



Quantum key distribution over FSO channel using error reconciliation protocol

Bandana Mallick¹ · Priyadarsan Parida¹ · Chittaranjan Nayak² · Pritam Keshari Sahoo³ · Gopinath Palai⁴

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Abstract

Quantum key distribution (QKD) has evolved as a robust way of secret key distribution based on renowned modern physics concepts. To transmit sensitive information in the government, private, and personal sectors, high-security levels are now necessary. All conventional cryptographic algorithms applied in the communication models, which rely on mathematical models and conceptual assumptions, are insecure. Thus, QKD systems are the best choice for protecting this information as a countermeasure since they provide unconditional security. In this paper, a design is proposed for the FSO channel using the CASCADE protocol under different atmospheric condition such as haze, rain and snow. The suggested framework's effectiveness and security in the context of QKD with two non-orthogonal photon states are assessed. Simulation results of this model show the percentage of original sequence recovery; the number of errors removed, optical spectrum at transmitter and receiver for a base frame length of 10^4 bits. Moreover, Error correction is calculated per iteration to improve signal quality at the receiver side and compared to previous work. The calculated value in this article shows a better result. Hence, both the sender and the receiver could achieve a security key using this method.

Keywords Quantum key distribution · CASCADE protocol · Information reconciliation · Privacy amplification

1 Introduction

In this decade, secure communication platforms are an important requirement by the people and large industries to demand reliable data transmission via an open environment. Hence, a secure channel for communication must be implemented from sender to receiver to transmit the information [1]. Cryptography ensures the security and

accuracy of data in the presence of threats in communication. An essential cryptography challenge in this is how to transfer a secret key from the sender to the recipient [2]. Generally, two types of encryption approaches are used: symmetric key and public-key cryptography [3].

QKD possesses the capability of secure communication, which is based on quantum mechanics instead of dubious assumptions about the present and prospective computational resources [4, 5]. QKD addresses the problem of key distribution without depending on the computational complexity of accomplishing such mathematical functions as one-way functions, which are studied as the backbone of public-key cryptography [6].

In QKD, let two communication entities are considered named Alice (sender) and Bob (receiver) transmit the data in the communication network. It allows both parties to identify an eavesdropper (Eve) and establish a secret key that is unknown to Eve. As shown in the Fig. 1, two communication channels are normally present in a QKD system: a quantum channel and an authenticated classical channel [7]. The function of a quantum channel or private

✉ Priyadarsan Parida
priyadarsanparida@giet.edu

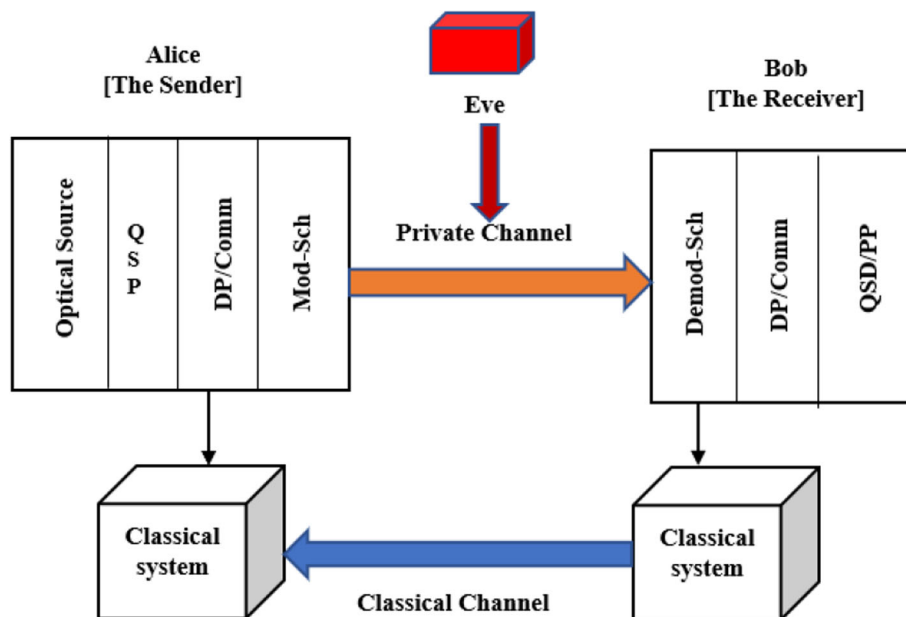
¹ Department of Electronics and Communication Engineering, GIET University, Gunupur, Rayagada, Odisha 765022, India

² Department of Communication Engineering, School of Electronics Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu 632014, India

³ Department of Electronics and Communication Engineering, ITER, Siksha 'O' Anusandhan University, Bhubaneswar, Odisha, India

⁴ Department of Electronics and Communication Engineering, GITA Autonomous College, Bhubaneswar, Odisha, India

Fig. 1 Representation of a QKD system with the required subsystems for both classical and private channel



channel is to transmit a single photon through a transparent optical path. It is a deterministic and lossy channel. Similarly, a classical channel can be a typical IP channel that relies on the system configuration for example any telephone line. It involves basic reconciliation, error correction, and privacy amplification protocols. By using these two channels a secret key can be obtained among Alice and Bob, which is known as prepare-and-measure protocols [8]. They must be able to limit the quantity of original data Eve can receive. There is a trade-off between the availability of data that Eve leaks and the amount of signal state disruption that can be created in any such attack [9].

In Fig. 1, the required sub-systems on Alice's sides are an optical device, quantum state preparation (QSP), a Digital Processor & Communication (DP&Comm) and the modulation scheme (Mod-Sch). By using quantum entanglement and transmitting the message in quantum states, a transmission system can be realized that identifies eve. Hence, the QSP subsystem is important to