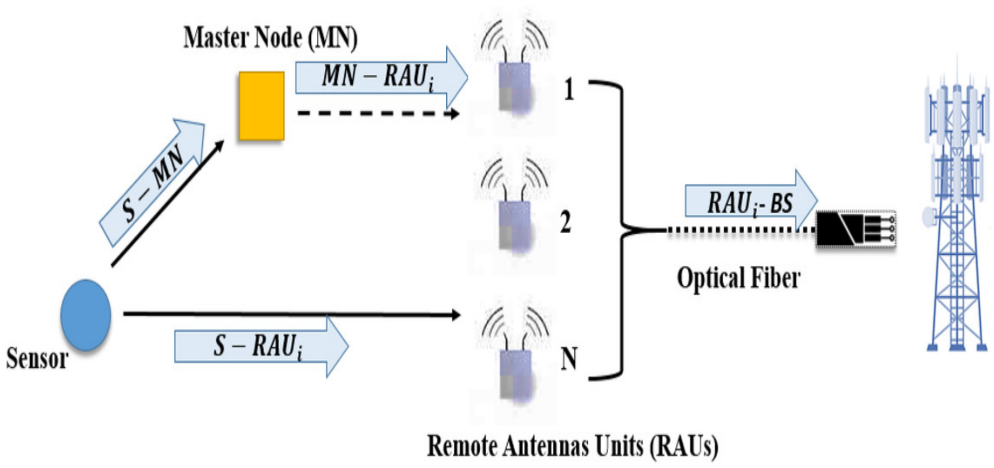

Figure 3.3: Two possible paths for the best RAU selection.

3.3 Mathematical Model of Propagation

The Radio Channel's Propagation Model

Within this subsection, the channel model is examined, and the likelihood of an outage across the $i-j$ connection is shown. According to [57], the signal-to-noise ratio $\gamma_{i,j}$ of the $i-j$ connection is as follows:

$$\gamma_{i,j} = \left(\frac{P_T}{P_N}\right)\rho_{i,j} = \mathrm{SNR}\cdot\rho_{i,j}. \tag{3.1}$$

- P_T ; transmission power.
- P_N : noise power.
- $\rho_{i,j}$: Gaussian complex random variable with unit variance.

Hence, $\rho_{i,j}$ is modeled as exponentially distributed random variable with the mean value E, so that $E\left[\rho_{i,j}\right] = \left|a_{i,j}\right|^2 d_{i,j}^{-\alpha}$, where $E\left[\rho_{i,j}\right]$ represents the expectation, which typically ranges from 2 to 6, $d_{i,j}$ is the distance between nodes i and j, and α represents the path loss factor, can be expressed [58]:

$$R_{i,j} = B\log_2\left(1+\mathrm{SNR}\cdot\left|a_{i,j}\right|^2\cdot\sigma_{i,j}^2\right)$$

$$2^{R_{i,j}/B} = \left(1 + \text{ SNR } |a_{i,j}|^2 \ \sigma_{i,j}^2 \ \right)$$

$$\frac{2^{\frac{R_{i,j}}{B}} - 1}{\sigma_{i,j}^2} = \text{SNR} \cdot |a_{i,j}|^2 \tag{3.2}$$

B presents the channel's bandwidth. The definition of an outage probability is when the transmission rate R_o is equal to or less than the required transmission rate. The following graphic can be used to show the likelihood of an outage:

$$P_{i,j}^{\text{out}} = P\left(R_{i,j} \leq R_o\right) = 1 - \exp\left(-\frac{\left(2^{R_o} - 1\right)}{\text{SNR} \cdot \sigma_{i,j}^2}\right) \tag{3.3}$$

It has been made clear that a lower probability of outage exists when the distance between nodes i and j are lower and the SNR is higher and reverse. Conversely,outage probability decrease as the target data rate R_o decrease, and vice versa. Therefore, to maintain reliable communication, it is essential to maximize the SNR and minimize the distance over the communication path as much as possible. An expression that represents the probability that successful transmission is achieved of the i-j connection is as follows:

$$P_{i,j}^{s} = 1 - P_{i,j}^{\text{out}} = \exp\left(-\frac{\left(2^{R_o} - 1\right)}{\text{SNR} \cdot \sigma_{i,j}^2}\right) \tag{3.4}$$

Depending on the information theory, can be illustrated a method to evaluate the capacity limit of communication systems on fiber optic. Over the i-j link the transmission rate as [58][59] is

$$R_{i,j} = B \log_2\left(1 + \text{SNR}\,|a_{i,j}|^2\,\sigma_{i,j}^2\right) \tag{3.5}$$

$$\text{OSNR} = \frac{R_b}{2B_{\text{ref}}}\text{SNR} \tag{3.6}$$

where:

- OSNR : optical signal-to-noise ratio.
- R_b : bit rate.
- B_{ref} : reference bandwidth (in Hz).

- SNR : electrical signal-to-noise ratio.

This section breaks down the math behind understanding the chances of an outage and the success of transmissions in our channel model.As shown in Equation (3.3), the outage probability analysis exemplifies how the transmission reliability can be dependent on such main variables as the signal-to-noise ratio (SNR) and transmission rate needed. This relationship emphasizes the importance of these issues in defining the effectiveness and the strength of the communication system. Next, Equation (3.4) offers an understanding of what are the chances to have a successful transmission. It outlines the concerns that it necessitates to assure stable and reliable communication. This formulation can be used as a basics tool in measuring the capabilities of the systems with different operating parameters. Moving on, Equations (3.5) and (3.6) have those ideas applied to fiber-optic communication. They integrate the optical signal-to-noise ratio (OSNR) as one of the important parameters that determine the performance of the system. Through this integration, more thorough evaluation of efficiency and reliability of the communication link, becomes possible.In sum, the set of equations is essential in the process of system parameters optimization to improve transmission efficiency. They help in the proper provision of data within the network. Culminating to this, there results enhanced total performance and soundness of the communication system.

3.4 Proposed Protocol for the Outage Probability

3.4.1 Formulation Model

Figure 3.3 illustration is the basis upon which the modeling and formulation of the proposed protocol is carried out. Particularly, it supports the creation of the Best Remote Antenna Unit Selection (BRAUS) protocol as RoF-IoT paradigms. The present subsection expands that framework to describe the structure and mechanism of working of the protocol. The obtained probability of the outage is:

$$P_{\text{BRAUS}}^{\text{out}} = \underbrace{\text{Path } \#1^{\text{out}}}_{S \to \text{RAU} \to \text{BS}} \cup \underbrace{\text{Path } \#2^{\text{out}}}_{S \to \text{MN} \to \text{RAU} \to \text{BS}} \tag{3.7}$$

$$P^{\text{out}}_{\text{BRAUS}} = \underbrace{\text{Path } \#1^{\text{out}}}_{S\to\text{RAU}\to\text{BS}} + \underbrace{\text{Path } \#2^{\text{out}}}_{S\to\text{MN}\to\text{RAU}\to\text{BS}} \tag{3.8}$$

whereby the Path#1's outage probability is given as

$$\text{Path } \#1^{\text{out}} = \left(P^{\text{out}}_{S,\text{RAU}} + \left(1 - P^{\text{out}}_{S,\text{RAU}}\right) P^{\text{out,AF}}_{\text{RAU,BS}}\right) P_{\beta_{\max}}(\omega\beta) \tag{3.9}$$

$P^{\text{out}}_{S,\text{RAU}}$ reffers to the outage probability of the path(S_RAU) , and $P^{\text{out,AF}}_{\text{RAU,BS}}$ refers to the outage probability of the path(RAU_BS) is expressed as:

$$P^{\text{out}}_{S,\text{RAU}} = 1 - \exp\left(-\frac{\left(2^{R_o} - 1\right)}{\text{SNR} \cdot \sigma^2_{S,\text{RAU}}}\right) \tag{3.10}$$

The amplify-and-forward outage probability, $P^{\text{out,AF}}_{\text{RAU,BS}}$, can be written as

$$P^{\text{out,AF}}_{\text{RAU,BS}} = 1 - \exp\left(-\frac{1}{\sigma^2_{S,\text{RAU}}}\left(\frac{2^{R_o} - 1}{\text{SNR}} - \frac{R_b}{2B_{\text{ref}}}\right)\right) \tag{3.11}$$

$P_{\beta_{\max}}(\omega\beta)$ refer to probability to the $S-\text{RAU}$ and $\text{RAU}-\text{BS}$ path selection, and it is expressed as

$$P_{\beta_{\max}}\left(\omega\beta_{\text{thd}}\right) = 1 - \left(1 - \exp\left(-\frac{\beta_{\text{thd}}}{\sigma^2_{S,\text{RAU}}}\frac{L_{\text{total}}}{L_{\max}}\right)\right)^R \tag{3.12}$$

in which β_{thd} is the threshold distance of the $S \to \text{RAU}$ remote antenna unit link, $\sigma^2_{S,\text{RAU}}$ is the $d^{-\alpha}_{S,\text{RAU}}$, ω is $\frac{L_{\text{total}}}{L_{\max}}$, result of division of total optical fiber length link, L_{total}, to maximum optical fiber link, $L_{\max}$, R is the number of the remote antenna units.

From the selection formula that has been proposed,Based on findings of this study, the following conclusions may be deduced.: as the number R approaches infinity, the $P_{\beta_{\max}}(\omega\beta_{\text{thd}})$ approaches one, which indicates that the probability of locating an appropriate RAU for the sensor grows, and vice versa. In addition, if the ω is low, the $P_{\beta_{\max}}(\omega\beta_{\text{thd}})$ is high, because the probability of path selection tends to select the best $S-\text{RAU}$ path with minimum fiber optics length. Then, the outage probability of the second path is given as

$$\text{Path } \#2^{\text{out}} = \left(P^{\text{out}}_{S,\text{MN}} + \left(1 - P^{\text{out}}_{S,\text{MN}}\right) P^{\text{out}}_{\text{MN,RAU}} + \left(1 - P^{\text{out}}_{\text{MN,RAU}}\right) P^{\text{out,AF}}_{\text{RAU,BS}}\right)\left(1 - P_{\beta_{\max}}\left(\omega\beta\right)\right) \tag{3.13}$$

where, $P^{\text{out}}_{S,\text{MN}}$ and $P^{\text{out}}_{\text{MN,RAU}}$ are the outage probability of the $S-\text{MN}$ and $\text{MN}-$

RAU links.

In what follows, $P^{\text{out}}_{S,\text{MN}}$ and $P^{\text{out}}_{\text{MN,RAU}}$ are expressed as

$$P^{\text{out}}_{S,\text{MN}} = 1 - \exp\left(-\frac{\left(2^{R_o} - 1\right)}{\text{SNR} \cdot \sigma^2_{S,\text{MN}}}\right) \tag{3.14}$$

$$P^{\text{out}}_{\text{MN,RAU}} = 1 - \exp\left(-\frac{\left(2^{R_o} - 1\right)}{\text{SNR} \cdot \sigma^2_{\text{MN,RAU}}}\right) \tag{3.15}$$

Where, $P^{\text{out}}_{S,MN}$ is the outage probability of the link S, MN and $P^{\text{out}}_{MN,RAU}$ is the outage probability of the link MN, RAU. Both outages probabilities effected by distance of the links S, MN and MN, RAU respectively, where higher distance, more bits will lost and high outage probabilities. In addition, SNR is important here, keeping SNR as much higher as possible, make outage probabilities less which perfectly maintain performance of the system.

Subsequently, the second path's outage probability appears as: we get:

$$\begin{aligned}
P^{\text{out}}_{\text{BRAUS}} = {} & \underbrace{\left(1 - \exp\left(-\frac{\left(2^{R_o}-1\right)}{\text{SNR}} \cdot \frac{1}{\sigma^2_{s',\text{rau}}}\right)\right)}_{P^{\text{out}}_{s',\text{rau}}} + \underbrace{\exp\left(-\frac{\left(2^{R_o}-1\right)}{\text{SNR}} \cdot \frac{1}{\sigma^2_{s',\text{rau}}}\right)}_{1-P^{\text{out}}_{s',\text{rau}}} \cdot \underbrace{\left(1 - \exp\left(-\frac{1}{\sigma^2_{s',\text{rau}}}\left(\frac{\left(2^{R_o}-1\right)}{\text{SNR}} - \frac{R_b}{2B_{\text{ref}}}\right)\right)\right)}_{P^{\text{out,AF}}_{\text{rau},bs}} \cdot \\
& \underbrace{\left(1 - \left(1 - \exp\left(-\frac{\beta_{\text{thd}} L_{\text{total}}}{\sigma^2_{s',\text{rau}} L_{\max}}\right)\right)^R\right)}_{P_{\beta_{\max}}(\omega\beta_{\text{thd}})} + \left(\underbrace{\left(1 - \exp\left(-\frac{\left(2^{R_o}-1\right)}{\text{SNR}} \cdot \frac{1}{\sigma^2_{s,\text{mn}}}\right)\right)}_{P^{\text{out}}_{s,\text{mn}}} + \underbrace{\exp\left(-\frac{\left(2^{R_o}-1\right)}{\text{SNR}} \cdot \frac{1}{\sigma^2_{s,\text{mn}}}\right)}_{1-P^{\text{out}}_{s,\text{mn}}} \cdot \right. \\
& \left. \underbrace{\left(1 - \exp\left(-\frac{\left(2^{R_o}-1\right)}{\text{SNR}} \cdot \frac{1}{\sigma^2_{\text{mn,rau}}}\right)\right)}_{P^{\text{out}}_{\text{mn,rau}}} \right) + \underbrace{\exp\left(-\frac{\left(2^{R_o}-1\right)}{\text{SNR}} \cdot \frac{1}{\sigma^2_{\text{mn,rau}}}\right)}_{1-P^{\text{out}}_{\text{mn,rau}}} \cdot \underbrace{\left(1 - \exp\left(-\frac{1}{\sigma^2_{s',\text{rau}}}\left(\frac{\left(2^{R_o}-1\right)}{\text{SNR}} - \frac{R_b}{2B_{\text{ref}}}\right)\right)\right)}_{P^{\text{out,AF}}_{\text{rau},bs}} \cdot \\
& \underbrace{\left(1 - \exp\left(-\frac{\beta_{\text{thd}} L_{\text{total}}}{\sigma^2_{s',\text{rau}} L_{\max}}\right)^R\right)}_{1-P_{\beta_{\max}}(\omega\beta_{\text{thd}})}
\end{aligned} \tag{3.16}$$

The expressions we've derived give us a solid model for understanding outage probability with the Best RAU Selection-based (BRAUS) protocol in RoF-IoT setups. In Equation (3.16), we are combining the outage probabilities of two different path while keeping in mind important factors like SNR, fiber length, and how we choose our paths. What we found is that when we add more remote antenna units (RAUs), it boosts our chances of finding the best transmission path, which in turn lowers the overall outage probability. Plus, by keeping the fiber length omega shorter, we increase the chances of picking the best RAU, which makes our transmissions even more reliable.

3.4.2 Band width Efficacy of Proposed Protocol

Bandwidth efficacy is an essential metric within the realm of communication systems. This thesis defines bandwidth efficiency as the quantity of channels or ports necessary to transmit a solitary packet or frame to its intended destination. In order to ensure that a packet or frame reaches its destination after two steps, it is necessary to utilize two channels or slots; thus, the bandwidth efficiency for above scenario is 0.2 [60][61]. The preceding part discussed the mathematical representation of the average bandwidth efficacy of the Best RAU Selection (BRAUS) protocol in the IoT-RoF scenario. It looks like this:

$$\begin{aligned} BE_{\text{BRAUS}} &= \underbrace{\frac{1}{2}P_{\beta_{\max}}(\omega\beta_{\text{thd}})}_{\text{case\#1}} + \underbrace{\frac{1}{3}\overline{P}_{\beta_{\max}}(\omega\beta_{\text{thd}})}_{\text{case\#2}} \\ &= \underbrace{\frac{1}{2}P_{\beta_{\max}}(\omega\beta_{\text{thd}})}_{\text{case\#1}} + \underbrace{\frac{1}{3}\left(1 - P_{\beta_{\max}}(\omega\beta_{\text{thd}})\right)}_{\text{case\#2}} \\ &= \frac{1}{6} + \frac{1}{3}P_{\beta_{\max}}(\omega\beta_{\text{thd}}) \end{aligned} \tag{3.17}$$

The probability of choosing the best RAU through direct transmission from the sensor to the RAU, denoted as $P(\emptyset) = f(d_o, d_{s,\text{RAU}})$, is found in equation (3.9). Considering that there is no direct transmission between the sensor and RAU, and that the best RAU cannot be found, is then $P(\emptyset)$, as stated in (10). Rewriting the equation(3.17) as:

$$BE_{\text{BRAUS}} = \frac{1}{6} + \frac{1}{3}\left(1 - \left(1 - \exp\left(-\frac{\beta_{\text{thd}}}{\sigma^2_{s,\text{RAU}}}\frac{L_{\text{total}}}{L_{\max}}\right)\right)^R\right) \tag{3.18}$$

It is obvious from that the equation (3.18), as the $P_{\beta_{\max}}(\omega\beta_{\text{thd}})$ approach to one, the bandwidth efficiency is 1/2, on the other hand, as the $P_{\beta_{\max}}(\omega\beta_{\text{thd}})$ approach to zero, the bandwidth efficiency is 1/3. Direct connection between sensors and RAU can preserve and improve bandwidth efficiency, as equation (3.18) predicts and demonstrates. Consequently, the utilization of multi-hop communication is not always favored in the context of traditional RoF communication in the IoT. On the contrary, multi-hop communication may offer greater reliability than direct transmission.

3.5 Results and discussion

For determining whether the suggested Best Remote Antenna Unit Selection Protocol (BRAUS) for RoF is useful in Internet of Things (IoT) predictive fire detection, we will employ computer simulations in this section. Within the simulations, the primary nodes and sensors are dispersed in a random fashion across an area that is four kilometers by four kilometers. A number of Remote Access Units (RAUs) are dispersed across a given region (with a maximum of 25 RAUs in this study), where these RAUs are linked to the base station or central office via a fiber optic cable that has a maximum length of 25 kilometers. The models are founded on the assumption that the distances between different nodes; that is, the sensors, the RAU, the host and the BS are different values. All links are from sensors and master nodes to the RAU as variables and assigned d_o. The transmission speed of all links is assumed to be β_o (b/s/Hz). In this work, the path loss exponent is not fixed in this work. The following Table 3.1 contains all the parameters list:

Table 3.1: Values and Parameters for BRAUS Protocol.

Symbol	**Definition**	**Value**
$\varphi_{i,j}$	Antennas gain over $i-j$ link	3
R_o	Transmission rate to bandwidth over $i-j$ link	0.5
$d_{i,j}$	Distance over $i-j$ link (within sensors region)	$5-50\ m$
α	Path-loss factor	$2-6$
SNR	Signal to noise ratio	$0-50\ dB$
$OSNR$	Optical signal to noise ratio	$0-50\ dB$
L_{total}	Total length of the optical fiber	$0-50\ km$
γ	Nonlinearity coefficient	$1-2$
B_{OF}	Optical fiber bandwidth	32 GHz
R	Number for remote antenna unit	$5-25$

The likelihood of the BRAUS protocol failing in comparison to [18] is shown in Figure(3.4) and Figure(3.5) , which plot the signal-to-noise ratio against the number of remote antenna units. Extraction of the following conclusions from the figures With increasing SNR, the failure probability of both the reference procedure and the suggested protocol reduces. With a lower success probability, the suggested approach is more efficient than the protocol suggested in [18]. Looking atFigure(3.4) and Figure(3.5) , we can see that, as expected, the failure probability improved as the number of RAUs increased. This is due to the fact that the capacity to determine the most effective RAUs improved in tandem with the number of RAUs, thereby decreasing the likelihood of failure. Figures(3.6) , Figure(3.7) and figure3.8 illustrate the resulting BRAUS probability relative to

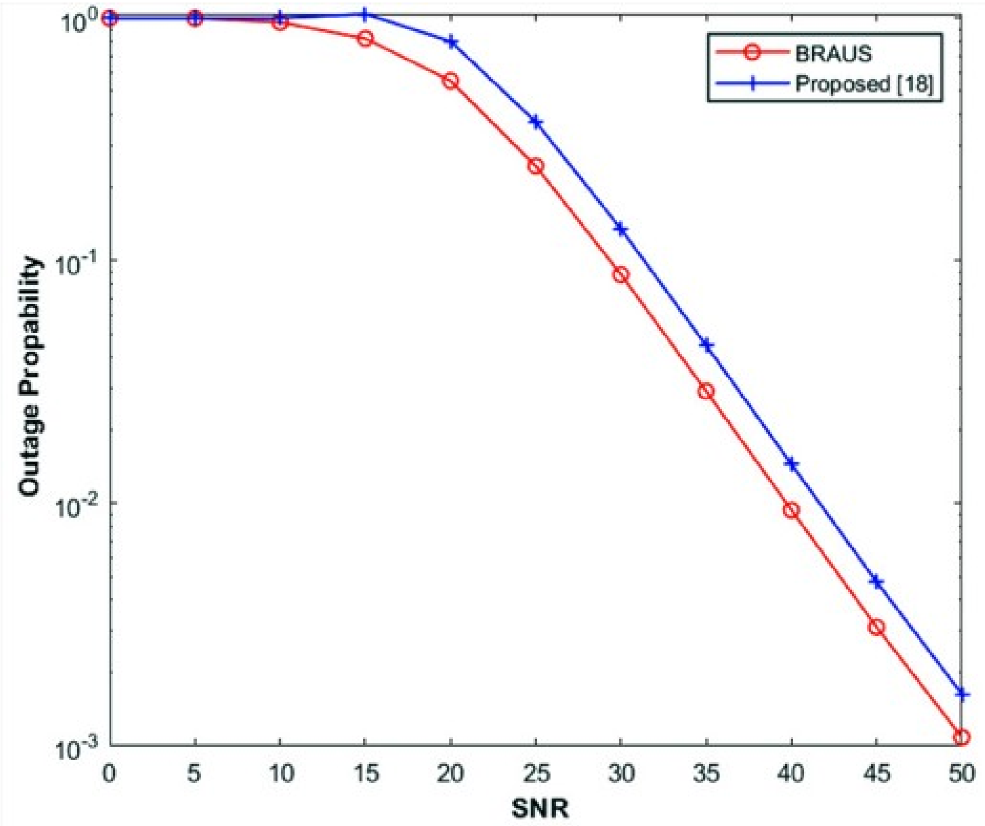

Figure 3.4: SNR together with the likelihood of an outage 30 RAUs are used.

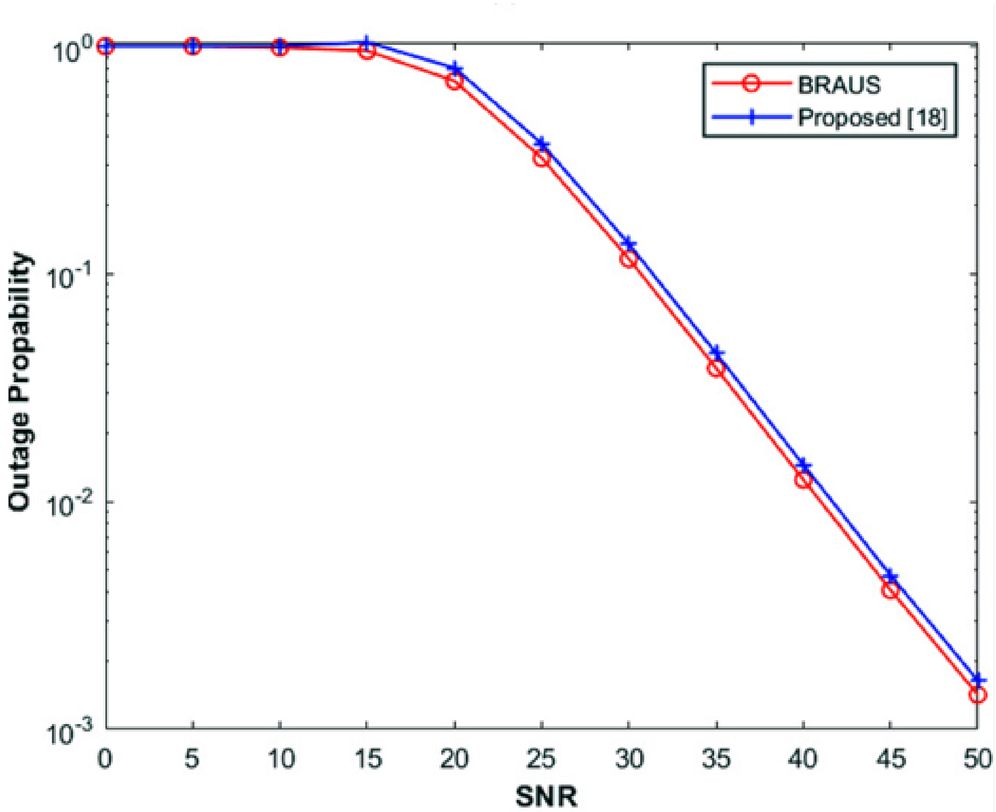

Figure 3.5: SNR together with the likelihood of an outage 10 RAUs are used.

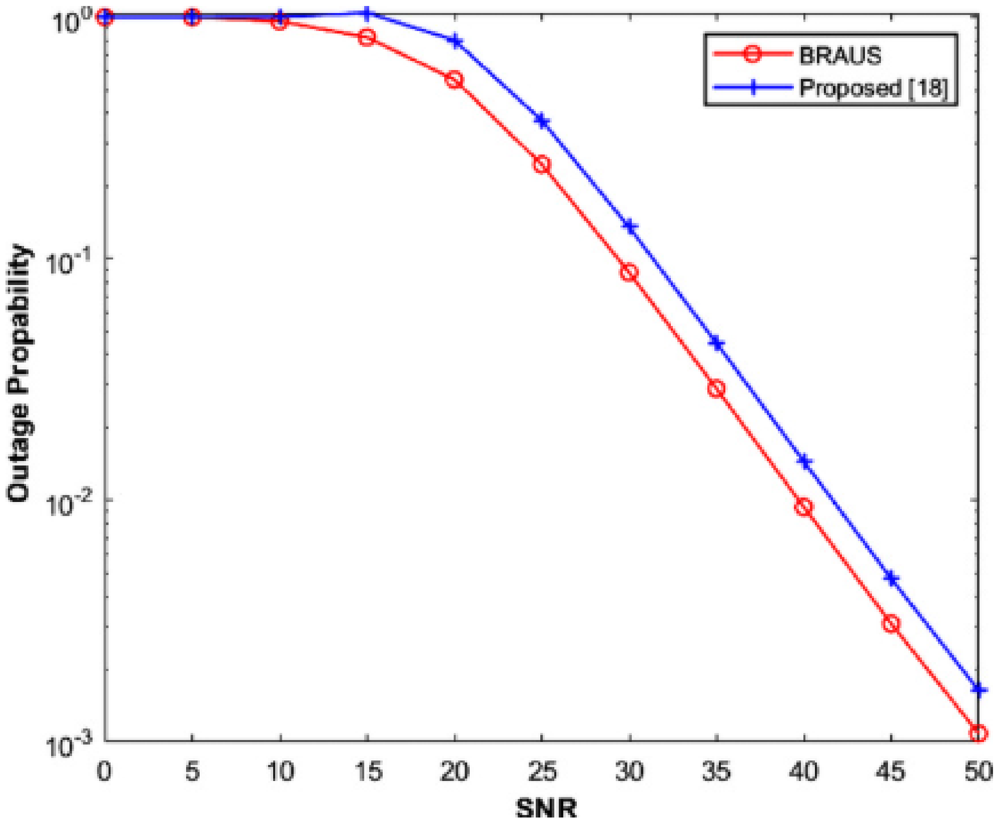

Figure 3.6: SNR with outage probability $\beta_{\text{thd}} = 0.5d_{s,\text{RAU}}^{-\alpha}$;

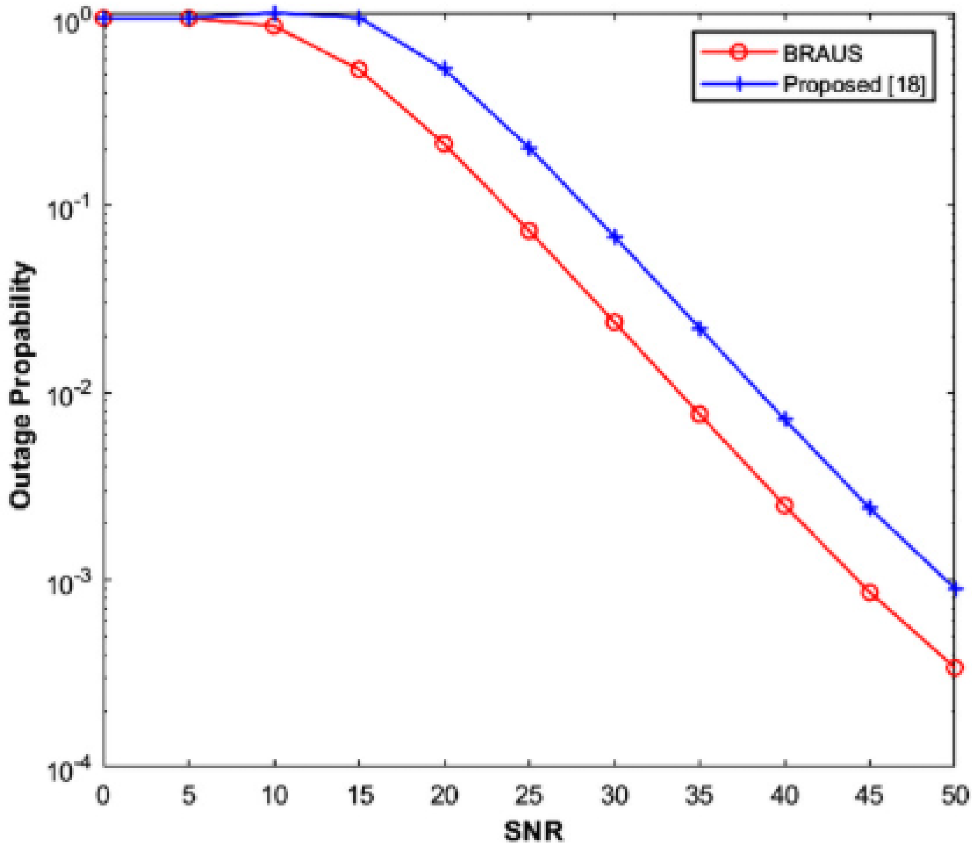

Figure 3.7: SNR with outage probability, $\beta_{\text{thd}} = 2d_{s,\text{RAU}}^{-\alpha}$.

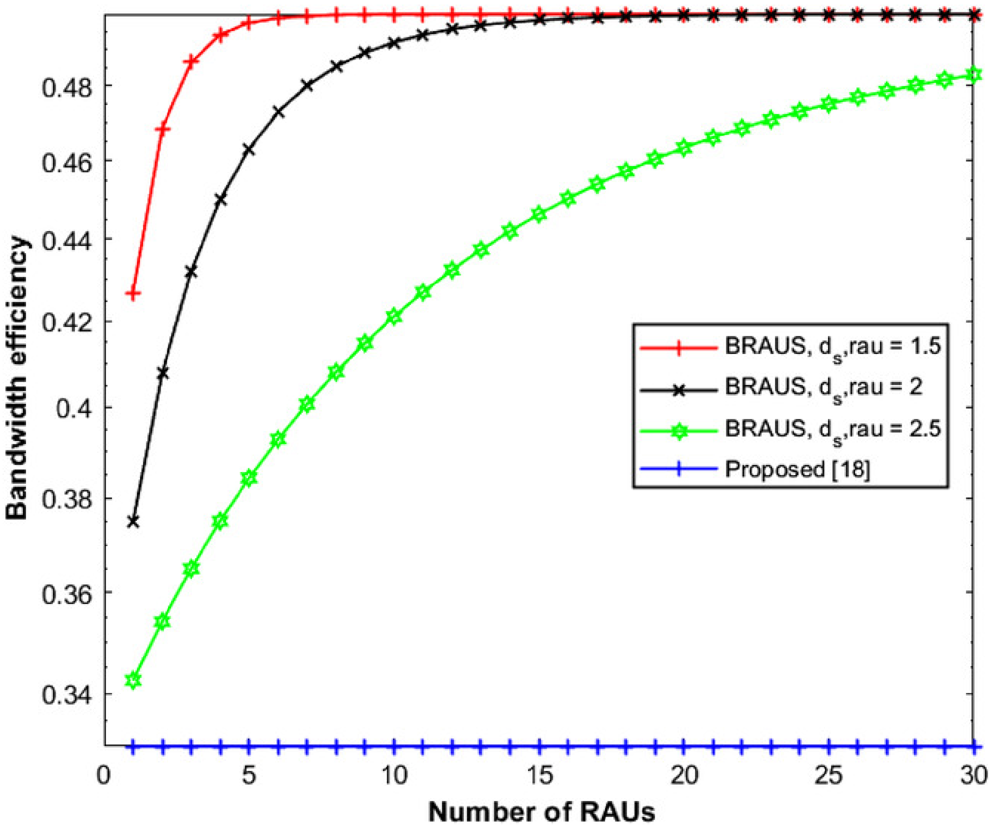

Figure 3.8: Number of remote antenna unit RAUs with bandwidth efficiency.

[18] as a function of SNR relative to the threshold value βthd As expected, the SNR increases as the failure probability decreases. Once again, we discovered that the suggested protocol outperformed the protocols given in [18]. This is because the suggested protocol chooses the optimal RAUs and path path depend on the equation 3.163.16, the optimal path can be selected based on the link s,rau and varying SNR, respectively.The results show that increasing the threshold value reduces the probability of failure. This is because greater distance increases the probability that the RAUs will remain in range of the transmitter, which increases the probability that a viable path can be detected for the RAU, which can then establish a connection through the transmitter and send data to the transmitter. base station.

Figure 3.8 illustrates the relationship between the bandwidth efficacy of the protocol being considered, BRAUS, and that of [18] with relative to the number of RAUs.Also, Figure3.8depicted the length from the sensor to the RAUs, $d_{s,\text{rau}}$, which has been adjusted between 1 and 2.5.As a result, as the number of the RUAs increased, so did the bandwidth efficiency; this is because, according to equation 3.12, as the number of RAUs increased, so did The probability of the best or near-best RAUs as well as the bandwidth efficiency were nearly 0.5. It was observed that as the distance between the sensor and RAUs decreased, there was an increase in bandwidth efficiency. This is possible to clarify through the protocol selection, as Figures3.6 and3.7demonstrate, the dual hop route instead of the triple hop one. We can conclude that when the number of RAUs is 30 and $d_{s,\text{rau}}$ is 1.5, the proposed protocol achieves a 65% in outage probability improvement see figure (3.4) and enhance the bandwidth efficiency by 34% see figure(3.8)compared to the previous work. Since two paths were available for data transmission, one requiring two and the other three steps, the performance of the chosen protocol was ultimately higher than [18].

3.6 Conclusion

The evolution of the Internet of Things (IoT) that comprises fiber optic and wireless sensor networks is the premise of the upcoming IoT-RoF technology. The above hybrid method is meant to capitalize on the advantage of both the optical and the wireless communication systems to increase the scope of data transmission. As a part of thesis, a modified IoT-RoF architecture is recommended to detect early fi re detection, which includes the development of a process of transferring data between environmental sensors and a smart cloud-based system. In addition, an innovative protocol named *Best Remote Antennas Unit Selection* (BRAUS) was launched. Depending on the number of RAUs, fiber length, distance, and attenuation factor, this protocol uses an innovative selection method. Both the bandwidth efficiency and the failure probability are computed and assessed mathematically with the help of the number of RAUs and the length of the cable. Our results demonstrate a 65% improvement in bandwidth efficiency and a 34% reduction in failure probability for the suggested protocol.

Chapter 4

IoT-RoF Quantum Entanglement-Based: Delay Investigation of MAC Protocol

4.1 Introduction

The basic benefit of the 802.11 RoF design is the deployment of the capacity and transparency of the fiber optic networks combined with the adaptability, resilience and mobility of the wireless networks.In addition, use of Remote Antenna Units (RAUs) within the vicinity of the mobile stations can make it easier to improve the quality of service substantially[62]. This structure lowers the dependency on long distance transmission by wireless. It will in turn help reduce power consumption in the communication network [63]. Radio-over-Fiber (RoF) technology is suitable both in indoor and outdoor radio environment because it meets high performance standards needed in continuous applications. This covers latency sensitive application like the haptic Internet. This allows it to be a perfect solution to such advanced scenarios in communication with its reliability and low-latency features[64]. But there's a major snag when you use IEEE 802.11 via RoF. Even though the MAC standard IEEE 802.11 is designed to work with a latency of less than 1 picosecond, the Radio-over-Fiber (RoF) has latency effects of about 5 picoseconds over each kilometer of the optical cable. Although this propagation delay is very small it is much greater at longer transmission distances. This makes it necessary to take into consideration in the design of high performance and time sensitive communication systems with a lot of care[65].The existing IEEE 802.11 MAC protocol is a threat to performance degradation and even network collapse since there is a high occurrence of the packet collisions and acknowledgment (ACK) latency. All these issues compromise the protocol performance, especially when a network is dense.[66]. Therefore, for the system to work effectively and benefit from the above-mentioned benefits of 802.11 RoF networks, existing systems must be modified to reflect additional optical equipment. There are two ways to consider solving the problems caused by RoF (Radio over Fiber). To transfer signals to the office over fiber optics, the first step is to design an appropriate Media Access Control (MAC) protocol that accounts for the propagation delay. Second, to remove the transmission delay of control packets for MAC protocols in RoF systems, one can employ quantum entanglement[67]. This study handles reliability and mitigation of packet control effects those are directly involved in propagation delay in Radio-over-Fiber (RoF) systems. With the aim of addressing these issues, an IoT-RoF model built on quantum entanglement is presented and elaborated. The purpose of this approach is to be able to improve on communications efficiency and eliminate delay in next generation networks[68]. There are five distinct functional domains in the IoT-RoF system that are not present in the wider concept Figure(4.1). This study's examples are summarized in the following way:

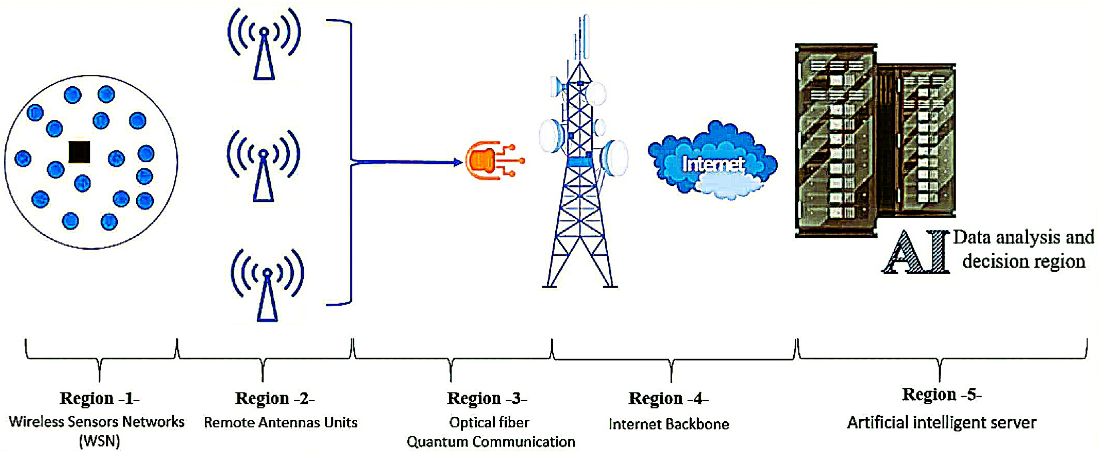

Figure 4.1: Conceptual communication scenario of IoT-RoF quantum entanglement.

A temporary or permanent disruption occurs in the first zone, known as the "sensor zone," where sensors such as webpages, alarms, and carbon monoxide detectors are located. Using the protocol outlined in the following section, the sensor transmits the data it has collected to the master node. The master node outshines regular sensors in every way: power, battery life, and enclosure size. When the master node processes the information taken by the sensor, it sends the information to the respective Remote Antenna Unit (RAU).Remote Antenna Unit (RAU) Zone 2 Reception, electrical-to-optical conversion, and data transmission via fiber optic cable are all functions of this network component. Section 3, Quantum Entanglement: Here, the signal that is received is either already entangled (data packets only) or has been transmitted directly through optical fiber (data alone) illustrated in figure(4.2). The RAU and each state's base station will communicate via control packet exchange; Area 4 will not receive these packets (by choosing the correct department). Zone 4 is the receiving area for papers prior to their storage and analysis by law enforcement. Recently, many scientists have speculated about the quantum entanglement phenomenon. However, there has been no research on using wireless sensor networks to explore RoF via quantum communication or using quantum entanglement in IoT-RoF to analyze the MAC protocol. Also, there is no study analyzing the delay, duty cycle, or power consumption of quantum entanglement-based IoT-RoF. The results of this study can be summarized as follows:

1. Sensors sense information from the environment and send data to the decision-making process; this research presents a new Internet of Things-RoF design that relies on quantum entanglement

2. The quantum entanglement-based IoT-RoF concept has two connections: one for data transmission through the classical link and another for data transfer through the MAC protocol. After mathematically modeling the suggested QE-MAC's latency, we were able to obtain a 35% reduction in delay when compared to our earlier work.

3. Additionally, the cycle and power consumption of the QE-task MAC are correlated with impulse and thought, and they have been reduced by 35% in comparison to that of previous research.

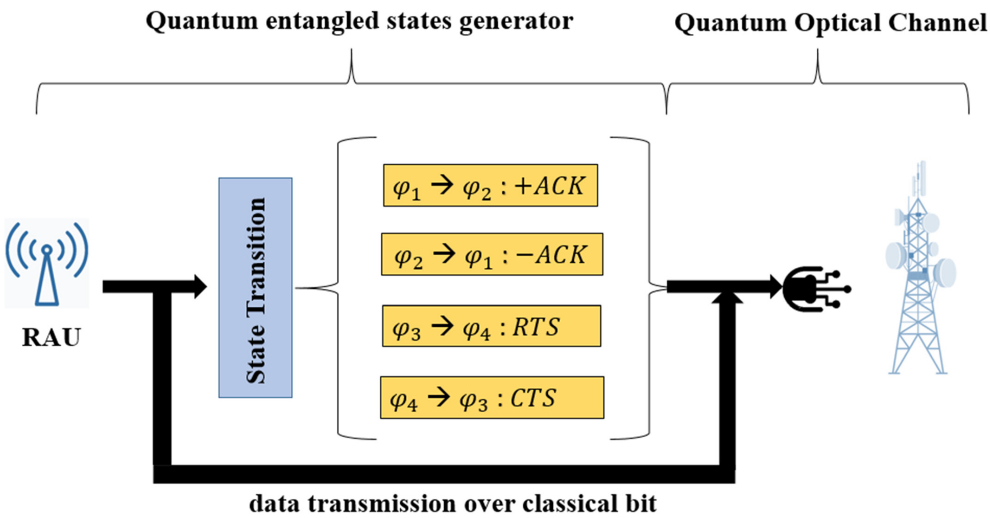

Figure 4.2: State transition of the proposed protocol.

4.2 Related Work: Quantum Entanglement

There are no studies in the existing literature that specifically explore quantum MAC protocols leveraging entanglement. However, entanglement has been extensively researched in various fields of quantum communication and other advanced applications. These applications cover some highlights of the quantum technology. Quantum cryptography is one of these areas as it secures data by using some basic laws of quantum. Decentralized quantum computing is a kind of quantum computing that distributes quantum computation overheads into several nodes, that is, it enhances scalability and computation power. At the same time quantum sensing technics especially quantum metrology, make use of quantum phenomena to gain the benefit of improved measurement sensitivity. These changes in concert make it possible to create very precise and distributed quantum-enabled systems[69]. Additionally, entanglement plays a crucial role in multipartite spectroscopy, enabling detailed analysis of quantum systems. Quantum entanglement and some of the most modern forms of quantum communication, including quantum encryption and quantum teleportation, for instance, rely on it. Furthermore, entanglement, which is a purely quantum phenomenon, also holds importance to the same extent as the creation of the basic infrastructure of the communication protocols. These two elements can by no means be separated once they have been joined together[70]. The study proposes a communication protocol in the form of two-way transfer of information through quantum entanglement. An ultra-dense coding scheme is first used to take classical information as the input, and then classical and quantum information, which is also in the form of qubits, will be sent in parallel via the quantum teleportation protocol. Such dual-layer wiring would allow transmitting classical and quantum information simultaneously through entangled quantum connections. A distinct benefit of this two-fold communication approach is a highly effective, and a secure quantum system, communication structure. The combination of the two mechanisms allows to create capabilities that cannot be done without when communicating in a modern way, by quantum means. This two-mode operation adds the flexibility of the protocol in quantum communicating systems. It has the capability of supporting large-capacity information transfer as well as safe quantum-state transfer at the same time. Several advantages of quantum communication are transmitting quantum information, propagating entanglement, and setting up security points[71]. To achieve the standard of quantum communication, the most favorable point-to-point spacing between the work site and the distal end of the quantum channel should be set. The need of such tuning arises due to the fact that with classical communication, unlike the case of quantum communication, distances are not usually limited. Such accurate tuning of this spatial variable allows achieving both efficient and reliable quantum information exchange.The communication speed that can be achieved is limited in this case, since the two supporting channels are present and the challenge of quantum repeaters has not been raised. The present paper includes a number of quantum elements, such as Bose lossy channels, QLA, phase shifters, and cancellation mechanisms of signals. All these constituents support the development of a smart quantum communication scheme.[72]. Energy distributions constrained in resources may be communicated along quantum channels which utilize the relative entropy of entanglement and a dimension independent protocol known as teleportation stretching. Such arrangement enables the creation of universal quantum communication channels on arbitrary-dimensional space[73]. To investigate the tradeoff between excellent work and process throughput, latency, and other performance metrics. Lastly, developing scheduling algorithms for quantum networks with the objective of enhancing their efficacy in a variety of scenarios is done[74]. Despite the numerous advantages of entanglement in the context of quantum information processing, its practical implementation is restricted by factors such as noise and loss. It has been recognized by scientists for decades that the transmission efficiency of lossy and chaotic boson channels can be enhanced through integration. On the other hand, this information has not been employed to create an efficient coding or decoding algorithm. This section elaborates on prevalent communication scenarios and the coding and decision-making processes that can be employed to address them[75]. It is evident that the primary constraints of covert communication can be surmounted through the application of phase coding to two distinct types of entangled compressed vacuum. This technique saturates the entanglement potential, which facilitates classical communication in a high-noise channel. Subsequently, we develop receivers that optimize the testing of hypotheses through phase discrimination and noise estimation through continuous phase. Improved communication and perception in the radio frequency spectrum and microwave are enabled by our discovery.Numerous technologies that facilitate quantum entanglement at a distance, including quantum distribution, encrypted communication, and absolute information, are currently in development [76].This study analyzes how to be able to de-entangle, at a very blistering pace, several user pairs. It can be done by using a quantum network whereby the nodes relied upon have restricted quantum capacities. Optical connection exists between these nodes referred to as eye therapy channels. By using various methods in the network, our proposed method for such quantum "repeater" nodes allows to achieve an increase in the connectivity between a pair of users in the quantum repeater network.A procedure is also formulated which is iterative and thus allows several pairs of users to create a common session, but much more quickly than in the previous time-sharing under a single shared system. The outcomes indicate that Bell state measurements, with short term quantum memory, have an enormous influence on the performance of quantum networks. This is more than the gains that can be made using the traditional standard vertical horizontal analysis.. The basic structure enables the researcher to smoothly pile ideas of quantum storage physics, quantum information theory, quantum error correction and computer network theory. This kind of integration enables creation of an integrated and complete theory. Finally, it helps in forming a universal quantum networks theory. In the last few years, there has been progress in attempts to demonstrate the properties of quantum repeaters [77].Repeater architectures with multiplexed quantum memories to supply entanglement have been suggested, and the problem of coherent entanglement in long range networks has not been solved. In order to facilitate the connectivity of a quantum network, we have developed a quantum router architecture. To ascertain the speed and fidelity of the entanglement distribution in this design, we employ an event-driven simulator. Our findings indicate that the router enhances entanglement fidelity as the multiplexing depth increases while continuously maintaining its speed. Even without channel loss, the router can provide the same integrity as a bad link. Additionally, our system automatically prioritizes access across the entire network without requiring global information. This design facilitates the startlingly different reality of multi-node quantum networks that may soon be there by utilizing extant photonic technologies. An isolated observer can create a small number of pure entangled pairs (i.e., near-perfect singlets) by local control of the impure states (i.e., singlets replaced by noise)[78]. These can be employed to facilitate the transfer of quantum states of observers, thereby enabling the transmission of quantum information over noise channels. Entanglement propagation between nodes in large quantum networks can be highly advantageous for secure communication[79] , decentralized quantum computing, sophisticated information, and quantum physics experiments. Decoherence must be overcome by the entanglement that is established between nodes in networks with more than two. The intervention process can be transformed into a potent building element that can enhance connections that were previously disconnected from the decision-making process once this critical point is resolved. According to, coherence serves as the fundamental principle of quantum physics. When analyzing the measurement of two or more related variables, the viewer will observe a relationship that contradicts the statistical description. The creation of a long-distance network on quantum-scale systems is seen as an important first step to realize its promise as a useful tool, especially in long-range quantum communication. We demonstrate the process of establishing and analyzing the entanglement of the spins of two rubidium-87 atoms that are placed 20 meters apart in a magnetic trap. Our findings indicate that they have the potential to revolutionize quantum physics and quantum information science investigations. According to the authors, the study is a new direction that has not gained exploration in the past.In contrast to the conventional MAC protocol, which uses controllers, dynamic switching is implemented. This novel methodology will enhance efficiency while simultaneously decreasing latency and power consumption[80].

4.3 Delay Analysis of conventional DCF in RoF

The primary objective of the IEEE 802.11 MAC sublayer is to guarantee the security of user data in the wireless channel, even when the wireless channel is unreliable. To achieve this, IEEE 802.11 MAC employs two methods: the two-way handshake and the four-way handshake[81]. Conventional DCF delay with or without RTS/CTS packet: Conventional DCF delay in the absence of RTS/CTS packet Afterward, the two-way communication can be finalized without the RTS/CTS packet in the following manner:

Calculating the Time for Packet Transmission:

- For a node to be allowed to send a packet, it has to first wait for the DIFS plus the turnaround time. The DIFS is a predetermined amount of time that the nodes must wait before attempting to transmit once the medium is idle. This makes certain that nodes have the optimum opportunity to access the medium without interferences.

- The turnaround time is an apparently random time interval aimed at preventing contention between the nodes that may attempt to access the medium simultaneously. Adding a random factor serves to actually lessen collisions because it makes it improbable that any nodes will repeatedly select the same transmission times.

Accessing the Medium:

- A node may attempt to send if the channel is sensed to be free and the node does not see any activity within the specified time. This idle time is checked against DIFS plus the pseudo-random turnaround time. If the channel is available at this time, the node forwards the packets for this node that are waiting in the buffer see Figure 4.3 .

Waiting for Acknowledgment:

- After a node has transmitted the packet, it brings Ack from the receiver in Short Interframe Space (SIFS). The SIFS is less than the DIFS and is used primarily to allow for a quick response to successful reception of packets. This small break makes certain that the ACK packet gets out as soon as possible and thus cuts the latency, enhancing the efficiency of the protocol. Starting New Conversations: Instead, there exists another communication cycle after the transmission and the acknowledgment process. Other stations or the nodes such as transmitters who were waiting, also begin their DIFS plus turnaround time-DIFS calculations. This helps in making sure that new packets are transmitted in an orderly manner, as all the nodes will check the medium, hence no collision as there is adherence to the DIFS and turnaround times. We can express the average length of a two-way handshake without RTS/CTS packets mathematically as:

$$E[\text{slot}] = P_{\text{idle}} \cdot T_s + P_{\text{suc}} \cdot T + (1 - P_{\text{suc}} - P_{\text{idle}}) \cdot T_c + P_{\text{suc}} \cdot 2\alpha \cdot (1 - P_{\text{suc}} - P_{\text{idle}}) \cdot 2\alpha \tag{4.1}$$

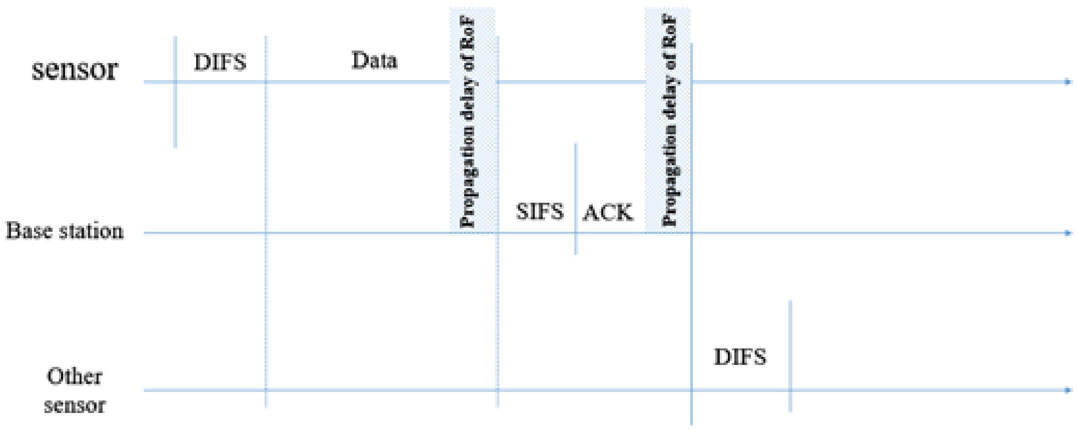

Figure 4.3: The IEEE 802.11 MAC for RoF for broadcast latency.

In which

$P_{\textbf{idle}}$**:** the probability that no sensor accesses a given slot.

T_s**:** denotes the CSMA slot length.

$P_{\textbf{suc}}$**:** probability that just one sensor accesses a slot.

T**:** defined as the total time to transmit a packet.

T_c**:** the average time the channel is sensed busy during a collision.

α**:** propagation delay time.

The mathematical expression for P_{idle} for N sensors (where the N sensors enter at different times and independently with the τ result) is expressed by:

$$P_{\text{idle}} = (1 - \tau)^N \tag{4.2}$$

The P_{suc} mathematicalexpression is given as:

$$P_{\text{suc}} = N \cdot \tau \cdot (1 - \tau)^{N-1} \tag{4.3}$$

The mathematical formulation of T=Tc encompasses several key time components, including the Distributed Inter-Frame Space (DIFS) time, Short Inter-Frame Space (SIFS) time, the duration for transmitting DATA, the Backoff time, and the Acknowledgment (ACK) packet time.

$$T = T_{\text{DIFS}} + T_{\text{SIFS}} + T_{\text{DATA}} + T_{\text{BC}} + T_{\text{ACK}} \tag{4.4}$$

T_{DATA}signifies the cumulative duration necessitated for the transmission of a data packet. This packet is constituted of various components: the preamble T_p,the physical layer header T_{PHY}, the MAC layer header T_{MAC}, the MAC frame body T_{BODY} and the frame check sequence T_{FCS} The comprehensive duration required for the transmission of a communication packet is computed as follows: .

$$T_{\text{DATA}} = T_p + T_{\text{PHY}} + T_{\text{MAC}} + T_{\text{BODY}} + T_{\text{FCS}} \tag{4.5}$$

where T_{BC} is given as:

$$T_{\text{BC}} = \frac{CW_{\min} \cdot T_s}{2} \tag{4.6}$$

In this context, $\text{Slot}(0, CW)$ refers to a pseudo-random integer that is uniformly distributed within range $(0, CW)$. Here, CW represents the contention window size, which determines the range of possible values for the slot time. A time slot is a defined time interval that exists due to protocol agreements, during which specific actions are permitted.

When a data packet or information packet is received,the extent of the contentious window CW is limited within the designated time duration.This mechanism guarantees the harmonious interaction between the time slot and contention window, facilitating effective network traffic management, mitigating the occurrence of collisions, and enhancing the efficiency of data transmission[82].

$$CW_{\min} \leq CW \leq CW_{\max}$$

In this scenario, CWmin represents the minimum size of the contention window, while CWmax denotes the maximum allowable size for the contention window. These parameters define the range within which the contention window can fluctuate. When a transmission is successfully completed, the size of the contention window CW is restored back to its initial value.CWmin. However, if a retransmission is necessary due to a collision or transmission failure, the contention window CW is doubled, effectively increasing the time before the next attempt, as demonstrated in the following diagram. This adaptive mechanism helps to reduce the likelihood of repeated collisions in high-traffic scenarios, thereby improving the overall efficiency and stability of the network.

$$CW_i = CW_{i-1} \cdot 2 \tag{4.7}$$

Traditional DCF delay via RTS/CTS packets: Conversely, we can reach a conclusion regarding the four-way handshake using RTS/CTS packets as follows:

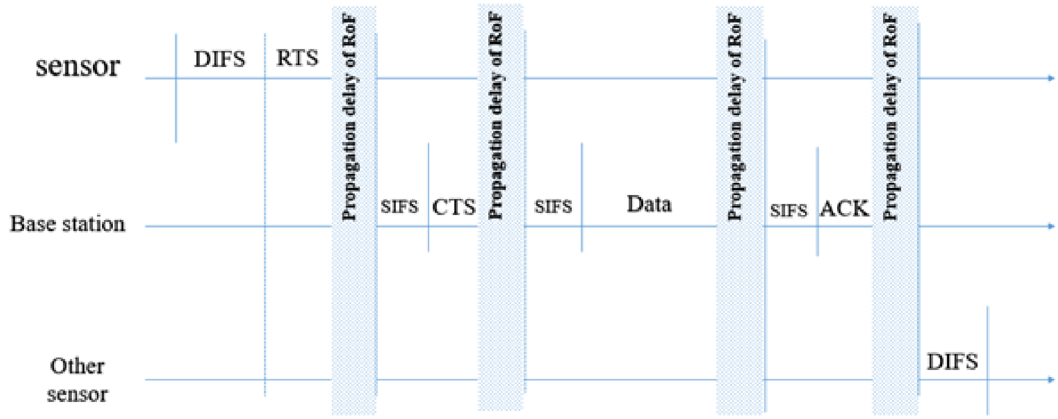

Figure 4.4: RoF, IEEE 802.11 MAC takes into account RTS/CTS control packets.t.

The architecture of the 802.11 Radio-over-Fiber(RoF) is based on combining the high-capacity potential of increased transmission rates and the transparency provided by fiber optic networks with flexibility, resilience and mobility of wireless networks. Such a combination of both makes a strong and flexible communication framework. It acts as a basis of the deployment of the next generation broadband networks An additional advantage of CS is its simplicity, which enables the direct use of RAUs, enhanced coverage, and the limitation of over-the-air broadcast and transmission capabilities because of the proximity of RAUs to mobile stations. In addition,Radio-over-Fiber (RoF) technology is an ideal solution to centralized or air interface radio system. It is especially appropriate in meeting the strict requirements of new applications like the so-called tactile Internet, both in terms of data rate, latency, and reliability. This helps RoF become a major enabler of the next-generation communication infrastructures[83].However,a major issue with the use of IEEE 802.11 on RoF.The 802.11 MAC protocol, aims to deliver a less than 1 microsecond propagation delay.Relative to these, the presented offset delay in the RoF network is 5 microseconds every kilometer of fiber. When using the existing IEEE 802.11 MAC protocol, this can cause significant outages due to many collisions or acknowledgment (ACK) delays and can even harm the network performance. Will the RTS/CTS packet of RoF slowdown in traditional DCF. Assuming that ACK frames are sent using SIFS cycles and therefore have priority, they will not collide with other frames in the normal DCF process as long as there is no terminal. However, ACKs may collide with frames sent by other STAs within the WLAN length.Conventional DCF delay in the absence of an RTS/CTS packet for RoF: Collision caused by a late ACK packet in this thesis. The ACK packet is transmitted using the SIFS period, which ensures that it never collides with other data packets or data frames in a conventional DCF procedure, unless concealed terminals are present. This is due to the ACK packets having a high priority. Nevertheless, in the Rof system, the ACK may collide with other packets conveyed by the other sensors (stations, STA)[84]. An ACK collision is illustrated in Figure4.4 13. Upon the completion of a data frame transmission from an STA to an AP, the AP and transmitter STA are required to wait for the ACK packet. However, the ACK packet may be received at a time that is greater than the time required to receive the packet due to the delay of the fiber optic cable. This delay may result in a collision with another data frame that was transmitted from another STA. $T_{\text{ack\_arrival}}$ is longer than received, meaning $T^{\text{RoF}}_{\text{ack\_arrival}} = \text{SIFS} + T_{\text{ACK}} + \text{DIFS}$, which will cause conflict with other data sent among other STAs[85].

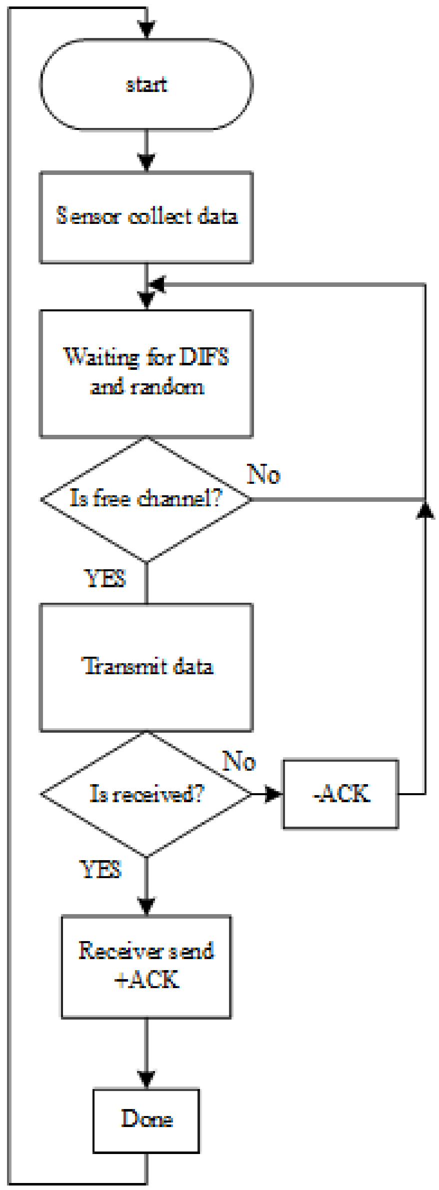

Figure 4.5: Flowchart of the Channel Access Mechanism in RoF-Based Wireless Sensor Networks.

As shown in Algorithm 4.1, the channel access follows a backoff and acknowledgment procedure.

Algorithm 4.1 Channel Access Procedure for RoF-Based Sensor Nodes

```
1: Sensor collects data from the environment.
2: Wait for DIFS and a random Backoff time.
3: if Channel is free then
4:     Sensor transmits data.
5:     Wait for the receiver's response.
6:     if Data is received correctly then
7:         Wait for SIFS time.
8:         Receiver sends a positive acknowledgment (+ACK) to the sender.
9:     else
10:        Wait for SIFS time.
11:        Receiver sends a negative acknowledgment (-ACK) to the sender.
12:        Go to Step 2 and retry transmission.
13:    end if
14: else
15:    Wait for the next round of competition.
16:    Go to Step 2 and retry.
17: end if
```

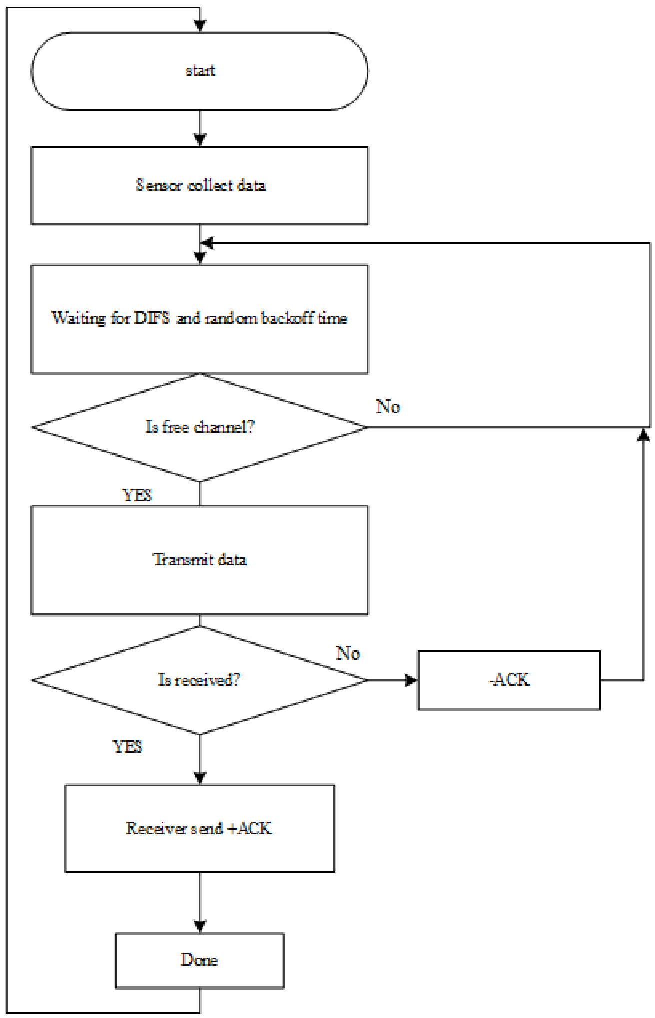

Figure 4.6: Flowchart of the Channel Access Mechanism in RoF-Based Wireless Sensor Networks.

Below is the numerical representation of the average length of RoF bidirectional processing without RTS/CTS packets:

$$\begin{aligned}\mathbb{E}[\text{slot}]_{\text{RoF}} = & P_{\text{idle}}T_s + P_{\text{suc}}T + (1 - P_{\text{suc}} - P_{\text{idle}})T_c + P_{\text{suc}}2\alpha \\ & + (1 - P_{\text{suc}} - P_{\text{idle}})2\alpha \\ & + \underbrace{2\alpha + T_c^{\text{ACK}}}_{\text{delay due to collision and propagation of RoF}}\end{aligned} \tag{4.8}$$

The time addition caused by the use of RoF system is expressed as:

$$T_{\text{delay}}^{\text{RoF}} = 2\alpha + T_c^{\text{ACK}} \tag{4.9}$$

Delay of normal DCF of RTS/CTS packets in RoF: When using normal DCF of RTS/CTS packets in RoF, collision will occur again from ACK Addition due to round trip of RTS/The more CTS packets, the longer the delay[86].In this case, the numerical average length of the two-way handshake mechanism of RTS/CTS packet of RoF can be represented in the form as:

$$\begin{aligned}E[\text{slot}] = & P_{idle}\, T_s + P_{suc}\left(T + T_{RTS+CTS} + T_{RTS+CTS}^{\text{delay, RoF}}\right) \\ & + (1 - P_{suc} - P_{idle})\left(T_{RTS+CTS}^{\text{delay, RoF}} + T_{RTS+CTS} + T_c\right) \\ & + \underbrace{P_{suc} \cdot 2\alpha + (1 - P_{suc} - P_{idle}) \cdot 2\alpha}_{\tilde{\alpha}} + \underbrace{\frac{2\alpha + T_c^{ACK}}{c}}_{\textit{delay due to collision and propagation of RoF}}\end{aligned}$$

$$\begin{aligned}E[\text{slot}] = & P_{idle}\, T_s + P_{suc}\, F_T\left(T_{RTS+CTS}^{\text{delay, RoF}}\right) + P_{ro}\, F_{T_c}\left(T_{RTS+CTS}^{\text{delay, RoF}}\right) \\ & + \bar{\alpha} + F(\alpha)\end{aligned} \tag{4.10}$$

Algorithm 4.2 Sensor Communication Protocol

```
1: Sensor collects data from the environment
2: Sensor waits for DIFS and a random Backoff time
3: if communication channel is free then
4:     Sensor transmits an RTS (Request to Send) packet to the receiver
5:     Both receiver and transmitter wait for SIFS time
6:     Receiver sends a CTS (Clear to Send) packet to the sender
7:     Transmitter waits for SIFS time, then sends the data to the receiver
8:     if data is received correctly then
9:         Receiver and sender wait for SIFS time
10:        Receiver sends a Positive Acknowledgment (+ACK) to the sender
11:    else
12:        Receiver and sender wait for SIFS time
13:        Receiver sends a Negative Acknowledgment (-ACK) to the sender
14:        Go back to step 2 and retry transmission
15:    end if
16: else
17:    Sensor waits for the second round of competition
18:    Go back to step 2 and retry
19: end if
```

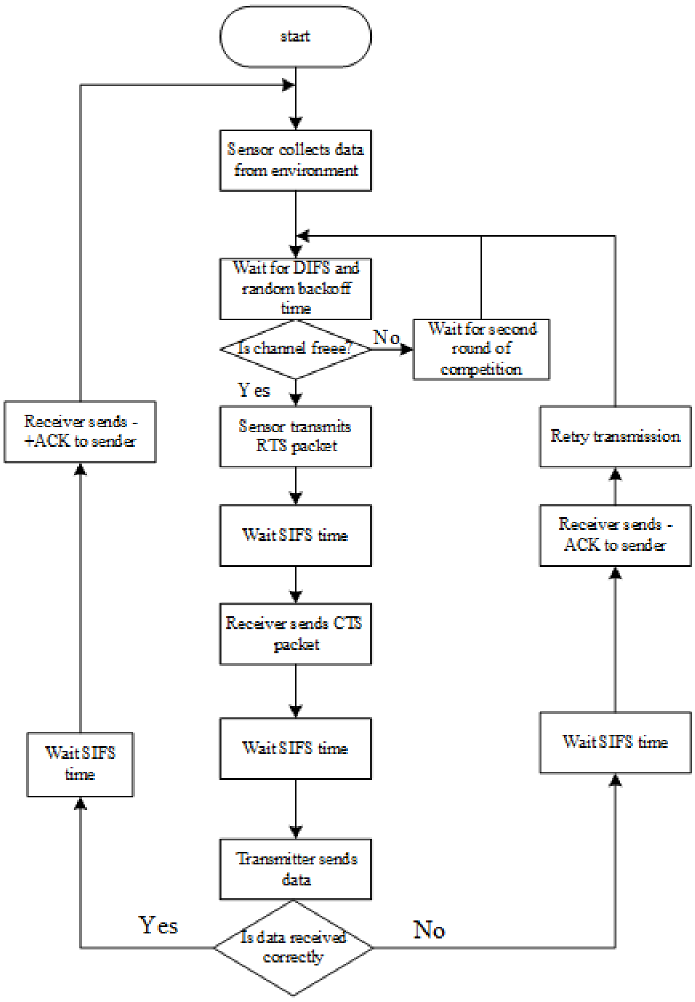

Figure 4.7: Flowchart of the Channel Access Mechanism in RoF-Based Wireless Sensor Networks.

4.4 Delay of Proposed Quantum Entanglement-based MAC protocol

4.4.1 Delay of Quantum Entanglement-based without RTS/CTS packet

Algorithms 1 and 2 are modified in accordance with the variations in the photon state. As the state changes, the quantum process will modify the +ACK and -ACK signal packets, each modification representing one of the control (signature) packets. Negative polarization will be entirely precluded in RoF systems, as the propagation delay will be zero because of the distance or fiber, as the time required to alter the polarization of the two ends is zero. When quantum is used, the delay caused by the laser source T_{laser} and the detector T_{detector} included in the total delay of the quantum entanglement-based MAC protocol[87] Therefore, the delay is denoted as:

$$\begin{aligned} E[\text{slot}] = P_{idle}\,T_s + P_{suc}\,(T + T_{\text{laser}} + T_{\text{detector}}) \\ + (1 - P_{suc} - P_{idle})\,(T_{\text{laser}} + T_{\text{detector}} + T_c) \\ + P_{suc} \cdot 2\alpha + (1 - P_{suc} - P_{idle}) \cdot 2\alpha \end{aligned}$$

$$E[\text{slot}] = P_{idle}T_s + P_{suc}F(T_Q) + (1 - P_{suc} - P_{idle})F(\bar{T}_Q) + F(\bar{\alpha}) \tag{4.11}$$

For two packets, it should have four states, φ_1 and φ_2. The entangled Quantum Entanglement-based MAC protocol without RTS/CTS packet of RoF algorithm is given below:

4.4.2 Delay of Quantum Entanglement-based without RTS/CTS packet

A modification is made to algorithms 1 and 2 in accordance with the alteration in the photon state. The +ACK, -ACK, RTS, and CTS signal packets are modified by the quantum operation through state transitions, each of which represents one of the controls (e.g., packets). As the time required to alter the polarization of the two extremities is zero, the propagation delay caused by distance or fiber will be nonexistent, and the drawbacks of RoF systems will be eliminated [88]. When

Algorithm 4.3 State-Based Transmission Algorithm for Sensor Communication

```
Sensor collects data from environment
Wait for DIFS and random Backoff time
if channel is free then
    Sensor transmits data
    if data received correctly by receiver then
        Wait SIFS time
        State transition: φ1 → φ2
    else
        Wait SIFS time
        State transition: φ2 → φ1
    end if
else
    Wait for next round of competition
end if
```

quantum is used, the delay caused by the T_{laser}laser light and the T_{detector}device includes the total delay of the MAC protocol as quantum entanglement, so the delay can be expressed as:

$$\begin{aligned} E[\text{slot}] = P_{idle}\, T_s + P_{suc}\,(T + T_{RTS+CTS} + T_{\text{laser}} + T_{\text{detector}}) \\ + (1 - P_{suc} - P_{idle})\,(T_{\text{laser}} + T_{\text{detector}} + T_{RTS+CTS} + T_c) \\ + P_{suc} \cdot 2\alpha + (1 - P_{suc} - P_{idle}) \cdot 2\alpha \end{aligned}$$

$$E[\text{slot}] = P_{idle} T_s + P_{suc} F(\bar{T}_Q) + (1 - P_{suc} - P_{idle}) F(\bar{T}_Q) + F(\bar{\alpha}) \tag{4.12}$$

$P_{\text{idle}} T_s$

- Probability of an **idle slot** multiplied by its duration T_s.
- P_{idle}: Probability that no station transmits in this slot.
- T_s: Duration of an idle slot.

$(1 - P_{\text{suc}} - P_{\text{idle}}) F'(\bar{T}_Q)$

- Represents the **collision case**, when multiple stations transmit.
- $1 - P_{\text{suc}} - P_{\text{idle}}$: Probability of a **collision**.
- $F'(\bar{T}_Q)$:Higher delay or retransmission time.

$P_{\text{suc}} F(\bar{T}_Q)$

- Expected duration contributed by **successful transmissions**.
- P_{suc}: Probability that exactly **one station** transmits (no collision).
- $F(\bar{T}_Q)$: Packet transmission time under success conditions.

$F'(\bar{\alpha})$

- Independent of the slot type.
- $\bar{\alpha}$: Contention window adjustment.
- F':Interference or control overhead.

For three packets, we should have four states, φ_1, φ_2, φ_3, and φ_4. The entangled DCF without RTS/CTS packet of RoF algorithm is given below:

Algorithm 4.4 RTS/CTS State-Based Sensor Communication with Acknowledgment Handling

```
1:  Sensor collects data from the environment
2:  Sensor waits for DIFS and a random Backoff time
3:  if channel is free then
4:      State transition: φ3 → φ4 (RTS packet transmitted)
5:      Both receiver and transmitter wait SIFS
6:      State transition: φ4 → φ3 (CTS packet transmitted)
7:      Transmitter waits SIFS and sends data to receiver
8:      if data is received correctly then
9:          Receiver and sender wait SIFS
10:         State transition: φ1 → φ2 (+ACK sent)
11:         return Successful transmission
12:     else
13:         Receiver and sender wait SIFS
14:         State transition: φ2 → φ1 (-ACK sent, indicating failure)
15:         return Retransmission required
16:     end if
17: else
18:     Sensor waits for the next contention round
19:     Go back to Step 3 (Sensor waits for DIFS and random Backoff time)
20: end if
```

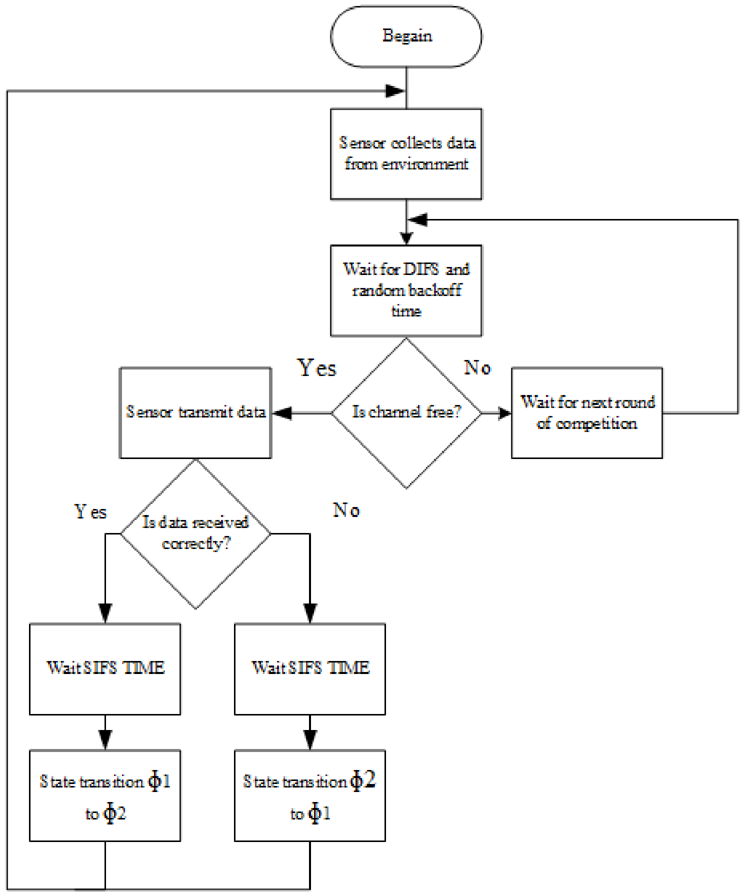

Figure 4.8: Flowchart of the Channel Access Mechanism in RoF-Based Wireless Sensor Networks.

4.5 Power Consumption and Duty Cycle of Proposed Quantum Entanglement-based MAC Protocol

The duty cycle (DC) and power of IEEE 802.11 CSMA/CA classical communication, which is based on RoF, will be the subject of this subsection. Subsequently, the proposed quantum entanglement-based MAC protocol will be described, along with its corresponding powers.Duty cycles are determined by the percentage of time that the system is in a "active" state.The sensor transceiver's RF active time is the duration during which it is operational, whether it is transmitting data, receiving data, or passively listening to an inactive channel [89]. The duty cycle is calculated as:

$$\text{Duty} = \frac{T_{\text{act}}}{T_{\text{sleep}}}(1 + \text{PER}) \tag{4.13}$$

This work defines the RF activity time as the time during which the sensor is inactive in order to preserve the network's lifespan. Assuming a very low transmission error rate (PER), 1+PER = 1. Based on the average current during the activity period and the duty cycle of RF activity, the energy consumption is determined. Energy consumption can be enhanced by reducing the transmission power and the overall transmission duration, as the current consumption during data reception remains constant[90]. The aggregate mean communication power P_{av} is calculated as follows: In this framework, T_{act} denotes the duration wherein the radio frequency (RF) module is actively functioning, executing operations related to data transmission and reception. In this research, T_{act} is characterized as the expected value of the time slot, $E[\text{slot}]$, which indicates the mean duration the RF module remains in an active state. Conversely, T_{sleep} pertains to the interval during which the sensor operates in a low-power sleep mode, an essential element in enhancing the overall longevity of the network by facilitating energy conservation. This analysis considers the Packet Error Rate (PER) but assumes a low enough value to be basically irrelevant: 1+PER=1. This assumption makes it easy to calculate errors as having minimal impact. Because transmission current dominates the whole receiver power consumption, it is not easy to decrease, though transmitter savings may be recordable for the total packets receiving time needed. The total average communication power, denoted byP_{av}, explains the energy efficiency of a system and aims to minimize energy consumption while ensuring communication reliability. The symbol P_{av}. is calculated like this:

$$P_{\text{av}} = \text{Duty} \cdot V_{dd} \cdot I_{\text{active}} \tag{4.14}$$

The duty cycle, in this context, relates to the "duty" of the RF module, which is basically a ratio between active time and the total operational period. It's basically a measure of the RF module transmitting or receiving data versus its operational time[91]. V_{dd} is the supply voltage given to the RF module, which plays an important role in keeping the device alive when it is awake. I_{active} is the average current the RF module consumes when it goes active within this one timeframe. The duty cycle is an essential feature that defines the energy efficiency of such a system. It has already been reported that the duty cycle of any application can be optimized by making the mentioned changes, and that on-time-on behavior will further help reduce power consumption when the RF module is kept awake only for the required time. Such a balance is essential to preserve the power budget of wireless devices, which often operate on limited energy sources[92]. The Quantum Entanglement-based duty-cycled protocol introduces a specific background RTS-CTS (Request to Send-Clear to Send), which exploits quantum effects to avoid sending any messages. Based on this, the asynchronization level introduced has a significant impact on final savings. This saves overhead that would be used up by RTS/CTS packets, eliminating unnecessary active time and helping save power. Let the (non-dimensional) duty cycle for this method be given by:

$$\text{Duty}_Q = \frac{P_{idle}T_s + P_{suc}F(T_Q) + (1 - P_{suc} - P_{idle})F(\bar{T}_Q) + F(\bar{\alpha})}{T_{\text{sleep}}} \tag{4.15}$$

Below is the average power consumption of quantum entanglement based RTS/CTS free devices

$$P_{\text{av}} = \left(\frac{P_{idle}\, T_s + P_{suc}\, F(T_Q) + (1 - P_{suc} - P_{idle})\, F(T_{\bar{Q}}) + F(\bar{\alpha})}{T_{\text{sleep}}} \right) V_{dd}\, I_{\text{active}} \tag{4.16}$$

Duty cycle of quantum entanglement based RTS/CTS packet implementation:

$$\text{Duty}_{\bar{Q}} = \frac{P_{idle}T_s + P_{suc}F(\bar{T}_Q) + (1 - P_{suc} - P_{idle})F(\bar{T}_Q) + F(\bar{\alpha})}{T_{\text{sleep}}} \tag{4.17}$$

The average energy consumption of quantum entanglement-based RTS/CTS packets is as follows:

$$P_{\text{av}} = \left(\frac{P_{idle}T_s + P_{suc}F(\bar{T}_Q) + (1 - P_{suc} - P_{idle})F(\bar{T}_Q) + F(\bar{\alpha})}{T_{\text{sleep}}} \right) V_{dd}\, I_{\text{active}} \tag{4.18}$$

4.6 Results and Discussion

In this part, proposed IoT-RoF Quantum Entanglement performance is evaluated by using computer simulations. The simulator distributes the random topology of sensors and master nodes over a 4 Km × 4 Km area. There are a large number of RAUs distributed in the same area, where the RAU is connected to the central office and the base station is connected to the optical fibers with a maximum of 25 Km. 4 photons are used for quantum channels. The proposed system uses two communication scenarios: the classical communication scenario for data transmission which use classic MAC protocol for transmission of the data and the control protocol; and second scenario is quantum communication scenario which use MAC with help quantum entanglement characteristic to transmit the control packet. All parameters are detailed in Table 4.1.

Table 4.1: Network Parameters and Their Values

Symbol	**Definition**	**Value**
CB	Channel bandwidth	20 MHz
R	Data rate	54 $Mbps$
R_l	Retry limit	7
CW_{max}	Contention Window Max	15
CW_{min}	Contention Window Min	7
$SIFS$	Short interframe space	16 μs
T_s	Slot time	9 μs
α_w	Propagation Delay – Wireless link	1 μs
α_{Fib}	Propagation Delay – Fiber Link	5 μs
T_{DATA}	Time required for data	216 μs
TRT S; CT S; ACK	Time delay: RTS, CTS and ACK packets	24 μs
T_{laser}	Delay for laser propagation	1 μs
$T_{detector}$	Delay for detecting of laser	1 ns
N_{pho}	Number of photons	4
V_{dd}	RF module supply voltage	1.8 $volts$
I_{active}	RF active average current	6.1 μA

Figure 4.9: The comparison between the classical MAC protocol and the quantum MAC protocol for IoT-RoF based on CWmin is shown. The results illustrated in Figure 4.10 clearly demonstrate that the classical MAC technique has a lower delay than the classical MAC technique with RTS/CTS, as the control packet increases the delay. However, the proposed Quantum MAC protocol exhibits superior performance. All control packets are invalidated, thereby preventing the propagation delay, in contrast to the MAC protocol and the classical MAC protocol with RTS/CTS. This outcome yields an intriguing observation: the Quantum MAC protocol and the Quantum MAC protocol with RTS/CTS have identical delays. Consequently, the RTS/CTS processing cycle can facilitate the classical communication depicted in Figure 15. We note that the duty cycle of classical communication with RTS/CTS packets is higher than that without RTS/CTS packets. In addition, the role of quantum entanglement is smaller than that of the communication with/without RTS/CTS packets because quantum entanglement uses the teleportation protocol to change the photon states without packet control. The quantum entanglement duty cycle and the duty cycle of classical communication increase with CWmin as we increase the turnaround time.

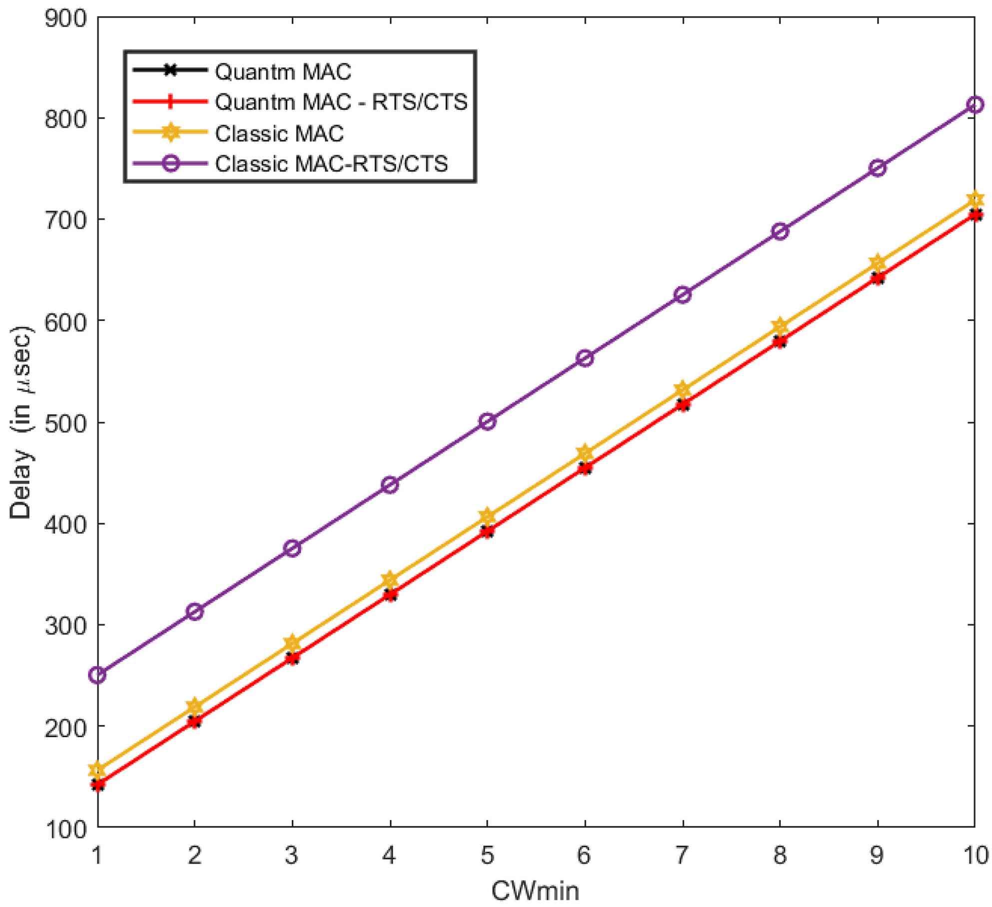

Figure 4.9: Classical MAC protocol and quantum MAC protocol for IoT-RoF.

In case when the QE-MAC protocol is used, the results of the performance of the RTS/CTS packet mechanism of protocol are just close to QE-MAC without the use of the RTS/CTS packets. The implication of this observation is significant with regards to collision avoidance and integrity of data.These are technically critical attributes in the area of sustaining reliability and soundness of the network communication schemes.

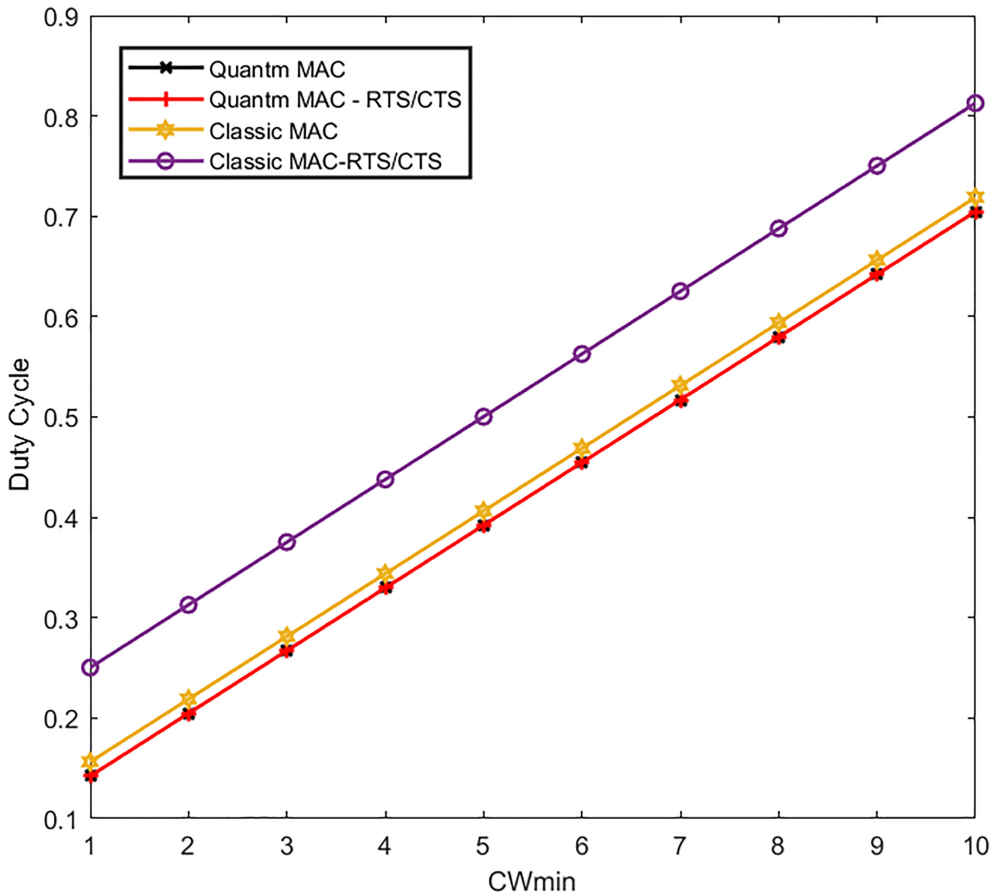

Figure 4.10: The role of quantum entanglement in IoT-RoF and classical IoT-RoF.

Figure 4.11 shows the power consumption as a function of CWmin for IoT-RoF quantum entanglement and classical IoT-RoF. Judging by the results, quantum entanglement wins in terms of utility because quantum entanglement with teleportation protocol does not require the transmission of photon states via body coupling, so it is a modest meal.

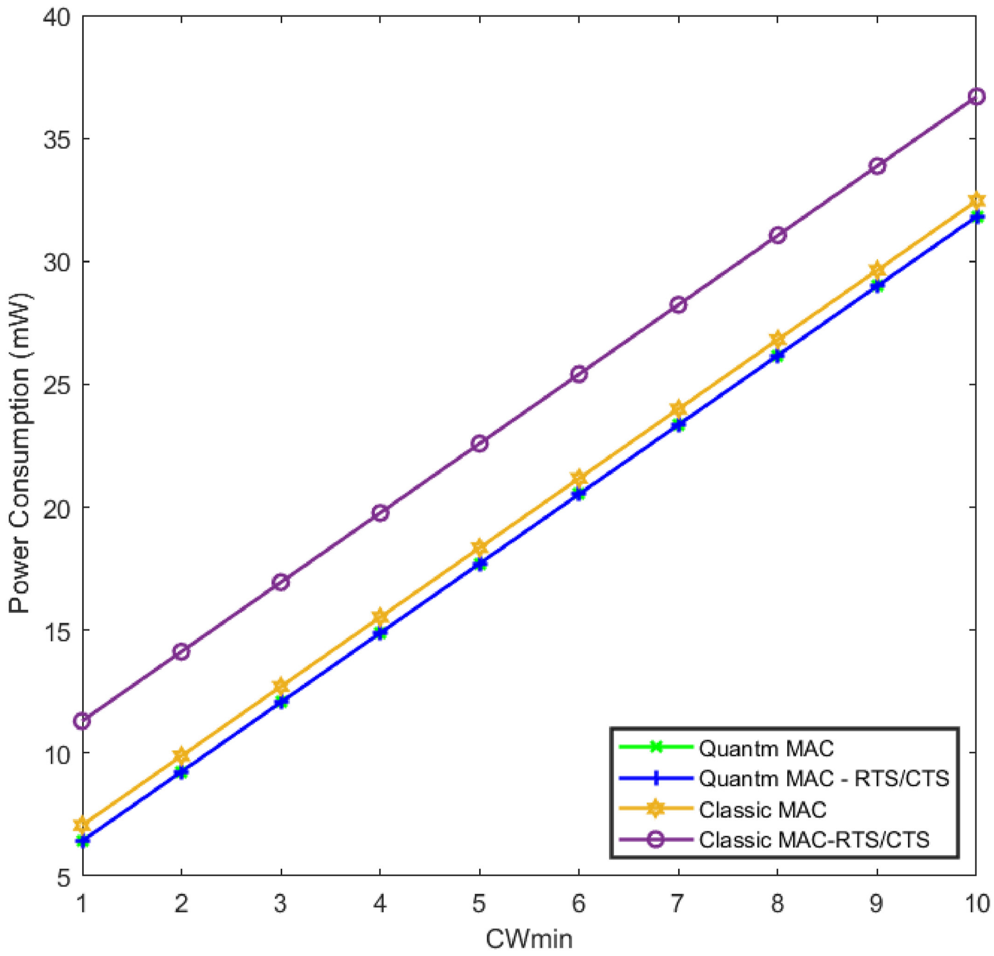

Figure 4.11: IoT-RoF benefit from quantum entanglement and classical IoT-RoF.

4.7 CONCLUSION

In this study,detailed models are analyzed the energy consumption, duty cycle, and latency of a newly proposed MAC protocol based on quantum entanglement (referred to as QE-MAC), which utilizes quantum teleportation technology. The research demonstrates that the QE-MAC protocol outperforms traditional methods in terms of power efficiency, duty cycle management, and delay reduction. Notably, the performance of the QE-MAC protocol with RTS/CTS (Request to Send/Clear to Send) packets is found to be on par with that of the QE-MAC protocol without RTS/CTS packets. This parity is significant because it indicates that the protocol effectively mitigates data loss and communication failures, crucial aspects for maintaining reliable network operation. Looking ahead, future research could focus on optimizing power distribution strategies for both host and sensor nodes to further enhance energy efficiency. Furthermore, expanding ways that will help in developing better means of collision avoidance might also boost performance. The study also established that employing a request function instead of a broadcast function decreases power demand by 35% and reduces communication delay and is hence viewed as a more effective tool in the management of the network resources.

Chapter 5

Energy Harvesting with network coding technique of Radio-over-Fiber: Toward minimizing of outage probability

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5.1 Introduction

One technology that has been adopted to become the technology of choice in next-generation access networks is the Radio-over-Fiber (RoF) technology. The multi-service feature of the system in question has been a result of the nature of the system itself whose design makes it possible to enable efficient co-existence of heterogeneous services. Besides, the low-power requirement coupled with the high transmission rate of the solution also increases its applicability to contemporary communication settings. All these qualities, altogether, make the system extremely effective and fit to more complicated, multi-service implementation conditions. Also, RoF has a high resistance to electromagnetic interference which adds to its suitability to the advanced communication infrastructures. Moreover, there is no lack of attraction of Multiple Radio frequency (RF) signal processing ability of Radio-over-Fiber (RoF) technology. This centralization minimizes hugely the peculiarity of the access nodes that are installed at the cell sites. The network architecture therefore ends up being efficient and manageable[93]. It enables the consolidation of intelligence, control, and signal processing in one place, such as a cloud-based system or a central office (CO). Electronic wireless communication (EW) has attracted considerable attention in recent years [94]. The technology could solve battery problems and extend the life of the network. Various charging technologies are used, including wind, solar, and electric energy. To extend the life of wireless sensor networks, a wind-powered wireless sensor network system is described and a new EW state and power transmission scheme is introduced. Due to its common and unique nature, wireless power transmission (WPT) using radio frequency (RF) signals is proposed[95].This study proposes wireless communication networks, focus being on data transmission and wireless power coordination. The organizing of these tasks is executed by a specific hybrid receiver which is called the H-slot. The H-slot intercedes the radio-frequency (RF) information to various single-hop nodes so that the connection of data transmission and power management is completed smoothly. Energy harvesting nodes with low-capacity batteries, multiple RF nodes, and various targets are also considered [96]. Hybrid Optical Wireless Networks commonly referred to in literature as MiWi, Hybrid Wireless Optical Broadband Access Networks, or Optical Wireless Networks are a low-cost implementation solution to the final-mile Internet access. Riding on optical and wireless innovations, they are striving to alleviate the restraints that have been witnessed with the traditional broadband delivery mechanisms. This combination of affordability and efficiency makes them a viable during delivery of broadband service to geographical areas that are under-served at the moment. Such networks are good compromiser of optical and wireless networks to make broadband available to end users. They are promising to tackle connectivity issues through deployment in the access network since they are economically viable.FiWi networks, which combine wireless access networks with fiber optic networks, have gained widespread attention over the last two decades and have witnessed increasing electricity bills. Their applications range from disaster relief, remote sensing, and multimedia communications[97]. The evaluation of the Radio-over-Fiber (RoF) effect on network performance is conducted on new methodologies, which are based upon the real-life conditions. Such assessments are part of the development of Heterogeneous Network (HetNet) designs. Specifically, the integration of the Mobile Edge Computing (MEC) and Fiber-Wireless (FiWi) LTE allows achieving the improvement.The MEC servers can now interact with the normal external cloud servers and as such permit the coordinated interoperable service, provisioning. This is important in reacting to the increasing demand of high performance and low latency process. Integration enables development of 5G applications by computing the computation-intensive and delay-sensitive applications[98]. A comprehensive offloading solution will be suggested in the context of this assessment paper and the immediate purpose of the solution will reduce the latency that the mobile users undergo. The system is increasingly implemented in the assessment stage after a process of analysis is duly completed. For long-distance low-cost optical data links using dark fiber. Identified a niche market for Internet of Things (IoToF) over fiber using passive switch eyes. This study proposes a physical layer (PHY) prototype using cost effective acousto-optic modulation, through the use of fiber Bragg gratings (FBG). The prototype was modeled, fabricated and tested to test the performance and viable modes of working. The design concept provides better performance in comparison to existing options such as LoRa or Sigfox, especially in terms of data rates and niche applications [99]. Reviewed and introduced two different optical fiber methods: intermediate frequency optical fiber (IFoF) and radio frequency optical fiber (RFoF). Both I FoF and RFoF are compatible with major new broadband services and are important components in the development of fiber optic wireless networks. For example, by incorporating the new capabilities of RAUs, 5G and satellite communication networks are expanding the physical dimension by using microelectronic layouts instead of technology. The potential of optical fiber and RoF technology and the evolution of IoT development from 5G to 6G are reviewed and analyzed in [100].This study examines rapid increase in the fiber optic radio business in combination with development of technologies allowing Internet of Things (IoT) and Radio over Fiber (RoF) convergence. Also, it takes a scan of new trends in some relevant fields. They then discuss new technology applications as well as future challenges for RoF-enabled 6G IoT systems. The analytical application of the AF backhaul method for hybrid FSO and fiber optic systems. This work explains and discusses the impacts of RF co-channel interference, pointing error, and modulator nonlinearity[101]. The ratio of the coupling potential, the asymptotic expression of the probability, and the average bit error are derived. The results showed that millimeter waves achieve fifty percent more capacity than previous studies. Power of Fiber (PoF) has recently been proposed and analyzed as a new state-of-the-art approach in the future 6G and 5G radio signals.An experiment was conducted to test Radio over Fiber (RoF) transmission over 100 meters to 10 kilometers using a single fiber (SMF). The injected PoF signal is limited to 2 W. The impact, analysis, and rationale of the RoF-IoT concept are currently under-researched topics[99].A method is proposed to meet the stringent requirements when considering the design of small systems using multi-user hybrid RF/FSO relays. Also, the coordination of directional error in the FSO link is taken into account when analyzing the interference factor for the hybrid RF/FSO method. The findings show that communication quality can be improved by using hybrid RF/FSO technology[102].Describes the performance of hybrid mmWave RoF and AF methods in 5G networks. Analyzing and evaluating how optical properties, fiber nonlinearities, and RF co-channel affect the hybrid mmWave RoF paradigm's performance is the goal of this study. Close-loop simpler model is used to mathematically describe average bit error rate and the probability of effect on the overall communication link. Radio-over-Fiber (RoF) system together with the novel energy harvesting (EH) cooperative communication technique is explored and the performance thereof is investigated[103]. The present analysis provides fresh perspectives on the prospect of RoF and EH-based linked technology. It is one of the milestones towards having more efficient and greener communication networks in the future.Two different concepts of communication are explored with the help of a Radio-over-Fiber (RoF) system through two different modes of communication: cooperative communication and direct communication. Evaluation of these modes is done with the aim of evaluating their effects on the system performance. The comparative analysis offers an insight into how they will perform well and adequately in different network circumstances.Outage probability is used for the performance, and it is analyzed for both modes. In this work, any node that act as helper (relay), it is get energy by RAU in return, the relay node help source sensor to send data to central office[104].

5.2 Proposed Energy Harvesting System for RoF

Energy harvesting over radio over fiber system with help of the cooperative communication is proposed in the chapter. To the best author knowledge, this first work has been done with RoF. Figure 5.1 shows the design and overall operation of the system. The proposed architecture has three levels:

- **First level (Data Transmission Level):** At this level, all channels (connections) are the same. The sensor collects data from the environment and broadcasts it to both the Master Node and the RAU over two channels, f and f', simultaneously during the time period $(1-\omega)T$. In this scenario, the Master Node operates as a relay node.
- **Second level (Energy Harvesting and Data Relaying Level):** Here, it is assumed that the RAU has the ability to transmit energy to the Master Node over channel h'. The Master Node receives energy during the time interval $\frac{\omega T}{2}$, and then it forwards an extra copy of the information received from the sensor to the RAU over channel h' during another period of $\frac{\omega T}{2}$.
- **Third level (Data Forwarding Level):** Finally, the data is forwarded to the Central Unit (CU) over channel k.

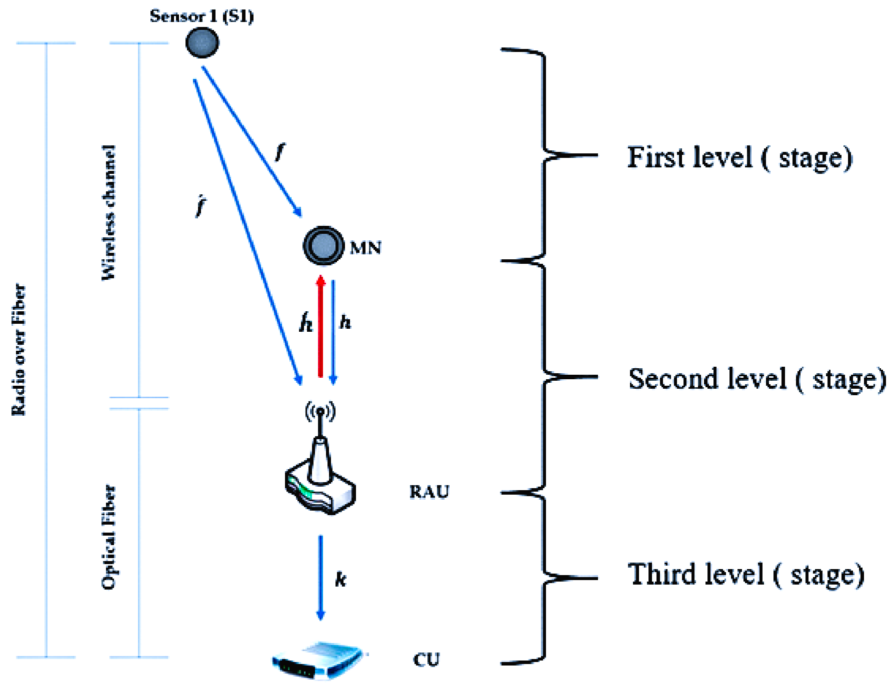

Figure 5.1: Energy Harvesting over Radio-over-Fiber using Analog network coding (EH-RoF-ANC) architecture.

5.3 Outage probability of EH-RoF-ANC

In this section, we derive the outage probability of the EH-RoF-ANC protocol. As described earlier in the figure 5.1 the outage probability is $P_{out} = 1 - P^s$ where P^s is the probability of successful transmission, and it is mathematically expressed as:

$$P^s_{\text{EH-RoF-ANC}} = P^s_{SD}\, P^s_{DC} + (1 - P^s_{SD})\, P^s_{SR}\, P^s_{RD}\, P^s_{DC} = (P^s_{SD} + (1 - P^s_{SD})\, P^s_{SR}\, P^s_{RD})\, P^s_{DC} \tag{5.1}$$

The equation 5.1 It consists of two events:

The **first event** represents the case where the source to destination channel(RAU),represented by channel f', successfully carries the data, and the channel from the RAU to the central office, represented by channel k, also successfully carries the data.

The **second event** represents the case where the source to destination (RAU) link via channel f' does not successfully carry the data. However, the source to Master Node (MN) link, represented by channel f, the link from MN to RAU, represented by channel h, and the link from RAU to the central office, represented by channel k, successfully carry the data, respectively. For the source to destination (RAU) link, which is represented by the channel f', the successful transmission probability is denoted by P^s_{SD}. For the source to relay sensor (sensor to MN) link, represented by the channel f, the successful transmission probability is P^s_{SR}. For the relay sensor to destination (RAU) link, represented by the channel h, the successful transmission probability is P^s_{RD}. Finally, for the RAU to Central Unit link, represented by the channel k, the successful transmission probability is P^s_{DC}.

From Equation5.1 the successful transmission probabilities are expressed mathematically as:

$$P^s_{SD} = \mathbb{P}\left(R_{SD} > \frac{2R}{1-\omega}\right) = \exp\left(-\frac{\left(2^{\frac{2R}{1-\omega}} - 1\right) N_0\, d_{SD}}{P_S}\right) \tag{5.2}$$

$$P^s_{SR} = \mathbb{P}\left(R_{SR} > \frac{2R}{1-\omega}\right) = \exp\left(-\frac{\left(2^{\frac{2R}{1-\omega}} - 1\right) N_0\, d_{SR}}{P_{SR}}\right) \tag{5.3}$$

$$P^s_{RD} = \mathbb{P}\left(R_{RD} > \frac{2R}{1-\omega}\right) = \exp\left(-\frac{\left(2^{\frac{2R}{1-\omega}} - 1\right) N_0\, d_{RD}}{P_R^{hrvstd}}\right) \tag{5.4}$$

Where

$$P_R^{hrvstd} = \frac{E_h}{(1-\omega)/2} = \frac{\omega}{1-\omega}\,\varphi P_D N_0 N_0 d_{DR} \tag{5.5}$$

- P_R^{hrvstd}: harvested power at the relay.
- E_h: harvested energy.
- ω: time-sharing factor.
- φ: energy conversion efficiency.
- P_D: power of data signal.
- N_0: noise power.
- d_{DR}: distance from destination to relay.

We can express E_{hrvstd} as

$$E_{hrvstd} = \varphi P_D N_0 d_{DR} \left(\frac{\omega}{2}\right) \tag{5.6}$$

Where, P_R^{hrvstd} is the harvested power received by the master node, ω is the slot time, P_D is the transmitted power by the RAU, N_0 is the noise power, d_{DR} is the path from the RAU to the master node, and d_{RD} is the distance from the master node to RAU. Then, we insert the equation 5.6 into (5.4), we re-write equation 5.4 as follows:

$$P_{RD}^s = \exp\left(-\frac{\left(2^{\frac{2R}{1-\omega}} - 1\right) d_{RD}\, d_{DR}}{\left(\frac{\omega}{1-\omega}\right) \varphi P_D N_0 d_{DR}}\right) \tag{5.7}$$

$$P_{DC}^s = 1 - 0.5\,\mathrm{erfc}\left(\frac{\ln\left(\frac{y_{th}}{y_{av}}\right) + 8\sigma}{\sqrt{32}\,\sigma}\right) \tag{5.8}$$

Where, R_b is the transmission rate, B_{ref} is the reference bandwidth. erfc(x) is the complementary error function of the variable x with variance σ.

We can define all the probabilities as follows: P_{SD}^s is the successful transmission probability between the source and RAU (destination), P_{SR}^s represents the successful transmission probability between the source and the Relay (another sensor within the network), P_{RD}^s represents the successful transmission probability between the Relay and the destination (RAU), and P_{DC}^s is the successful transmission probability between the destination and the central office.

Finally, the overall probability of successful transmission is expressed as:

$$\begin{aligned} P_{\text{EH-RoF-ANC}}^s = {} & \exp\left(-\frac{\left(2^{\frac{2R}{1-\omega}} - 1\right) N_0 d_{SD}}{P_S}\right) \\ & + \left(1 - \exp\left(-\frac{\left(2^{\frac{2R}{1-\omega}} - 1\right) N_0 d_{SD}}{P_S}\right) \exp\left(-\frac{\left(2^{\frac{2R}{1-\omega}} - 1\right) N_0 d_{SR}}{P_{SR}}\right)\right. \\ & \times \exp\left(-\frac{\left(2^{\frac{2R}{1-\omega}} - 1\right) d_{RD}}{\left(\frac{\omega}{1-\omega}\right) \varphi P_D N_0}\right) \\ & \left.\times \left(1 - 0.5\,\mathrm{erfc}\left(\frac{\ln\left(\frac{y_{th}}{y_{av}}\right) + 8\sigma}{\sqrt{32}\sigma}\right)\right)\right) \end{aligned} \tag{5.9}$$

5.4 Results and Discussion

This section uses computer simulations to assess the effectiveness of the suggested Energy Harvesting with Network Coding Technique of Radio-over-Fiber protocol for RoF in the IoT. The simulations involve a stochastic arrangement of sensors arranged in a single RAU within a normalized area of 1 Km × 1 Km. The RAUs are linked to the central office or base station through *Free-space optics* (FSO) at a maximum distance of 25 km.

It is postulated that the distances between the sensors and the relay node, RAU, and BS are subject to variation in the simulations. All linkages are from the sensors to RAU as variables and are represented by d_o^ρ, where ρ is the path loss. The transmission rate across all links is assumed to be R (b/s/Hz). The path-loss exponent is not fixed in this work.

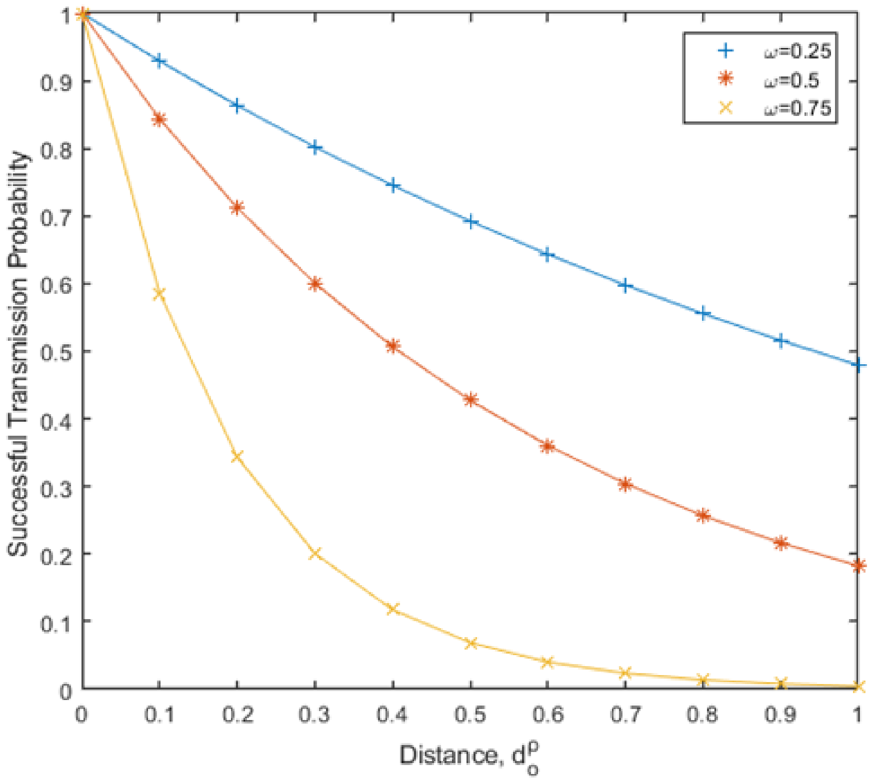

Figure 5.2: successful transmission probability vs distance using Free-space optics (FSO).

First, referring to Figure 5.2 it is evident that the probability of effective transmission reduces when the distance between is increase between the transmitter as well as the receiver. This observation presupposes that the strength of the signal reduces with the distance, hence reducing the successful signal transmission's probability. This behavior can be linked to several factors, some of which include loss interference and fading effects; hence, the manifestation is more profound over distance. Therefore, these outcomes can suggest that in the achievement of multiple transmissions and signal reconstruction, the long-term efficiency is improved. Also, in Figure 5.2,There is a particular trend that can be observed with reference to the ω parameter, which is the energy harvesting time probability in achieving successful transmission. It proves that with decreasing ω, the energy harvesting is emphasized more, and the probability of successful transmission rises.This means that further time on the energy harvesting allows the system to store enough energy thus improving on overall transmission performance.There is an obvious balance between available energy resources and the ability to transmit energy successfully, and the parameter ω explains this. By increasing the time period that the energy harvesting system is given for power regeneration, it is possible to achieve better reserves of energy to transmit, and thus a stronger signal. This makes it possible for the system to avoid energy deficiencies and hence have a much higher successful transmission probability. Meanwhile,When less time is available to the energy harvesting process, then a system can incur an energy shortfall. Consequently, chances of effective transmission are lowered because of the lacking power supply. This brings out the dilemma between the amount of time that can be used to harvest energy and the reliability of the communication. From the aspect of distance and time distribution in energy harvesting, Figure 5.2,presents an overall idea of the probability of effective transmission. The study shows the necessity to take these effects into account when designing and enabling wireless communications, especially those that rely on electronic devices. This way, researchers and developers can have a better idea of how transmission efficiency is affected by harvesting energy duration as well as the distance, and therefore improve wireless network operation reliability and efficacy.

Chapter 6

Energy Efficiency of Cooperative Communication over RoF

6.1 Introduction

The fifth-generation (5G) network represents the latest advancement in communication technology, crucial for achieving significantly higher data rates compared to previous technologies. Among the most important benefits of the implementation of 5G technology, there should be mentioned a wide range of the available spectrum and unimpaired reliability. It is also capable of rendering ultra-low latency, which can as low as 1 ms, and comes with minimal jitter that makes it especially compliant with the application of real-time and mission-critical applications. In addition 5G makes significant improvement in network capacity facilitating connection by a large number of devices simultaneously with a noticeably greater network performance. To fulfill the increased capacity demands and stringent high data rate requirements of 5G networks, optical fiber infrastructure serves as an indispensable component for their backhaul[105].The optical fibers are characterized by the ability to transmit data at high speeds hence are quite efficient in the contemporary communication requirements. They have large bandwidth and are electric interference free grounds hence signal integrity. Also, the extensive data that are generated through the 5G applications can be easily processed through their scalability. Recently, the integration of Wireless Sensor Networks (WSN) into 5G networks using Radio-over-Fiber (RoF) technologies has gained considerable research attention. In this scenario, where the sensors integrated into a cluster send the data to the Remote Antenna Units (RAUs) via radio. Remote Antenna Units (RAUs) including all that are needed as essential junction nodes, which integrate the data sent among the fiber-optic cables. Through passing such information to the core of the network, they prevent smooth data flow within the system. This type of integration is the basis of high-speed network communication services delivery which are essential to advanced, contemporary applications provision.This integration facilitates efficient data handling, improved network scalability, reduced energy consumption, and enhanced overall network performance[106]. As clusters are integrated into radio over fiber networks, there is a likelihood of cluster heads overlapping, enabling collaboration between the cluster heads of each cluster. This study focuses on communication between cluster heads and extends into the surrounding area. Consequently, we introduce the concept of Inter-Cluster Head Cooperation over Radio over Fiber (ICHC-RoF). The study begins by examining the network and proposed architecture within the Radio over Fiber paradigm. Following that, a mathematical model for outage probability is derived. Moreover, a mathematical analysis of throughput is conducted for the suggested protocol.The results shows that ICHC-RoF system has better performance through simulation and numerical simulation. It is also indicated as hybrid optic wireless network or hybrid wireless optical broadband access[107]. Over the last 20 years, the number of applications of FiWi networks combining optical fiber and wireless access has increased significantly and attracted attention from the technical community. These applications include multimedia communications, remote locations, and disaster help. IoT is a rapidly growing topic of great interest. The use of this technology is mainly done by one of the current wireless communication systems. New mobile technologies that can be used in the industry and many efforts are being made to acclimate novel IoT applications to diverse wireless technologies . Mobile applications' need for data traffic is increasing, and the solution seems to be the interconnection between optical fiber and wireless technologies.So far, no single model can meet all the needs of IoT applications, whether it is transmission speed, energy efficiency, complexity, or smart city [108]. Wired networks based on fiber being connected directly to IoT devices are also bringing about a changing IoT network landscape. The challenge is to overcome the limitations of wireless networks. One possible answer is to use passive optical networks (PONs) with high data rates and distances. For many IoT devices, electro-optic conversion can be expensive and energy intensive. Most IoT applications need not have a physical layer (PHY) interface, due to the low data rates that are involved in the application. There was therefore a long time need to close the gap towards full passive optical systems with the ability to support low transmission rates. The RoF-based environmental monitoring Internet of Things (IoT) testbed used by the H2020 FUTEBOL project was developed and evaluated [109]. The study conducts research on the impact of Radio over Fiber (RoF) on the network performance in a solid, empirically inspired framework. With this aim a Heterogeneous Network (HetNet) system is envisaged comprising Fiber-Wireless (FiWi) and Long-Term Evolution (LTE) technology. Mobile Edge Computing (MEC) is deployed to extend the network coverage and make a fast response.[110]. This enables integration and collaboration between traditional cloud (remote) and MEC servers. Fill the gap between high-performance, delay-sensitive workloads and the increasing need to develop 5G applications[111]. Introducing the analytical technique to measure the power delay and discussing the integration of integrated feedback to reduce the average response time of telephone users. A potential research area for long-range, low-power data using dark fibers and all blind modifications is the Internet of Things over Fiber (IoToF). A cheap acoustic-optic modulation scheme according to Fiber Bragg Grating (FBG) prototype physical link (PHY) is designed and constructed. This design concept has more insight and professional use than existing models such as Sigfox or LoRa[112].Two fiber optic radios, called intermediate frequency over fiber (IFoF) and RF over fiber (RFoF), are reviewed and introduced. The use of fiber-optic wireless networks, which have become the next-generation satellite communication, and the 5G, is based on a set of transmission technologies that exist with support of advanced transmission mechanisms. The centrepiece of these solutions is in fact the Remote Antenna Unit (RAU), whose enhanced capabilities have been designed to be as physically compact as possible. This aim is achieved by introduction of non-metric microelectronics, which create efficiency and attainable scalability of network implementation. This technology is also compatible with new broadband services[113]. The evolution of IoT from 5G to 6G, the power of optical fiber, and RoF technology are reviewed and analyzed. In the context of the more recent literature, the growth of the fiber optic radio industry is investigated together with the technological progress in the development of Internet of Things (IoT) integration and Radio over Fiber (RoF) availability. The conversation is a synthesis of the current study in various fields hence bringing light on the new dynamics of communications technologies and its broadening uses. Then, the challenges faced by the 6G IoT system supported by RoF and the development of new technologies were discussed. Power over fiber (PoF) uses radio signals to power future 6G and 5G networks and is considered a more modern and advanced [114].Then the fiber optic radio transmission using single-mode fiber (SMF) was tested to achieve connectiveness between 100 meters up to 10 kilometers. In this assessment injections of Power-over-Fiber (PoF) signals were used. The design of the system assumed the maximum transmission power as 2 watts conforming to the network technology specification.[115].Power can be sent to a remote location or system using PoF technology.There are very few papers that have studied, evaluated, or addressed the potential impact in the RoF-IoT paradigm. The effects of directional error, co-channel RF interference, and modulator non-linearity are described and explained [116].The analysis of hybrid fiber and FSO with AF backhaul technology is presented.It provides the asymptotic formula of the probability distribution of average bit error rate, the probability distribution and the link probability distribution.The results showed that using millimeter waves can increase efficiency by 50% compared to previous research[117]. In order to improve the strict requirements while considering the compact cell design, a multi-user hybrid RF/FSO transmission approach is provided. The link power capacity of the hybrid RF/FSO scheme, which considers the effect of directional errors in the FSO link, is also analyzed. The findings show how hybrid RF/FSO technology can enhance global communication[118].The performance of hybrid mm-Wave-RoF and AF technology in 5G networks is investigated. The effects of fiber, RF co-channel interference, and optical modulators are studied, and their relationship with the performance of the hybrid millimeter wave RoF paradigm is investigated. The resulting average BER and probability of the entire link are presented by a simple closed equation and explained theoretically[119]. This the steps of contributions illustrated the work.

1. Cluster Integration: investigated how clusters could be integrated into radio over fiber networks and found possible cluster head overlap, opening the door for cooperation amongst cluster heads inside each cluster.

2. Inter-Cluster Head Cooperation: Introduced and proposed the concept of Inter-Cluster Head Cooperation over Radio over Fiber (ICHC-RoF) as a novel approach to enhance communication efficiency.

3. Network Architecture Examination: Conducted a thorough examination of the network and proposed architecture within the Radio over Fiber paradigm, providing insights into the structural aspects of the communication system.

4. Mathematical Model for Outage Probability: Developed a robust mathematical model to analyze and quantify the outage probability within the proposed ICHC-RoF framework.

5. Mathematical Analysis of Throughput: Conducted a mathematical analysis of throughput for the proposed protocol, providing a quantitative assessment of the system's data transfer capabilities.

6. Simulation and Numerical Results: Implemented simulations and numerical analyses to validate the proposed ICHC-RoF system, demonstrating its superior performance compared to existing methods.

6.2 Proposed Communication Structurer of Co-operative Communication over Fiber

Distributed antenna systems, or DAS in RoF networks, are the idea of positioning RAUs in a certain region to be fully covered by radio signals. This allows sensors that are dispersed throughout challenging terrain or unreachable locations for the dense wireless sensor network to be reached. To offer good coverage radio signal across a specified area, the recommended structure in our scenario consists of small Cluster Heads (CH) placed in industrial areas or heavy terrain. Section 1 will outline the specifics of the message later. Our work suggests using distributed RAUs in Internet of Things paradigms with RoF technology to offer extended reach, increased bandwidth, signal integrity, and data security. Figure6.1 depicts the envisaged or suggested paradigms, which are divided into four regions, each of which has a distinct function and is a component of the overall Internet of Things system. This paper considers an early detection and remediation system for fires. The suggested paradigm can be summed up as follows:

Region 1: (sensing regional/camera-based sensors): In this region, sensors are distributed either randomly or in a predictable pattern inside the designated area (which may be a heavily populated or inaccessible area). These sensors can be cameras, smoke detectors, CO detectors, or anything else. Sensors acquire information, which is then transmitted to RAUs or the Cluster Head (CH) in line with protocol will discussed.The Cluster Head (CH), unlike the normal sensors, was able to act under situated circumstances and have larger size and battery.Data is forwarded to the RAU by the Cluster Head (CH) once it has received what the sensors have transmitted.

Region 2: The second region encompasses the remote antenna units (RAUs), wherein data is received and transformed from electrical impulses to optical signals in order to facilitate fiber optic transmission. Based on fiber optic cables that have undergone optical-to-electrical conversion.

Region 3: constitutes a base station, alternatively named the super Cluster Head (CH), which receives data. Super Cluster Heads (or CHs) are primarily responsible for two tasks: first, they process data and choose which department or places the data forwarded, and then they forward the data to Region 4.

Region 4: After evaluated data is received, a specific agency—such as the fire department or the beacon system—takes action. A Wireless Sensor Network

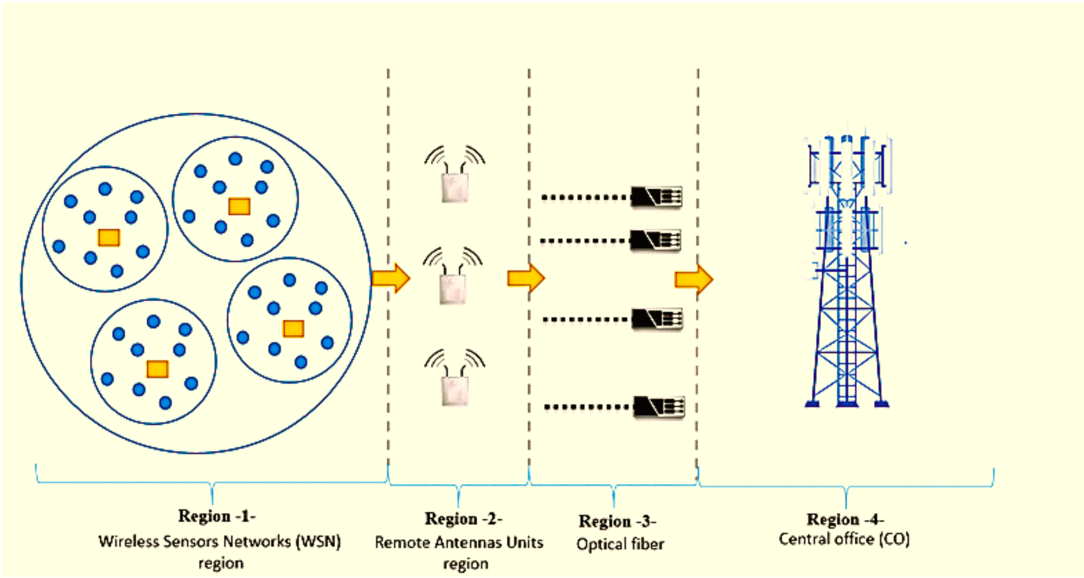

Figure 6.1: Planned distributed RoF RAU in the context of the IoT.

(WSN) is a common example of a distributed network service, consisting of multiple sensors deployed over a large geographic area. In this particular scenario, we utilize a network architecture based on Radio-over-Fiber (RoF). Sensors collect data and send it to a Cluster Head (CH) designated for their group. The CH aggregates the information received from each sensor and then forwards it to a Remote Antenna Unit (RAU). Once the RAU has collected all the data from the respective CH, it transmits this aggregated information to the central base station. This setup results in multihop forwarding within the WSN when interconnected with the RoF network. Here, sensors act as data-gathering points, the CH functions as an intermediate data aggregator, and the RAU serves as a communication gateway to the central base station. The fundamental concept involves data being relayed from one sensor to another before ultimately being delivered through the farthest relay node to the monitoring center.

In practical applications, such as Wireless Sensor Networks (WSN) employing Radio-over-Fiber (RoF) architecture, clusters may overlap. In such cases, collaboration between Cluster Head nodes (CHs) becomes necessary. In this chapter, we propose new network architecture called "Inter-Cluster Head Cooperation over Radio over Fiber" (ICHC-RoF). In our setup, two clusters are collocated in range and able to share data efficiently with each other. For example, suppose there

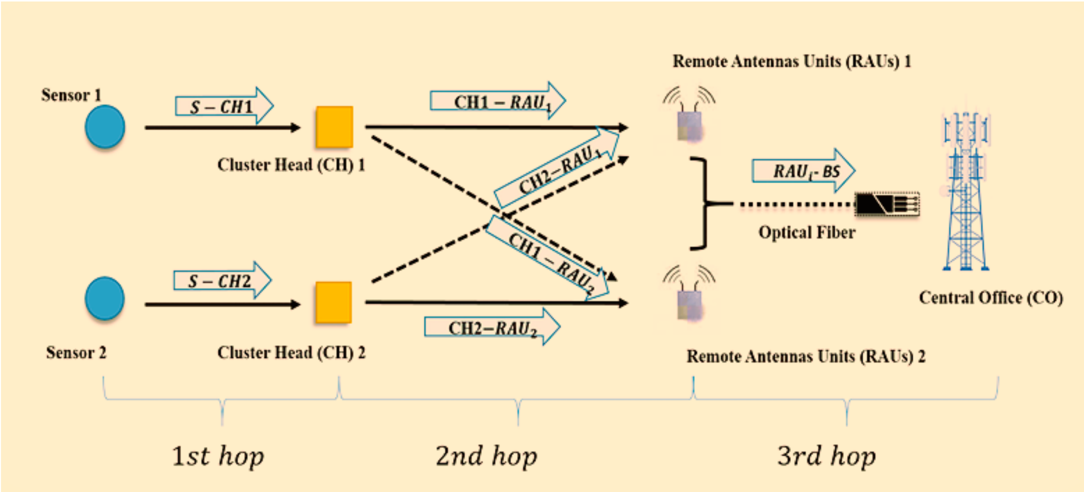

Figure 6.2: Communication structure of the ICHC-RoF.

are two sensors, one in each of these collocated clusters that are generating data from the environments they belong to. This data, in turn, is sent to their cluster heads, e.g., CH1 and CH2. These RAU nodes must be within the transmission range of these data to each FHSS Cluster Head. After the data is received and successfully interpreted by RAUs, each signal finds a way to make it with the help of MRC (Maximal Ratio Combining) in order to combine and treat softened elements. Figure 6.2 illustrates this novel communication, all of which—clusters, Cluster Heads (CH), RAUs, and data flow synergy.

6.3 Outage and Link Probability Analysis

In this section, we will discuss the propagation model and the outage probability between two nodes. The average signal-to-noise ratio ($\mathrm{SNR}_{i,j}^{\mathrm{av}}$) between node i and node j is as :

$$\mathrm{SNR}_{i,j}^{\mathrm{av}} = \mathrm{SNR}_{i,j} \cdot X_{i,j} = \frac{P_{i,j} \cdot k_{i,j}}{P_N + P_I} \cdot X_{i,j} \tag{6.1}$$

where $P_{i,j}$ is the transmission power, P_N is the noise power, and $X_{i,j}$ is a complex Gaussian random variable with unit variance. The channel gain $|X_{sd}|^2$ is then an exponentially distributed random variable with the mean value $\mathbb{E}\left[|X_{i,j}|^2\right] = d_{ij}^{-\alpha}$, where $\mathbb{E}$ signifies an expectation. The d_{ij} is the distance linking two nodes. The $k_{i,j}$ is the channel component and it is expressed as

$$k_{i,j} = \frac{G \cdot \lambda}{(4\pi)^2 \cdot M_l \cdot N_f} \tag{6.2}$$

where G is the overall gain of the transmit and receive antennas, λ is the wavelength, M_l represents the link margin, and N_f represents the noise figure at the receiver. The outage probability is the chance that the transmission rate will either meet or exceed the essential transmission rate β. The formula for calculating the outage probability is:

$$P_{i,j}^{\text{out}} = P\left(\beta_{i,j} \leq \beta\right) = 1 - \exp\left(-U_{i,j} \cdot d_{ij}^{\alpha_1}\right) \tag{6.3}$$

where $\beta_{i,j} = \log_2\left(1 + \text{SNR}_{i,j} \cdot X_{i,j}\right)$ and $U_{i,j}$ is expressed as

$$U_{i,j} = \frac{2^{\beta} - 1}{\text{SNR}_{i,j}} \tag{6.4}$$

6.4 Outage Probability Analysis of ICHC-RoF

This section evaluates the ICHC-RoF outage risk in the radio over fiber paradigm, in accordance with the two-tandem transmission rate region shown in Figure 6.2. The equilibrium of the suggested topology makes it possible to calculate the end-to-end outage probability of sensor 1 to T2. The rate zones for the two sensors and the two CNs are shown in Figure6.2. Take note of the four zones that divide the pairs in Figure 6.3, (β_1, β_1).Let's look at sensor 1's error region. Data from sensor 1 is incorrect in regions 3 (R3) and 4 (R4), but data from sensor 2 might be error-free in R3. Analogously, data from sensor 1 might be accurate in R2, whereas data from sensor 2 might contain errors in regions 3 and 4 (R2).A common example of a distributed network service is a Wireless Sensor Network, consisting of multiple sensors deployed over a large geographic area.In this particular scenario,Network architecture based on Radio-over-Fiber (RoF) is utilized. Sensors collect data and send it to a Cluster Head (CH) designated for their group.

The CH aggregates the data comes from each sensor then forwards information to a Remote Antenna Unit (RAU). Once the RAU has collected all the data from the respective CH, it transmits this aggregated information to the central base station. This setup results in multihop forwarding within the WSN when interconnected with the RoF network. Here, sensors act as data-gathering points, the CH functions as an intermediate data aggregator, and the RAU serves as a communication gateway to the central base station. The fundamental concept involves data being relayed from one sensor to another before ultimately being delivered through the farthest relay node to the monitoring center[120].

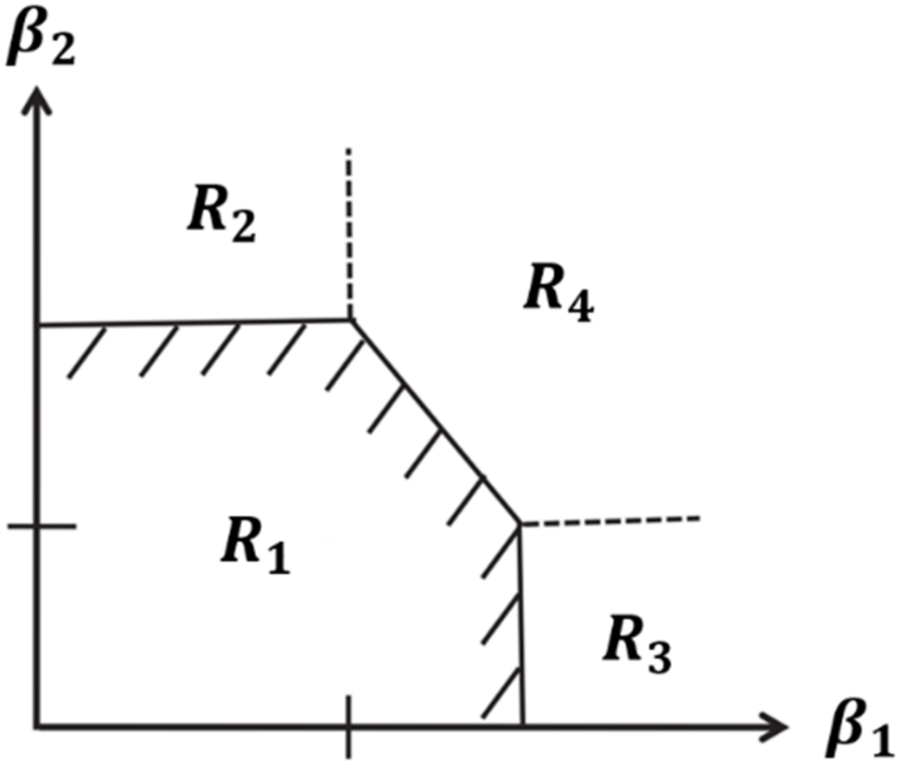

Figure 6.3: The ICHC-ROF protocol's rate-region

Triple hops communications model for the ICHC-ROF is shown in Figure 21 and described: the 1st hop is direct transmission, and then 2nd hop is cooperative with dual sources communications, finally, last hop, data transmitted over fiber optics with help of RAUs. As a result, ICHC-ROF outage probability can be expressed as

$$\begin{aligned} P^{o}_{\text{ICHC}} = & \underbrace{\left((\text{1st hop})^{\text{out}} \cap \left[1-(\text{2nd hop})^{\text{out}}\right] \cap \left[1-(\text{3rd hop})^{\text{out}}\right]\right)}_{\text{1st event}} \\ & \cup \underbrace{\left(\left[1-(\text{1st hop})^{\text{out}}\right] \cap (\text{2nd hop})^{\text{out}} \cap \left[1-(\text{3rd hop})^{\text{out}}\right]\right)}_{\text{2nd event}} \\ & \cup \underbrace{\left(\left[1-(\text{1st hop})^{\text{out}}\right] \cap \left[1-(\text{2nd hop})^{\text{out}}\right] \cap (\text{3rd hop})^{\text{out}}\right)}_{\text{3rd event}} \end{aligned} \tag{6.5}$$

The above formula consists of three events. The first event represents an outage in the first hop, while the second and third hops are not in outage. The second event represents an outage in the second hop, with the first and third hops functioning normally. The third and final event represents an outage in the third hop, while the first and second hops are operational. Since all paths are independent, intersections translate into multiplication, and unions translate into summation. Thus, the equation above can be rewritten as follows:

$$\begin{aligned} P^{o}_{\text{ICHC}} = &\underbrace{\left((\text{1st hop})^{\text{out}}\left[1-(\text{2nd hop})^{\text{out}}\right]\left[1-(\text{3rd hop})^{\text{out}}\right]\right)}_{\text{1st event}} \\ &+\underbrace{\left(\left[1-(\text{1st hop})^{\text{out}}\right](\text{2nd hop})^{\text{out}}\left[1-(\text{3rd hop})^{\text{out}}\right]\right)}_{\text{2nd event}} \\ &+\underbrace{\left(\left[1-(\text{1st hop})^{\text{out}}\right]\left[1-(\text{2nd hop})^{\text{out}}\right](\text{3rd hop})^{\text{out}}\right)}_{\text{3rd event}} \end{aligned} \tag{6.6}$$

$$+\underbrace{\left(\left[1-(\text{1st hop})^{\text{out}}\right]\left[1-(\text{2nd hop})^{\text{out}}\right](\text{3rd hop})^{\text{out}}\right)}_{\text{3rd event}} \tag{6.6}$$

Where $(\text{1st hop})^{\text{out}}$, $(\text{2nd hop})^{\text{out}}$, and $(\text{3rd hop})^{\text{out}}$ are the first hop outage probability, second hop outage probability, and third hop outage probability, respectively. The first-hop outage probability refers to direct link transmission. Therefore, we can simply use the formulas from equations(6.1)to(6.4) to mathematically express the outage as follows:

$$(\text{1st hop})^{\text{out}} = \underbrace{P^{o}_{s1\text{-}ch1}}_{1^{\text{st}}\ \text{hop}} = 1-\exp\left(-\frac{(2^{\beta}-1)}{\text{SNR}_{s1\text{-}ch1}}\cdot d^{\alpha_1}_{s1\text{-}ch1}\right)$$

Simplify it as:

$$(\text{1st hop})^{\text{out}} = \underbrace{P^{o}_{s1\text{-}ch1}}_{1^{\text{st}}\ \text{hop}} = 1-\exp\left(\omega_{s1\text{-}ch1}\right) \tag{6.7}$$

$$\omega_{s1\text{-}ch1} = -\left(\frac{2^{\beta}-1}{\text{SNR}_{s1\text{-}ch1}}\right) d^{\alpha_1}_{s1\text{-}ch1}$$

$\text{SNR}_{s1\text{-}ch1}$ represents the SNR of the link $S1-ch1$, $d_{s1\text{-}ch1}$ is the distance for $S1-ch1$ link, and α_1 refers to path loss factor of the link $S1-ch1$.

Then,the mathematically expression of outage probability for the second hop is:

$$(\text{2nd hop})^{\text{out}} = \underbrace{\left(P^{\text{out}}_{ch1\text{-}rau1} \cap P^{\text{out}}_{ch1\text{-}rau2}\right)}_{2^{\text{nd}}\text{ hop}} \tag{6.8}$$

where, $P^{\text{out}}_{ch1\text{-}rau1}$ represents the $ch1 - rau1$ link outage probability and $P^{\text{out}}_{ch1\text{-}rau2}$ represents the $ch1 - rau2$ link outage probability, then $(\text{2nd hop})^{\text{out}}$ can be expressed as:

$$P^{\text{out}}_{ch1\text{-}rau1} = P^{\text{out}}\left(R_3^{ch1\text{-}rau1}\right) + P^{\text{out}}\left(R_4^{ch1\text{-}rau2}\right) \tag{6.9}$$

where, $P(R_3^{ch1\text{-}rau1})$ and $P(R_4^{ch1\text{-}rau2})$ are the sensor 1's rate region to the $rau1$. The term $P(R_3^{ch1\text{-}rau1})$ and $P(R_4^{ch1\text{-}rau2})$ in (6.9) can be further expressed as:

$$P\left(R_3^{ch1\text{-}rau1}\right) = \frac{1}{2^{\beta_2}}\left[\exp\left(-U_{2,1}\right) - \exp\left(-\omega_{ch1\text{-}rau1}\right)\right] \tag{6.10}$$

where $\omega = -\frac{2^{\beta_1+\beta_2}-1}{\text{SNR}_{ch1\text{-}rau1}}$ and

$$\begin{aligned} P\left(R_4^{ch1\text{-}rau2}\right) = 1 - \Bigg(& \frac{1}{2^{\beta_1}}\exp\left(-U_{1,1}\right) + \frac{1}{2^{\beta_2}}\exp\left(-U_{2,1}\right) \\ & + \exp\left(-\frac{2^{\beta_1+\beta_2}-1}{\text{SNR}_{ch1\text{-}rau2}}\right)\left[\left(1 - \frac{1}{2^{\beta_1}} - \frac{1}{2^{\beta_2}}\right)\right. \\ & \left. + U_{1,1}U_{2,1}\text{SNR}_{ch1\text{-}rau2}\right]\Bigg) \end{aligned} \tag{6.11}$$

Where, $\text{SNR}_{ch1\text{-}rau1}$ is the SNR of the link $ch1 - rau1$ and $\text{SNR}_{ch1\text{-}rau2}$ is the SNR of the link $ch1 - rau2$. Then, inserting (6.10)and (6.11) in (6.9)and (6.9)into(6.8) , we obtain the outage probability of $(\text{2nd hop})^{\text{out}}$ as:

$$\begin{aligned} (\text{2nd hop})^{\text{out}} = & \frac{1}{2^{\beta_2}}\left[\exp\left(-U_{2,1}\right) - \exp\left(-\frac{2^{\beta_1+\beta_2}-1}{\text{SNR}_{ch1\text{-}rau1}}\right)\right] \\ & \times \Bigg[1 - \Bigg(\frac{1}{2^{\beta_1}}\exp\left(-U_{1,1}\right) + \frac{1}{2^{\beta_2}}\exp\left(-U_{2,1}\right) \\ & + \exp\left(-\frac{2^{\beta_1+\beta_2}-1}{\text{SNR}_{ch1\text{-}rau2}}\right)\left(\left[1 - \frac{1}{2^{\beta_1}} - \frac{1}{2^{\beta_2}}\right] + U_{1,1}U_{2,1}\text{SNR}_{ch1\text{-}rau2}\right)\Bigg)\Bigg] \end{aligned} \tag{6.12}$$

Finally, third hop outage probability can be mathematically expressed as

$$\underbrace{P^{o}_{rau1\text{-}cn}}_{\text{3rd hop}} = 1 - 0.5\ \text{erfc}\left(\frac{\ln\left(\frac{\text{SNR}_{th}}{\text{SNR}_{av}}\right) + 8\sigma}{\sqrt{32}\sigma}\right) \tag{6.13}$$

Where, SNR_{th} and SNR_{av} are the threshold SNR and average SNR of the $rau1-cn$ link, respectively. σ is the variance of the $rau1-cn$ link, and $\text{erfc}(x)$ is the complementary error function of variable x.

To obtain the outage probability of the proposed ICHC-RoF, we insert (6.7,(6.12), and(6.13) in(6.6). We can then write the final outage probability of the proposed protocol as:

$$\begin{aligned} P^{o}_{ICHC} = {} & (1-\exp(\omega_{s1\text{-}ch1}))\left[1-\frac{1}{2^{\beta_2}}\left[\exp(-U_{2,1})-\exp\left(-\frac{2^{\beta_1+\beta_2}-1}{\text{SNR}_{ch1\text{-}rau1}}\right)\right]\right. \\ & \times\left[1-\left(\frac{1}{2^{\beta_1}}\exp(-U_{1,1})+\frac{1}{2^{\beta_2}}\exp(-U_{2,1})\right.\right. \\ & \left.\left.\left.+\exp\left(-\frac{2^{\beta_1+\beta_2}-1}{\text{SNR}_{ch1\text{-}rau2}}\right)\left(\left[1-\frac{1}{2^{\beta_1}}-\frac{1}{2^{\beta_2}}\right]+U_{1,1}U_{2,1}\text{SNR}_{ch1\text{-}rau2}\right)\right)\right]\right. \\ & \times\left[1-0.5\ \text{erfc}\left(\frac{\ln\left(\frac{\text{SNR}_{th}}{\text{SNR}_{av}}\right)+8\sigma}{\sqrt{32}\sigma}\right)\right] \end{aligned} \tag{6.14}$$

$+$

$$\left([1-1-\exp(\omega_{s1\text{-}ch1})]\left[1-\frac{1}{2^{\beta_2}}\left[\exp(-U_{2,1})-\exp\left(-\frac{2^{\beta_1+\beta_2}-1}{\text{SNR}_{ch1\text{-}rau1}}\right)\right]\right.\right.$$

$$\times\left[1-\left(\frac{1}{2^{\beta_1}}\exp(-U_{1,1})+\frac{1}{2^{\beta_2}}\exp(-U_{2,1})+\exp\left(-\frac{2^{\beta_1+\beta_2}-1}{\text{SNR}_{ch1\text{-}rau2}}\right)\right.\right.$$

$$\left.\left.\left.\times\left(\left[1-\frac{1}{2^{\beta_1}}-\frac{1}{2^{\beta_2}}\right]+U_{1,1}U_{2,1}\text{SNR}_{ch1\text{-}rau2}\right)\right)\right]\right]$$

$$\left.\times\left[1-0.5\ \text{erfc}\left(\frac{\ln\left(\frac{\text{SNR}_{th}}{\text{SNR}_{av}}\right)+8\sigma}{\sqrt{32}\sigma}\right)\right]\right)$$

$+$

$$\left([1-1-\exp(\omega_{s1\text{-}ch1})]\left[1-\frac{1}{2^{\beta_2}}\left[\exp(-U_{2,1})-\exp\left(-\frac{2^{\beta_1+\beta_2}-1}{\text{SNR}_{ch1\text{-}rau1}}\right)\right]\right.\right.$$

$$\times \left[1 - \left(\frac{1}{2^{\beta_1}} \exp\left(-U_{1,1}\right) + \frac{1}{2^{\beta_2}} \exp\left(-U_{2,1}\right) + \exp\left(-\frac{2^{\beta_1+\beta_2} - 1}{\mathrm{SNR}_{ch1\text{-}rau2}}\right)\right.\right.$$

$$\left.\left.\times \left(\left[1 - \frac{1}{2^{\beta_1}} - \frac{1}{2^{\beta_2}}\right] + U_{1,1}U_{2,1}\mathrm{SNR}_{ch1\text{-}rau2}\right)\right)\right]\Bigg]$$

.

$$\left[1 - 0.5 \text{ erfc}\left(\frac{\ln\left(\frac{\mathrm{SNR}_{th}}{\mathrm{SNR}_{av}}\right) + 8\sigma}{\sqrt{32}\sigma}\right)\right]$$

+

$$+\left(\left[1 - 1 - \exp(\omega_{s1\text{-}ch1})\right]\left[1 - \frac{1}{2^{\beta_2}}\left[\exp(-U_{2,1}) - \right.\right.\right.$$

$$\left.\left.\exp\left(-\frac{2^{\beta_1+\beta_2} - 1}{\mathrm{SNR}_{ch1\text{-}rau1}}\right)\right]\right]$$

$$\times \left[1 - \left(\frac{1}{2^{\beta_1}} \exp(-U_{1,1}) + \frac{1}{2^{\beta_2}} \exp(-U_{2,1}) + \right.\right.$$

+

$$\exp\left(-\frac{2^{\beta_1+\beta_2} - 1}{\mathrm{SNR}_{ch1\text{-}rau2}}\right)\left(\left[1 - \frac{1}{2^{\beta_1}} - \frac{1}{2^{\beta_2}}\right] + U_{1,1}U_{2,1}\mathrm{SNR}_{ch1\text{-}rau2}\right)$$

$$\times \left(1 - 0.5 \text{ erfc}\left(\frac{\ln\left(\frac{\mathrm{SNR}_{th}}{\mathrm{SNR}_{av}}\right) + 8\sigma}{\sqrt{32}\sigma}\right)\right)$$

In this part, a closer look at the end-to-end outage probability for our proposed ICHC-RoF system is taken.By examining how multiple transmission hops impact performance is done.The results gives a clearer picture of how different outage events play a role in the overall system function. More specifically,The outage probability calculating for each hop—cooperative communication, tandem direct transmission, and final reception—using techniques from probabilistic modeling and rate-region analysis is found.It is useful to derive this, in that the proposed derivation provides a way of quantitatively measuring the reliability of the system: that is, in measuring how well the ICHC-RoF system performs with different signal-to-noise ratios (SNRs). By pinpointing key outage events and understanding their relationships, System parameters such as transmission power, relay placement, and coding schemes to improve network reliability can be set.The informational model developed in the present study broadens the knowledge base of next-generation use cases of hybrid optical-wireless systems, thus forming a solid foundation upon which the potential of performance benefits in the framework of the next generation 5G and beyond 5G can be measured.

6.5 Results and discussion

A computer-based simulation utilised by the current research aims at evaluating the proposed ICH-RoF networking architecture on the basis of its operational attributes. To design the testbed, two cluster heads are assumed to exist under their sphere of radio-communication. They feature a random topology, and several wireless sensors arranged in a $3 \times 3\ m$. The notation, $d_o \cdot \beta_o\ (b/s/Hz)$ indicates the expected transmission rate for all links. The simulations operate under the assumption that the distances are variable and that each link has the same distance. The carrier frequency is $f_C = 2.5\ GHz$, the path-loss exponent is 4, $Ml = 40\ dB$ and $Nf = 10\ dB$, the overall antenna gain is $G = 5\ dBi$, and $N_o = -70\ dBm$. The circuit's power usage for amplification, sending, and receiving was indicated as $P_o\ (mW)$ in the following. As expected, with an increase in the number of interfering nodes and the level of interference power, the outage probabilities for all protocols demonstrated a noticeable escalation as depicted in Figure 6.4. This trend is attributed to the collective effect of heightened interference power, which effectively diminishes the signal-to-noise ratio (SNR) experienced at the receiver's end. As interference power accumulates, it exerts a detrimental impact on the clarity and reliability of the received signals, thereby increasing the likelihood of communication breakdowns or outages.

Nevertheless, the ICHC-RoF protocol was observed to have greater performance enhancement as compared to the typical technique for the same degree of interferences. Compared to other protocols, this protocol can be set apart for it has two relays for forwarding signals gotten from the sensors.

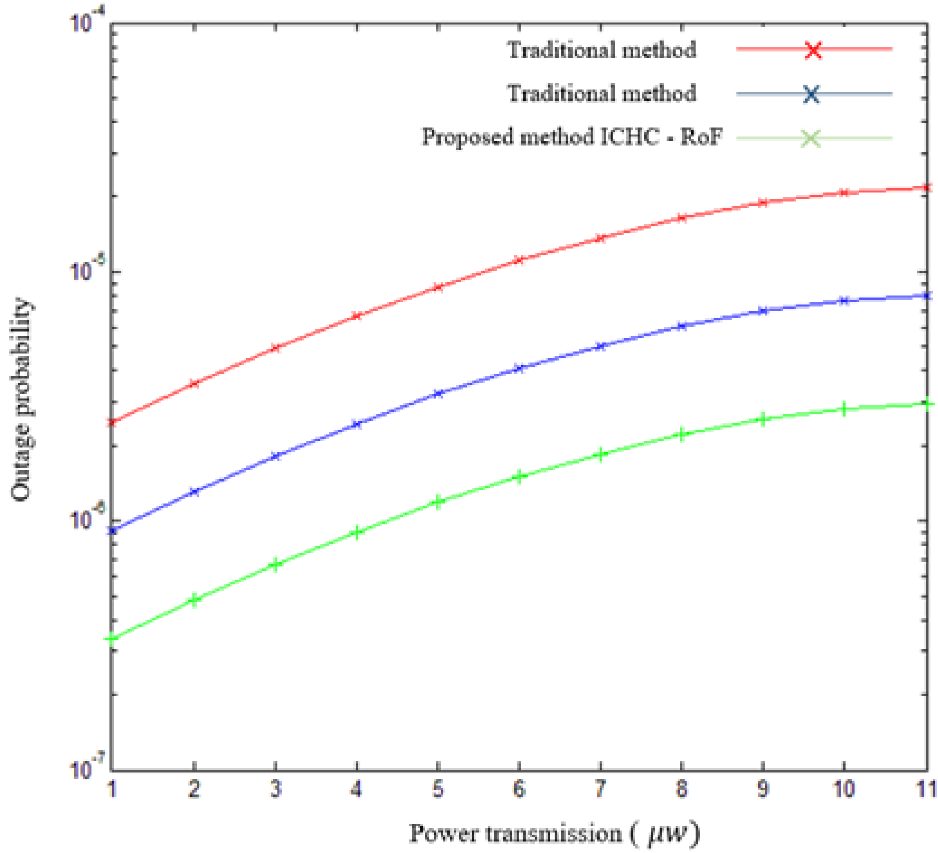

Figure 6.4: Outage Probability vs Power Transmission.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

Forming the IoT-RoF, which is Inernet of Things (IoT) that combines both optical fiber and wireless sensors networks is a promising technology. This thesis designs new early fire-detection IoT-RoF, the proposed design takes into consideration data journey from the sensors to the smart cloud system. The BRAUS protocol has also been suggested and its selection method based on the new proposed method as a function of RAUs number, length of optic fibre, attenuation factor and distance. Outage probability and bandwidth efficiency are two metrics that have been mathematically formulated and analysed in terms of number of RAUs and fibre optics length. We demonstrate that our protocol performed 30% better than any other existing protocols Formulation of quantum entanglement-based MAC protocol (QE-MAC) using Quantum teleportation and estimation of its delay, cycle duty and power consumption are then described. The results indicated that the proposed approach achieves enhanced performance with respect to delay,duty cycle, and power consumption than other approaches. It is also evident that QE-MAC with the RTS/CTS mechanism has similar performance as QE-MAC without RTS/CTS which is essential in avoiding data loss and collisions. The future work could involve finding optimal power allocation for both master and sensors nodes as well as formulation of throughput in the presence of collision. When compared to published works, our proposed work has shown a reduction in both delay and power consumption by 35The analysis of the energy harvesting (EH) in cooperative communication technique performance through the very dynamic Radio-over Fiber (RoF). It is important to note that this case study involved two different types of communication modes such as direct communication mode over radio over fiber system and cooperative communication mode. The conducted performance was done with outage probability for both modes. In this case, we introduce the concept of Inter-Cluster Head Cooperation over Radio over Fiber (ICHC-RoF) at last. It begins by considering the network and proposed architecture of this vision under RoF paradigm. Following that, an outage probability mathematical model is presented. Likewise, a mathematical analysis of throughput is also carried out for the proposed protocol. Moreover, it is also to be noted from both simulation as well as numerical results that the ICHC-RoF system has high performance.

7.2 Future Works

The discussion of Energy Harvesting over Inter-WBSN Analog Network Coding (EH-IWANC) is the foundation to open a new horizon of improvement of IoT-enabled communication systems. Future research could focus on several promising areas:

1. **Optimization Algorithms:** The ability to design mechanisms of self-tuning of such values as ω, which are responsible for the energy harvesting period in the network. This adaptive approach could increase the quality of the protocol concerning energy levels and communication differences.

2. **Security Enhancements:** Research on security aspects focused on the EH-IWANC protocol to enhance data security. This includes countering potential threats that could be exploited by attackers and exploring appropriate encryption mechanisms for WBSN devices with constrained resources.

3. **Experimental Validation:** Real-world testing of the proposed EH-IWANC protocol in different and diverse environments to ascertain its viability. The practical validations of an adaptive and functional communication protocol are the key to its viability in natural environments with scale deployments of the IoT.

4. **Multi-hop Communication:** A talking about the extension of current multi-hop protocols where the signal that is sent between multiple intermediate or relays nodes and then there is the final destination. It would result in the network in a larger scale deployment becoming more efficient and robust with such an architecture.

5. **combining with 5G :** This study will be aimed at discussing how the EH-IWANC process is to coexist with the future 5G and beyond networks based on its ability to meet the most significant demands of these systems, namely, the exceedingly low latency and fast data transmission.

6. **Energy-Efficient Coding Schemes:** The presented paper in the framework of the EH-IWANC-situation traces the energy-efficient coding schemes that can be considered in the situation of analog network coding. One of the main aims is to define coding methods that allow reducing power level needed to transmit the signals and receive them and can add to the energy-efficient communication.

In conclusion, EH-IWANC protocol is a strong and energy-saving system of developing IoT and cooperative systems. The given study provides a detailed investigation of the possibilities of the protocol and how it can be utilized in practice. Subsequent studies can therefore be devoted to other risks and possible ways of improving wireless communication processes that will be resilient as well as efficient in the real world.

References

[1] Ragini Tripathi, Ramgopal Gangwar, and Nar Singh. “REDUCTION OF CROSSTALK IN WAVELENGTH DIVISION MULTIPLEXED FIBER OPTIC COMMUNICATION SYSTEMS”. en. In: *Progress In Electromagnetics Research* 77 (2007), pp. 367–378. ISSN: 1559-8985. DOI: 10.2528/PIER07081002. URL: http://www.jpier.org/PIER/pier.php?paper=07081002 (visited on 06/11/2025).

[2] Yan Duan and Degang Chen. “Accurate jitter decomposition in high-speed links”. In: *2017 IEEE 35th VLSI Test Symposium (VTS)*. Las Vegas, NV, USA: IEEE, Apr. 2017, pp. 1–6. ISBN: 9781509044825. DOI: 10.1109/VTS.2017.7928918. URL: http://ieeexplore.ieee.org/document/7928918/ (visited on 06/11/2025).

[3] T.-S. Chu and M.J. Gans. “Fiber optic microcellular radio”. In: *IEEE Transactions on Vehicular Technology* 40.3 (Aug. 1991), pp. 599–606. ISSN: 00189545. DOI: 10.1109/25.97514. URL: http://ieeexplore.ieee.org/document/97514/ (visited on 06/11/2025).

[4] Institute of Electrical and Electronics Engineers, ed. *3rd IEEE International Conference on "Computational Intelligence and Communication Technology" (IEEE-CICT 2017): 9th & 10th February, 2017, ABES Engineering College, Ghaziabad*. eng. Piscataway, NJ: IEEE, 2017. ISBN: 9781509062188.

[5] Anatolii Yu. Pylypchuk. “CREATION OF INFORMATION AND COMMUNICATION TECHNOLOGIES MEANS FOR EDUCATION SYSTEM UNIFIED INFORMATION SPACE: PROBLEMS AND POSSIBLE WAYS OF THEIR DECISION”. In: *Information Technologies and Learning Tools* 7.3 (Jan. 1970). ISSN: 2076-8184. DOI: 10.33407/itlt.v7i3.116. URL:

https://journal.iitta.gov.ua/index.php/itlt/article/view/116 (visited on 06/11/2025).

[6] Yang Bai and Mingyu Fan. "A Method to Improve the Privacy and Security for Federated Learning". In: *2021 IEEE 6th International Conference on Computer and Communication Systems (ICCCS)*. Chengdu, China: IEEE, Apr. 2021, pp. 704–708. ISBN: 9781665412568. DOI: 10.1109/ICCCS52626.2021.9449214. URL: https://ieeexplore.ieee.org/document/9449214/ (visited on 06/11/2025).

[7] Richard W.N. Pazzi and Azzedine Boukerche. "Mobile data collector strategy for delay-sensitive applications over wireless sensor networks". en. In: *Computer Communications* 31.5 (Mar. 2008), pp. 1028–1039. ISSN: 01403664. DOI: 10.1016/j.comcom.2007.12.024. URL: https://linkinghub.elsevier.com/retrieve/pii/S0140366407005464 (visited on 06/11/2025).

[8] Massoud Hadian Dehkordi and The Society of Digital Information and Wireless Communication. "A New Scheme to Secure Communication and Data, based on the Integration of Cryptography and Steganography". en. In: *International Journal of Cyber-Security and Digital Forensics* 7.2 (2018), pp. 183–188. ISSN: 2305-0012. DOI: 10.17781/P002393. URL: http://sdiwc.net/digital-library/a-new-scheme-to-secure-communication-and-data-based-on-the-integration-of-cryptography-and-steganography.html (visited on 06/11/2025).

[9] Mona Andrei et al. "Design of the nano / micro scale structure of nanostructured composites activable in the radio frequency/microwave range depending on the frequency of the electromagnetic field". In: *2021 International Conference on Electromechanical and Energy Systems (SIELMEN)*. Iasi, Romania: IEEE, Oct. 2021, pp. 491–497. ISBN: 9781665400787. DOI: 10.1109/SIELMEN53755.2021.9600282. URL: https://ieeexplore.ieee.org/document/9600282/ (visited on 06/11/2025).

[10] Ampalavanapillai Nirmalathas et al. "Photonics enabled wireless networks: Optical wireless and optical backhaul". In: *2014 IEEE Photonics Conference*. San Diego, CA: IEEE, Dec. 2014, pp. 79–79. ISBN: 9781457715044. DOI: 10.1109/IPCon.2014.6995219. URL: http://ieeexplore.ieee.org/document/6995219/ (visited on 06/11/2025).

[11] Daniel J. Muller. "Automod® : Performance, scalability and accuracy". In: *2017 Winter Simulation Conference (WSC)*. Las Vegas, NV, USA: IEEE, Dec. 2017, pp. 4451–4451. ISBN: 9781538634288. DOI: 10.1109/WSC.2017.

8248158. URL: https://ieeexplore.ieee.org/document/8248158/ (visited on 06/11/2025).

[12] Masato Yamawaki, Norihide Takeyama, and Yousuke Katsumura. "Study of Reflection and Connection Materials Used for Transmitting and Condensing Scintillation Light by Means of Optical Fiber". In: *Japanese Journal of Applied Physics* 47.2R (Feb. 2008), p. 1104. ISSN: 0021-4922, 1347-4065. DOI: 10.1143/JJAP.47.1104. URL: https://iopscience.iop.org/article/10.1143/JJAP.47.1104 (visited on 06/11/2025).

[13] Mikhail A. Vorontsov and Thomas Weyrauch. "Laser Beam Engineering and Atmospheric Turbulence Effects Mitigation with Coherent Fiber Array Systems". en. In: *Propagation Through and Characterization of Atmospheric and Oceanic Phenomena*. Washington, DC: OSA, 2016, Tu2A.1. ISBN: 9781943580125. DOI: 10.1364/PCAOP.2016.Tu2A.1. URL: https://opg.optica.org/abstract.cfm?URI=pcAOP-2016-Tu2A.1 (visited on 06/11/2025).

[14] Jan Bohata et al. "Extended measurement tests of dual polarization radio over fiber and radio over FSO fronthaul in LTE C-RAN architecture". In: *2016 IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*. New York, NY: IEEE, Oct. 2016, pp. 1–5. ISBN: 9781509007240. DOI: 10.1109/WiMOB.2016.7763233. URL: http://ieeexplore.ieee.org/document/7763233/ (visited on 06/11/2025).

[15] David S. Sumida et al. "All-optical true-time-delay photonics network for high-bandwidth, free-space laser communication applications". In: ed. by G. S. Mecherle, Cynthia Y. Young, and John S. Stryjewski. San Jose, Ca, June 2004, p. 214. DOI: 10.1117/12.529731. URL: http://proceedings.spiedigitallibrary.org/proceeding.aspx?doi=10.1117/12.529731 (visited on 06/11/2025).

[16] M. P. Ninos et al. "Outage Performance of Uplink Pre-Amplified FSO Links Over Turbulence, Beam Wander, and Pointing Errors". In: *IEEE Communications Letters* 27.12 (Dec. 2023), pp. 3275–3279. ISSN: 1089-7798, 1558-2558, 2373-7891. DOI: 10.1109/LCOMM.2023.3331510. URL: https://ieeexplore.ieee.org/document/10313289/ (visited on 06/11/2025).

[17] K. Rottwitt, M. Nissov, and F. Kerfoot. "Detailed analysis of Raman amplifiers for long haul transmission". In: *OFC '98. Optical Fiber Communication Conference and Exhibit. Technical Digest. Conference Edition. 1998*

OSA Technical Digest Series Vol.2 (IEEE Cat. No.98CH36177). San Jose, CA, USA: Opt. Soc. America, 1998, pp. 30–31. ISBN: 9781557525215. DOI: 10.1109/OFC.1998.657178. URL: http://ieeexplore.ieee.org/document/657178/ (visited on 06/11/2025).

[18] Ahmed E. Morra and Steve Hranilovic. "Mixed mmWave and Radio-Over-Fiber Systems With Fiber Nonlinearity". In: *IEEE Photonics Technology Letters* 31.1 (Jan. 2019), pp. 23–26. ISSN: 1041-1135, 1941-0174. DOI: 10.1109/LPT.2018.2880951. URL: https://ieeexplore.ieee.org/document/8533419/ (visited on 06/11/2025).

[19] "Ensuring Efficient Data Transmission in Wireless Sensor Networks in Secure Way". In: *International Journal of Science and Research (IJSR)* 5.4 (Apr. 2016), pp. 1936–1939. ISSN: 23197064. DOI: 10.21275/v5i4.NOV163073. URL: https://www.ijsr.net/archive/v5i4/NOV163073.pdf (visited on 06/11/2025).

[20] "Centralized network management system". en. In: *Computer Communications* 9.5 (Oct. 1986), p. 271. ISSN: 01403664. DOI: 10.1016/0140-3664(86)90202-1. URL: https://linkinghub.elsevier.com/retrieve/pii/0140366486902021 (visited on 06/11/2025).

[21] Faris Keti, Salih M. S. Atroshey, and Jalil A. Hamadamin. "A Review of the Impairments and Challenges of Radio over Fiber Technology and their Mitigation Strategies". In: *2022 International Conference on Computer Science and Software Engineering (CSASE)*. Duhok, Iraq: IEEE, Mar. 2022, pp. 95–100. ISBN: 9781665426329. DOI: 10.1109/CSASE51777.2022.9759619. URL: https://ieeexplore.ieee.org/document/9759619/ (visited on 06/11/2025).

[22] Xun Lu et al. "Performance Analysis of IEEE 802.11 Distributed Coordination Function in Low-Load Simulcast Radio-Over-Fiber-Based Distributed Antenna Systems". en. In: *Asia Communications and Photonics Conference 2013*. Beijing: OSA, 2013, AF2G.22. ISBN: 9781557529893. DOI: 10.1364/ACPC.2013.AF2G.22. URL: https://opg.optica.org/abstract.cfm?URI=ACPC-2013-AF2G.22 (visited on 06/11/2025).

[23] Vishal Sharma, Amarpal Singh, and Ajay K. Sharma. "Challenges to radio over fiber (RoF) technology and its mitigation schemes – A review". en. In: *Optik* 123.4 (Feb. 2012), pp. 338–342. ISSN: 00304026. DOI: 10.1016/j.ijleo.2011.02.031. URL: https://linkinghub.elsevier.com/retrieve/pii/S0030402611001926 (visited on 06/11/2025).

[24] Jacopo Nanni et al. "Controlling Rayleigh-Backscattering-Induced Distortion in Radio Over Fiber Systems for Radioastronomic Applications". In: *Journal of Lightwave Technology* 38.19 (Oct. 2020), pp. 5393–5405. ISSN: 0733-8724, 1558-2213. DOI: 10.1109/JLT.2020.2993203. URL: https://ieeexplore.ieee.org/document/9089231/ (visited on 06/11/2025).

[25] Alan S. Michaels. "Controlled release: Challenges and opportunities for the next decade". en. In: *Journal of Controlled Release* 2 (Nov. 1985), pp. 405–410. ISSN: 01683659. DOI: 10.1016/0168-3659(85)90062-8. URL: https://linkinghub.elsevier.com/retrieve/pii/0168365985900628 (visited on 06/11/2025).

[26] Yilun Shang. "Vulnerability of networks: Fractional percolation on random graphs". en. In: *Physical Review E* 89.1 (Jan. 2014), p. 012813. ISSN: 1539-3755, 1550-2376. DOI: 10.1103/PhysRevE.89.012813. URL: https://link.aps.org/doi/10.1103/PhysRevE.89.012813 (visited on 06/11/2025).

[27] Michal Wydra et al. "Overhead Transmission Line Sag Estimation Using a Simple Optomechanical System with Chirped Fiber Bragg Gratings. Part 1: Preliminary Measurements". en. In: *Sensors* 18.1 (Jan. 2018), p. 309. ISSN: 1424-8220. DOI: 10.3390/s18010309. URL: https://www.mdpi.com/1424-8220/18/1/309 (visited on 06/11/2025).

[28] Carlos A. Astudillo et al. "Internet of Things for Environmental Monitoring Based on Radio Over Fiber". In: *2018 IEEE 4th International Forum on Research and Technology for Society and Industry (RTSI)*. Palermo: IEEE, Sept. 2018, pp. 1–6. ISBN: 9781538662823. DOI: 10.1109/RTSI.2018.8548384. URL: https://ieeexplore.ieee.org/document/8548384/ (visited on 06/11/2025).

[29] Amin Ebrahimzadeh and Martin Maier. "Distributed cooperative computation offloading in multi-access edge computing fiber–wireless networks". en. In: *Optics Communications* 452 (Dec. 2019), pp. 130–139. ISSN: 00304018. DOI: 10.1016/j.optcom.2019.06.060. URL: https://linkinghub.elsevier.com/retrieve/pii/S0030401819305693 (visited on 06/11/2025).

[30] Camilo A. R. Díaz et al. "IoToF: A Long-Reach Fully Passive Low-Rate Upstream PHY for IoT over Fiber". en. In: *Electronics* 8.3 (Mar. 2019), p. 359. ISSN: 2079-9292. DOI: 10.3390/electronics8030359. URL: https://www.mdpi.com/2079-9292/8/3/359 (visited on 06/11/2025).

[31] Diego Fabián Paredes Páliz et al. "Radio over Fiber: An Alternative Broadband Network Technology for IoT". In: *Jornada de Jóvenes Investigadores del I3A* 8 (Dec. 2020). ISSN: 2341-4790. DOI: 10.26754/jjii3a.4870. URL: https://papiro.unizar.es/ojs/index.php/jji3a/article/view/4870 (visited on 06/11/2025).

[32] Na Chen and Minoru Okada. "Toward 6G Internet of Things and the Convergence With RoF System". In: *IEEE Internet of Things Journal* 8.11 (June 2021), pp. 8719–8733. ISSN: 2327-4662, 2372-2541. DOI: 10.1109/JIOT.2020.3047613. URL: https://ieeexplore.ieee.org/document/9309383/ (visited on 06/11/2025).

[33] Ahmed E. Morra, Khaled Ahmed, and Steve Hranilovic. "Impact of Fiber Nonlinearity on 5G Backhauling via Mixed FSO/Fiber Network". In: *IEEE Access* 5 (2017), pp. 19942–19950. ISSN: 2169-3536. DOI: 10.1109/ACCESS.2017.2753178. URL: http://ieeexplore.ieee.org/document/8038778/ (visited on 06/11/2025).

[34] Isiaka A. Alimi, Paulo P. Monteiro, and António L. Teixeira. "Outage Probability of Multiuser Mixed RF/FSO Relay Schemes for Heterogeneous Cloud Radio Access Networks (H-CRANs)". en. In: *Wireless Personal Communications* 95.1 (July 2017), pp. 27–41. ISSN: 0929-6212, 1572-834X. DOI: 10.1007/s11277-017-4413-y. URL: http://link.springer.com/10.1007/s11277-017-4413-y (visited on 06/11/2025).

[35] A. Taheri, A. Singh, and A. Emmanuel. "Location fingerprinting on infrastructure 802.11 wireless local area networks (WLANs) using Locus". In: *29th Annual IEEE International Conference on Local Computer Networks*. Tampa, FL, USA: IEEE (Comput. Soc.), 2004, pp. 676–683. ISBN: 9780769522609. DOI: 10.1109/LCN.2004.74. URL: http://ieeexplore.ieee.org/document/1367305/ (visited on 06/11/2025).

[36] Takayuki Nishio et al. "VRMAC: A novel WLAN medium access control mechanism using LEDs and a camera". In: *2013 IEEE Globecom Workshops (GC Wkshps)*. Atlanta, GA: IEEE, Dec. 2013, pp. 1121–1126. ISBN: 9781479928514. DOI: 10.1109/GLOCOMW.2013.6825143. URL: http://ieeexplore.ieee.org/document/6825143/ (visited on 06/11/2025).

[37] Mihir Pant et al. "Routing entanglement in the quantum internet". en. In: *npj Quantum Information* 5.1 (Mar. 2019), p. 25. ISSN: 2056-6387. DOI: 10.1038/s41534-019-0139-x. URL: https://www.nature.com/articles/s41534-019-0139-x (visited on 06/11/2025).

[38] Ahmed Mohamed and The Society of Digital Information and Wireless Communication. "PERFORMANCE EVALUATION OF ADAPTIVE LDPC CODED MODULATION COOPERATIVE WIRELESS COMMUNICATION SYSTEM WITH BEST-RELAY SELECTION". en. In: *International Journal of Digital Information and Wireless Communications* 4.1 (2014), pp. 155–168. ISSN: 2225-658X. DOI: 10.17781/P001093. URL: http://sdiwc.net/digital-library/performance-evaluation-of-adaptive-ldpc-coded-modulation-cooperative-wireless-communication-system-with-bestrelay-selection.html (visited on 07/08/2025).

[39] H.J. Keiho, H.J. Koivisto, and H.V. Jaakkola. "A new business strategy for teleoperators: opportunity for modern broadband access technologies". In: *IEMC '98 Proceedings. International Conference on Engineering and Technology Management. Pioneering New Technologies: Management Issues and Challenges in the Third Millennium (Cat. No.98CH36266)*. San Juan, PR, USA: IEEE, 1998, pp. 399–402. ISBN: 9780780350823. DOI: 10.1109/IEMC.1998.727793. URL: http://ieeexplore.ieee.org/document/727793/ (visited on 07/08/2025).

[40] Yuan Lee et al. "A quantum router architecture for high-fidelity entanglement flows in quantum networks". en. In: *npj Quantum Information* 8.1 (June 2022), p. 75. ISSN: 2056-6387. DOI: 10.1038/s41534-022-00582-8. URL: https://www.nature.com/articles/s41534-022-00582-8 (visited on 06/11/2025).

[41] Charles H. Bennett et al. "Purification of Noisy Entanglement and Faithful Teleportation via Noisy Channels". en. In: *Physical Review Letters* 76.5 (Jan. 1996), pp. 722–725. ISSN: 0031-9007, 1079-7114. DOI: 10.1103/PhysRevLett.76.722. URL: https://link.aps.org/doi/10.1103/PhysRevLett.76.722 (visited on 06/11/2025).

[42] S. Sarkar, S. Dixit, and B. Mukherjee. "Hybrid Wireless-Optical Broadband-Access Network (WOBAN): A Review of Relevant Challenges". In: *Journal of Lightwave Technology* 25.11 (Nov. 2007), pp. 3329–3340. ISSN: 0733-8724, 1558-2213. DOI: 10.1109/JLT.2007.906804. URL: http://ieeexplore.ieee.org/document/4357916/ (visited on 06/11/2025).

[43] K. Hamidian and J. Payne. "Combined CDMA with TDMA increases the capacity of a cellular communication system". In: *Proceedings of IEEE Pacific Rim Conference on Communications Computers and Signal Processing*. Vol. 2. Victoria, BC, Canada: IEEE, 1993, pp. 769–773. ISBN:

9780780309715. DOI: 10.1109/PACRIM.1993.407248. URL: http://ieeexplore.ieee.org/document/407248/ (visited on 06/28/2025).

[44] Julian Hofmann et al. "Heralded Entanglement Between Widely Separated Atoms". en. In: *Science* 337.6090 (July 2012), pp. 72–75. ISSN: 0036-8075, 1095-9203. DOI: 10.1126/science.1221856. URL: https://www.science.org/doi/10.1126/science.1221856 (visited on 06/11/2025).

[45] P.M. Wala. "A new microcell architecture using digital optical transport". In: *IEEE 43rd Vehicular Technology Conference*. Secaucus, NJ, USA: IEEE, 1993, pp. 585–588. ISBN: 9780780312661. DOI: 10.1109/VETEC.1993.507541. URL: http://ieeexplore.ieee.org/document/507541/ (visited on 06/11/2025).

[46] N. Ghazisaidi, M. Maier, and C. Assi. "Fiber-wireless (FiWi) access networks: A survey". In: *IEEE Communications Magazine* 47.2 (Feb. 2009), pp. 160–167. ISSN: 0163-6804. DOI: 10.1109/MCOM.2009.4785396. URL: http://ieeexplore.ieee.org/document/4785396/ (visited on 06/11/2025).

[47] Navid Ghazisaidi and Martin Maier. "Fiber-wireless (FiWi) access networks: Challenges and opportunities". In: *IEEE Network* 25.1 (Jan. 2011), pp. 36–42. ISSN: 0890-8044. DOI: 10.1109/MNET.2011.5687951. URL: http://ieeexplore.ieee.org/document/5687951/ (visited on 06/11/2025).

[48] Leonid Kazovsky et al. "Hybrid Optical–Wireless Access Networks". In: *Proceedings of the IEEE* 100.5 (May 2012), pp. 1197–1225. ISSN: 0018-9219, 1558-2256. DOI: 10.1109/JPROC.2012.2185769. URL: http://ieeexplore.ieee.org/document/6168211/ (visited on 06/11/2025).

[49] Antonios G. Sarigiannidis et al. "Architectures and Bandwidth Allocation Schemes for Hybrid Wireless-Optical Networks". In: *IEEE Communications Surveys & Tutorials* 17.1 (2015), pp. 427–468. ISSN: 1553-877X, 2373-745X. DOI: 10.1109/COMST.2014.2356640. URL: https://ieeexplore.ieee.org/document/6898810/ (visited on 06/11/2025).

[50] Martin Maier. "Fiber-Wireless (FiWi) Broadband Access Networks in an Age of Convergence: Past, Present, and Future". en. In: *Advances in Optics* 2014 (June 2014), pp. 1–23. ISSN: 2356-6817, 2314-7741. DOI: 10.1155/2014/945364. URL: https://www.hindawi.com/journals/ao/2014/945364/ (visited on 06/11/2025).

[51] Farhan Aslam et al. "Innovation in the Era of IoT and Industry 5.0: Absolute Innovation Management (AIM) Framework". en. In: *Information* 11.2

(Feb. 2020), p. 124. ISSN: 2078-2489. DOI: 10.3390/info11020124. URL: https://www.mdpi.com/2078-2489/11/2/124 (visited on 06/12/2025).

[52] Ivo Bizon Franco De Almeida et al. "5G Waveforms for IoT Applications". In: *IEEE Communications Surveys & Tutorials* 21.3 (2019), pp. 2554–2567. ISSN: 1553-877X, 2373-745X. DOI: 10.1109/COMST.2019.2910817. URL: https://ieeexplore.ieee.org/document/8688497/ (visited on 06/12/2025).

[53] Chi-Wai Chow et al. "WDM extended reach passive optical networks using OFDM-QAM". en. In: *Optics Express* 16.16 (Aug. 2008), p. 12096. ISSN: 1094-4087. DOI: 10.1364/OE.16.012096. URL: https://opg.optica.org/oe/abstract.cfm?uri=oe-16-16-12096 (visited on 06/27/2025).

[54] Xiao Min and H. J. Kimble. "Propagation of quantum fluctuations through passive optical systems". en. In: *Annual Meeting Optical Society of America*. Seattle, Washington: Optica Publishing Group, 1986, TUJ4. DOI: 10.1364/OAM.1986.TUJ4. URL: https://opg.optica.org/abstract.cfm?URI=OAM-1986-TUJ4 (visited on 06/27/2025).

[55] Marcelo Kuchar Matte et al. "Active Fire Detection in Forests with 5 Deep Learning Techniques". In: *Anais do XVIII Workshop de Visão Computacional (WVC 2023)*. Brasil: Sociedade Brasileira de Computação - SBC, Nov. 2023, pp. 1–5. DOI: 10.5753/wvc.2023.27523. URL: https://sol.sbc.org.br/index.php/wvc/article/view/27523 (visited on 06/27/2025).

[56] Hieu Duy Nguyen, Jingon Joung, and Sumei Sun. "Precoder design for distributed antenna systems (DAS) with limited channel state information". In: *2015 IEEE International Conference on Communications (ICC)*. London: IEEE, June 2015, pp. 1733–1738. ISBN: 9781467364324. DOI: 10.1109/ICC.2015.7248575. URL: http://ieeexplore.ieee.org/document/7248575/ (visited on 06/27/2025).

[57] J.N. Laneman, D.N.C. Tse, and G.W. Wornell. "Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior". en. In: *IEEE Transactions on Information Theory* 50.12 (Dec. 2004), pp. 3062–3080. ISSN: 0018-9448. DOI: 10.1109/TIT.2004.838089. URL: http://ieeexplore.ieee.org/document/1362898/ (visited on 06/12/2025).

[58] René-Jean Essiambre et al. "Capacity Limits of Optical Fiber Networks". In: *Journal of Lightwave Technology* 28.4 (Feb. 2010), pp. 662–701. ISSN: 0733-8724, 1558-2213. DOI: 10.1109/JLT.2009.2039464. URL: https://ieeexplore.ieee.org/document/5420239/ (visited on 06/12/2025).

[59] G. Bosco et al. "Analytical results on channel capacity in uncompensated optical links with coherent detection". en. In: *Optics Express* 19.26 (Dec. 2011), B440. ISSN: 1094-4087. DOI: 10.1364/OE.19.00B440. URL: https://opg.optica.org/oe/abstract.cfm?uri=oe-19-26-B440 (visited on 06/12/2025).

[60] A.S. Ibrahim et al. "Cooperative communications with relay-selection: when to cooperate and whom to cooperate with?" In: *IEEE Transactions on Wireless Communications* 7.7 (July 2008), pp. 2814–2827. ISSN: 1536-1276. DOI: 10.1109/TWC.2008.070176. URL: http://ieeexplore.ieee.org/document/4570248/ (visited on 06/12/2025).

[61] Ahmed Alkhayyat and Sattar B. Sadkhan. "Bandwidth efficiency analysis of cooperative communication with Reactive Relay Selection". In: *2018 International Conference on Engineering Technology and their Applications (IICETA)*. Al-Najaf: IEEE, May 2018, pp. 77–80. ISBN: 9781538678589. DOI: 10.1109/IICETA.2018.8458077. URL: https://ieeexplore.ieee.org/document/8458077/ (visited on 06/12/2025).

[62] Hamed Al-Raweshidy and Shozo Komaki, eds. *Radio over fiber technologies for mobile communications networks*. eng. Artech House universal personal communications series. Boston London: Artech House, 2002. ISBN: 9781580531481.

[63] Shakir Salman Ahmad, Hamed Al-Raweshidy, and Ahmed Alkhayyat. "Distributed remote antenna unit with selection-based of (RoF-IoT) paradigm: Performance improvement". en. In: *IET Communications* (Oct. 2022), cmu2.12524. ISSN: 1751-8628, 1751-8636. DOI: 10.1049/cmu2.12524. URL: https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/cmu2.12524 (visited on 06/12/2025).

[64] Dongkyu Kim et al. "Quantum-correlation-based free-space optical link with an active reflector". en. In: *Current Applied Physics* 41 (Sept. 2022), pp. 156–162. ISSN: 15671739. DOI: 10.1016/j.cap.2022.06.018. URL: https://linkinghub.elsevier.com/retrieve/pii/S1567173922001651 (visited on 06/12/2025).

[65] Ebrahim E. Elsayed and Bedir B. Yousif. "Performance evaluation and enhancement of the modified OOK based IM/DD techniques for hybrid fiber/FSO communication over WDM-PON systems". en. In: *Optical and Quantum Electronics* 52.9 (Sept. 2020), p. 385. ISSN: 0306-8919, 1572-817X. DOI: 10.1007/s11082-020-02497-0. URL: https://link.springer.com/10.1007/s11082-020-02497-0 (visited on 06/12/2025).

[66] Nancy Alshaer, Ahmed Moawad, and Tawfik Ismail. "Reliability and Security Analysis of an Entanglement-Based QKD Protocol in a Dynamic Ground-to-UAV FSO Communications System". In: *IEEE Access* 9 (2021), pp. 168052–168067. ISSN: 2169-3536. DOI: 10.1109/ACCESS.2021.3137357. URL: https://ieeexplore.ieee.org/document/9656915/ (visited on 06/12/2025).

[67] Anastasios Valkanis, Petros Nicopolitidis, and Georgios Papadimitriou. "A Hybrid Link-TDMA MAC Protocol for Conventional and Radio over Fiber WLANs". en. In: *Wireless Communications and Mobile Computing* 2020 (Aug. 2020), pp. 1–15. ISSN: 1530-8669, 1530-8677. DOI: 10.1155/2020/9340272. URL: https://www.hindawi.com/journals/wcmc/2020/9340272/ (visited on 06/12/2025).

[68] Takayuki Nishio et al. "MAC Protocol for Improving Throughput and Balancing Uplink/Downlink Throughput for Wireless Local Area Networks with Long Propagation Delays". en. In: *IEICE Transactions on Communications* E100.B.5 (2017), pp. 874–883. ISSN: 0916-8516, 1745-1345. DOI: 10.1587/transcom.2016EBP3074. URL: https://www.jstage.jst.go.jp/article/transcom/E100.B/5/E100.B_2016EBP3074/_article (visited on 06/12/2025).

[69] Gayane Vardoyan et al. "On the Stochastic Analysis of a Quantum Entanglement Distribution Switch". In: *IEEE Transactions on Quantum Engineering* 2 (2021), pp. 1–16. ISSN: 2689-1808. DOI: 10.1109/TQE.2021.3058058. URL: https://ieeexplore.ieee.org/document/9351761/ (visited on 06/12/2025).

[70] Laszlo Gyongyosi, Sandor Imre, and Hung Viet Nguyen. "A Survey on Quantum Channel Capacities". In: *IEEE Communications Surveys & Tutorials* 20.2 (2018), pp. 1149–1205. ISSN: 1553-877X, 2373-745X. DOI: 10.1109/COMST.2017.2786748. URL: https://ieeexplore.ieee.org/document/8242350/ (visited on 06/12/2025).

[71] Huawang Qin and Yuewei Dai. "Sharing the Quantum State and the Classical Information Simultaneously". en. In: *International Journal of Theoretical Physics* 55.8 (Aug. 2016), pp. 3777–3787. ISSN: 0020-7748, 1572-9575. DOI: 10.1007/s10773-016-3006-y. URL: http://link.springer.com/10.1007/s10773-016-3006-y (visited on 07/08/2025).

[72] Stefano Pirandola et al. "Fundamental limits of repeaterless quantum communications". en. In: *Nature Communications* 8.1 (Apr. 2017), p. 15043.

ISSN: 2041-1723. DOI: 10.1038/ncomms15043. URL: https://www.nature.com/articles/ncomms15043 (visited on 06/12/2025).

[73] Jianping Wu and Wendy Hall. "[No title found]". en. In: *Proceedings of the ACM Special Interest Group on Data Communication*. Beijing China: ACM, Aug. 2019. ISBN: 9781450359566.

[74] Haowei Shi, Zheshen Zhang, and Quntao Zhuang. "Practical Route to Entanglement-Assisted Communication Over Noisy Bosonic Channels". en. In: *Physical Review Applied* 13.3 (Mar. 2020), p. 034029. ISSN: 2331-7019. DOI: 10.1103/PhysRevApplied.13.034029. URL: https://link.aps.org/doi/10.1103/PhysRevApplied.13.034029 (visited on 06/12/2025).

[75] Junzhen Sui and Qin Yue. "Twisted Goppa Codes With an Efficient Decoding Algorithm and Quasi-Cyclic Properties". In: *IEEE Transactions on Information Theory* 69.9 (Sept. 2023), pp. 5660–5669. ISSN: 0018-9448, 1557-9654. DOI: 10.1109/TIT.2023.3271652. URL: https://ieeexplore.ieee.org/document/10113345/ (visited on 06/27/2025).

[76] Gilles Brassard, Richard Cleve, and Alain Tapp. "Cost of Exactly Simulating Quantum Entanglement with Classical Communication". en. In: *Physical Review Letters* 83.9 (Aug. 1999), pp. 1874–1877. ISSN: 0031-9007, 1079-7114. DOI: 10.1103/PhysRevLett.83.1874. URL: https://link.aps.org/doi/10.1103/PhysRevLett.83.1874 (visited on 06/27/2025).

[77] Kazem Mahdavi and Deborah Koslover. *Advances in quantum computation: representation theory, quantum field theory, category theory, mathematical physics, and quantum information theory, September 20-23, 2007, University of Texas at Tyler*. eng. Contemporary mathematics 482. Providence, R.I: American mathematical society, 2009. ISBN: 9780821846278.

[78] Peter C. Humphreys et al. "Publisher Correction: Deterministic delivery of remote entanglement on a quantum network". en. In: *Nature* 562.7725 (Oct. 2018), E2–E2. ISSN: 0028-0836, 1476-4687. DOI: 10.1038/s41586-018-0314-9. URL: https://www.nature.com/articles/s41586-018-0314-9 (visited on 06/12/2025).

[79] Ryosuke Yoshii, Shion Yamashika, and Shunji Tsuchiya. "Entanglement Propagation in Thermalization of an Isolated Quantum System". en. In: *Journal of the Physical Society of Japan* 91.5 (May 2022), p. 054601. ISSN: 0031-9015, 1347-4073. DOI: 10.7566/JPSJ.91.054601. URL: https://journals.jps.jp/doi/10.7566/JPSJ.91.054601 (visited on 06/28/2025).

[80] Wallace J. Gingerich. "Building Sophisticated Information Systems with the Clarion Professional Developer". en. In: *Computers in Human Services* 5.3-4 (Sept. 1989), pp. 213–219. ISSN: 0740-445X. DOI: 10.1300/J407v05n03_19. URL: http://www.tandfonline.com/doi/abs/10.1300/J407v05n03_19 (visited on 06/12/2025).

[81] Divya Choudhary and The Society of Digital Information and Wireless Communication. "A NEW APPROACH TO WIRELESS CHANNEL MODELING USING FINITE MIXTURE MODELS". en. In: *International Journal of Digital Information and Wireless Communications* 4.2 (2014), pp. 169–183. ISSN: 2225-658X. DOI: 10.17781/P001096. URL: http://sdiwc.net/digital-library/a-new-approach-to-wireless-channel-modeling-using-finite-mixture-models.html (visited on 06/12/2025).

[82] Azade Khalaj, Nasser Yazdani, and Maseud Rahgozar. "Effect of the contention window size on performance and fairness of the IEEE 802.11 standard". en. In: *Wireless Personal Communications* 43.4 (Nov. 2007), pp. 1267–1278. ISSN: 0929-6212, 1572-834X. DOI: 10.1007/s11277-007-9300-5. URL: http://link.springer.com/10.1007/s11277-007-9300-5 (visited on 06/28/2025).

[83] B. Kalantari-Sabet et al. "Performance Impairments in Single-Mode Radio-Over-Fiber Systems Due to MAC Constraints". In: *Journal of Lightwave Technology* 26.15 (Aug. 2008), pp. 2540–2548. ISSN: 0733-8724. DOI: 10.1109/JLT.2008.927158. URL: http://ieeexplore.ieee.org/document/4652281/ (visited on 06/12/2025).

[84] Muhammet Ali Karabulut, A. F. M. Shahen Shah, and Haci Ilhan. "The Performance of the IEEE 802.11 DCF for Different Contention Window in VANETs". In: *2018 41st International Conference on Telecommunications and Signal Processing (TSP)*. Athens: IEEE, July 2018, pp. 1–4. ISBN: 9781538646953. DOI: 10.1109/TSP.2018.8441481. URL: https://ieeexplore.ieee.org/document/8441481/ (visited on 06/12/2025).

[85] L. Gannoune and S. Robert. "Dynamic tuning of the contention window minimum (CW/sub min/) for enhanced service differentiation in IEEE 802.11 wireless ad-hoc networks". In: *2004 IEEE 15th International Symposium on Personal, Indoor and Mobile Radio Communications (IEEE Cat. No.04TH8754)*. Barcelona, Spain: IEEE, 2004, pp. 311–317. ISBN: 9780780385238. DOI: 10.1109/PIMRC.2004.1370885. URL: http://ieeexplore.ieee.org/document/1370885/ (visited on 06/12/2025).

[86] M. Ferguson. "An Approximate Analysis of Delay for Fixed and Variable Length Packets in an Unslotted ALOHA Channel". en. In: *IEEE Transactions on Communications* 25.7 (July 1977), pp. 644–654. ISSN: 0096-2244. DOI: 10.1109/TCOM.1977.1093885. URL: http://ieeexplore.ieee.org/document/1093885/ (visited on 06/12/2025).

[87] Sen Zhang and Daniel R. Franklin. "Feasibility study on the implementation of IEEE 802.11 on cloud-based radio over fibre architecture". In: *2014 IEEE International Conference on Communications (ICC)*. Sydney, NSW: IEEE, June 2014, pp. 2891–2896. ISBN: 9781479920037. DOI: 10.1109/ICC.2014.6883763. URL: http://ieeexplore.ieee.org/document/6883763/ (visited on 06/12/2025).

[88] Kaito Funabiki et al. "ATRAS: adaptive MAC protocol for efficient and fair coexistence between radio over fiber-based and CSMA/CA-based WLANs". en. In: *EURASIP Journal on Wireless Communications and Networking* 2017.1 (Dec. 2017), p. 129. ISSN: 1687-1499. DOI: 10.1186/s13638-017-0907-2. URL: https://jwcn-eurasipjournals.springeropen.com/articles/10.1186/s13638-017-0907-2 (visited on 06/12/2025).

[89] Vedika Saravanan and Samah M. Saeed. "Pauli Error Propagation-Based Gate Rescheduling for Quantum Circuit Error Mitigation". In: *IEEE Transactions on Quantum Engineering* 3 (2022), pp. 1–11. ISSN: 2689-1808. DOI: 10.1109/TQE.2022.3161197. URL: https://ieeexplore.ieee.org/document/9740569/ (visited on 06/12/2025).

[90] Donghwa Han et al. "Block Orthogonal Sparse Superposition Codes for L^3 Communications: Low Error Rate, Low Latency, and Low Transmission Power". In: *IEEE Journal on Selected Areas in Communications* 43.4 (Apr. 2025), pp. 1183–1199. ISSN: 0733-8716, 1558-0008. DOI: 10.1109/JSAC.2025.3531569. URL: https://ieeexplore.ieee.org/document/10845812/ (visited on 06/28/2025).

[91] C.J. Bouwkamp. "Hallén's theory for a straight, perfectly conducting wire, used as a transmitting or receiving aerial". en. In: *Physica* 9.7 (July 1942), pp. 609–631. ISSN: 00318914. DOI: 10.1016/S0031-8914(42)80028-2. URL: https://linkinghub.elsevier.com/retrieve/pii/S0031891442800282 (visited on 06/12/2025).

[92] Shakir Salman Ahmad, Hamed Al-Raweshidy, and Rajagopal Nilavalan. "Investigating delay of the media access control protocols for IoT-RoF using quantum entanglement". en. In: *IET Networks* 13.4 (July 2024), pp. 324–337. ISSN: 2047-4954, 2047-4962. DOI: 10.1049/ntw2.12117.

URL: https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/ntw2.12117 (visited on 06/12/2025).

[93] Hosein Azarhava and Javad Musevi Niya. "Energy Efficient Resource Allocation in Wireless Energy Harvesting Sensor Networks". In: *IEEE Wireless Communications Letters* (2020), pp. 1–1. ISSN: 2162-2337, 2162-2345. DOI: 10.1109/LWC.2020.2978049. URL: https://ieeexplore.ieee.org/document/9023361/ (visited on 06/12/2025).

[94] Patricio Fuentes et al. "On the Logical Error Rate of Sparse Quantum Codes". In: *IEEE Transactions on Quantum Engineering* 3 (2022), pp. 1–12. ISSN: 2689-1808. DOI: 10.1109/TQE.2022.3196609. URL: https://ieeexplore.ieee.org/document/9850409/ (visited on 06/12/2025).

[95] Fadoua Yakine and Adil Kenzi. "Energy Harvesting in wireless communication: A survey". In: *E3S Web of Conferences* 336 (2022). Ed. by B. Benhala et al., p. 00074. ISSN: 2267-1242. DOI: 10.1051/e3sconf/202233600074. URL: https://www.e3s-conferences.org/10.1051/e3sconf/202233600074 (visited on 06/12/2025).

[96] Siron Anita Susan T and B. Nithya. "Cluster Based Key Management Schemes in Wireless Sensor Networks: A Survey". en. In: *Procedia Computer Science* 171 (2020), pp. 2684–2693. ISSN: 18770509. DOI: 10.1016/j.procs.2020.04.291. URL: https://linkinghub.elsevier.com/retrieve/pii/S1877050920312849 (visited on 06/12/2025).

[97] Xiaolong Pan et al. "Photonic vector mm-wave signal generation by optical dual-SSB modulation and a single push-pull MZM". en. In: *Optics Letters* 44.14 (July 2019), p. 3570. ISSN: 0146-9592, 1539-4794. DOI: 10.1364/OL.44.003570. URL: https://opg.optica.org/abstract.cfm?URI=ol-44-14-3570 (visited on 06/12/2025).

[98] Zizheng Cao et al. "200 Gbps OOK Transmission over an Indoor Optical Wireless Link Enabled by an Integrated Cascaded Aperture Optical Receiver". en. In: *Optical Fiber Communication Conference Postdeadline Papers*. Los Angeles, California: OSA, 2017, Th5A.6. ISBN: 9781943580248. DOI: 10.1364/OFC.2017.Th5A.6. URL: https://opg.optica.org/abstract.cfm?URI=OFC-2017-Th5A.6 (visited on 06/12/2025).

[99] Fahad M. A. Al-Zubaidi et al. "Optically Powered Radio-Over-Fiber Systems in Support of 5G Cellular Networks and IoT". In: *Journal of Lightwave Technology* 39.13 (July 2021), pp. 4262–4269. ISSN: 0733-8724, 1558-2213. DOI: 10.1109/JLT.2021.3074193. URL: https://ieeexplore.ieee.org/document/9409616/ (visited on 06/11/2025).

[100] Ray E. Sheriff and Y. Fun Hu. *Mobile Satellite Communication Networks*. en. 1st ed. Wiley, Oct. 2001. ISBN: 9780471720478 9780470845561. DOI: 10.1002/0470845562. URL: https://onlinelibrary.wiley.com/doi/book/10.1002/0470845562 (visited on 06/27/2025).

[101] Giovanni Tomasi. "Fiber Optic Systems for Avionics Illumination". en. In: *SAE International Journal of Aerospace* 5.1 (Oct. 2012), pp. 201–205. ISSN: 1946-3901. DOI: 10.4271/2012-01-2127. URL: https://www.sae.org/content/2012-01-2127/ (visited on 06/27/2025).

[102] E. L. Afraimovich and K. S. Palamarchuk. "A spectral-polarization method for analyzing the interference pattern of a radio signal". en. In: *Radiophysics and Quantum Electronics* 41.6 (June 1998), pp. 485–492. ISSN: 0033-8443, 1573-9120. DOI: 10.1007/BF02676681. URL: http://link.springer.com/10.1007/BF02676681 (visited on 06/27/2025).

[103] Yuanyuan Cheng et al. "Average Bit Error Rate and Sum Capacity in Heterogeneous Cloud Radio Access Networks". In: *2015 IEEE 82nd Vehicular Technology Conference (VTC2015-Fall)*. Boston, MA, USA: IEEE, Sept. 2015, pp. 1–5. ISBN: 9781479980918. DOI: 10.1109/VTCFall.2015.7390850. URL: http://ieeexplore.ieee.org/document/7390850/ (visited on 06/27/2025).

[104] Ding Xu and Qun Li. "Service Outage Constrained Outage Probability Minimizing Joint Channel, Power and Rate Allocation for Cognitive Radio Multicast Networks". en. In: *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences* E98.A.8 (2015), pp. 1854–1857. ISSN: 0916-8508, 1745-1337. DOI: 10.1587/transfun.E98.A.1854. URL: https://www.jstage.jst.go.jp/article/transfun/E98.A/8/E98.A_1854/_article (visited on 06/27/2025).

[105] Beneyam B. Haile, Edward Mutafungwa, and Jyri Hamalainen. "Coordinated Multipoint transmission for LTE-Advanced networks in dense informal settlements". In: *2013 Africon*. Pointe-Aux-Piments: IEEE, Sept. 2013, pp. 1–5. ISBN: 9781467359405 9781467359436. DOI: 10.1109/AFRCON.2013.6757791. URL: https://ieeexplore.ieee.org/document/6757791/ (visited on 06/12/2025).

[106] Juan C. Juarez et al. "High-sensitivity DPSK receiver for high-bandwidth free-space optical communication links". en. In: *Optics Express* 19.11 (May 2011), p. 10789. ISSN: 1094-4087. DOI: 10.1364/OE.19.010789. URL: https://opg.optica.org/oe/abstract.cfm?uri=oe-19-11-10789 (visited on 06/12/2025).

[107] Arfip Jikaraji and Vitawat Sittakul. "Transmission of 3 GHz bandwith data over radio over fiber". In: *2017 International Conference on Communication and Signal Processing (ICCSP)*. Chennai: IEEE, Apr. 2017, pp. 0486–0490. ISBN: 9781509038008. DOI: 10.1109/ICCSP.2017.8286405. URL: http://ieeexplore.ieee.org/document/8286405/ (visited on 06/12/2025).

[108] E. Stauffer and A. Paulraj. "Minimizing outage probability for arbitrary channel distributions". In: *IEEE International Conference on Communications, 2005. ICC 2005. 2005.* Vol. 4. Seoul, Korea: IEEE, 2005, pp. 2402–2406. ISBN: 9780780389380. DOI: 10.1109/ICC.2005.1494766. URL: http://ieeexplore.ieee.org/document/1494766/ (visited on 06/12/2025).

[109] Debasis Sarkar, Harsh Patel, and Bhargav Dave. "Development of integrated cloud-based Internet of Things (IoT) platform for asset management of elevated metro rail projects". en. In: *International Journal of Construction Management* 22.10 (July 2022), pp. 1993–2002. ISSN: 1562-3599, 2331-2327. DOI: 10.1080/15623599.2020.1762035. URL: https://www.tandfonline.com/doi/full/10.1080/15623599.2020.1762035 (visited on 06/12/2025).

[110] Kailong Li, Wei Guo, and Weisheng Hu. "Ethernet Frame Aggregation at Optical Network Unit Mesh Point Portal (ONU-MPP) in Fiber Wireless (FiWi) Access Networks". en. In: *Asia Communications and Photonics Conference*. Guangzhou: OSA, 2012, AF4A.56. ISBN: 9781557529572. DOI: 10.1364/ACPC.2012.AF4A.56. URL: https://opg.optica.org/abstract.cfm?URI=ACPC-2012-AF4A.56 (visited on 06/15/2025).

[111] Toshihiro Yamauchi et al. "Analysis of commands of Telnet logs illegally connected to IoT devices". In: *2021 10th International Congress on Advanced Applied Informatics (IIAI-AAI)*. Niigata, Japan: IEEE, July 2021, pp. 913–915. ISBN: 9781665424202. DOI: 10.1109/IIAI-AAI53430.2021.00160. URL: https://ieeexplore.ieee.org/document/9791030/ (visited on 06/12/2025).

[112] Na Liu et al. "Nyquist 4-ary pulse amplitude modulation scheme based on electrical Nyquist pulse shaping and fiber Bragg grating filter". en. In: *Optical Engineering* 54.4 (Apr. 2015), p. 046105. ISSN: 0091-3286. DOI: 10.1117/1.OE.54.4.046105. URL: http://opticalengineering.spiedigitallibrary.org/article.aspx?doi=10.1117/1.OE.54.4.046105 (visited on 06/12/2025).

[113] Diego F. Paredes-Páliz et al. "CMOS Linear Laser Driver for Intermediate Frequency over Fiber (IFoF) Links". en. In: *Electronics* 12.15 (July 2023), p. 3251. ISSN: 2079-9292. DOI: 10.3390/electronics12153251. URL: https://www.mdpi.com/2079-9292/12/15/3251 (visited on 06/12/2025).

[114] Optical Society of America and Institute of Electrical and Electronics Engineers, eds. *Optical Fiber Communication Conference: [part of] Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2011 ; 6 - 10 March 2011, Los Angeles, California, United States ; [including the] Meeting the Computercom Challenge Symposium, Packet Switching Symposium*. eng. OSA technical digest. Washington, DC: OSA, The Optical Society, 2011. ISBN: 9781557529060.

[115] J.-M.P. Delavaux and T. Stfusser. "10 Gb/s 120-km Bidirectional Repeaterless Transmission over Single-Mode Fiber". en. In: *Optical Fiber Technology* 1.4 (Oct. 1995), pp. 318–321. ISSN: 10685200. DOI: 10.1006/ofte.1995.1024. URL: https://linkinghub.elsevier.com/retrieve/pii/S1068520085710243 (visited on 06/15/2025).

[116] Qi Zhou, Hanlin Feng, and Mable P. Fok. "Broadband co-site and co-channel RF interference cancellation system". en. In: *Asia Communications and Photonics Conference 2014*. Shanghai: OSA, 2014, ATh1F.5. ISBN: 9781557528520. DOI: 10.1364/ACPC.2014.ATh1F.5. URL: https://opg.optica.org/abstract.cfm?URI=ACPC-2014-ATh1F.5 (visited on 06/15/2025).

[117] Narendra Vishwakarma and Swaminathan R. "Performance analysis of hybrid FSO/RF communication over generalized fading models". en. In: *Optics Communications* 487 (May 2021), p. 126796. ISSN: 00304018. DOI: 10.1016/j.optcom.2021.126796. URL: https://linkinghub.elsevier.com/retrieve/pii/S0030401821000468 (visited on 06/12/2025).

[118] C.E. Uc-Rios and D. Lara-Rodriguez. "On the effect of directional antennas on the reverse link capacity of CDMA cellular systems". In: *IEEE 54th Vehicular Technology Conference. VTC Fall 2001. Proceedings (Cat. No.01CH37211)*. Vol. 1. Atlantic City, NJ, USA: IEEE, 2001, pp. 217–221. ISBN: 9780780370050. DOI: 10.1109/VTC.2001.956589. URL: http://ieeexplore.ieee.org/document/956589/ (visited on 06/15/2025).

[119] I. R. Fedorov et al. "Blockchain Technology in 5G Networks: Performance Comparison of Private and Public Blockchains". en. In: *Automatic Control and Computer Sciences* 56.8 (Dec. 2022), pp. 1025–1029. ISSN: 0146-4116,

1558-108X. DOI: 10.3103/S0146411622080053. URL: https://link.springer.com/10.3103/S0146411622080053 (visited on 06/12/2025).

[120] S. M. Mohd Hassan et al. "Implementation of Remote Antenna Unit and Outdoor/Indoor Unit for Multi-Service Radio-over-Fiber". In: *2018 IEEE International RF and Microwave Conference (RFM)*. Penang, Malaysia: IEEE, Dec. 2018, pp. 278–281. ISBN: 9781538667200. DOI: 10.1109/RFM.2018.8846479. URL: https://ieeexplore.ieee.org/document/8846479/ (visited on 06/28/2025).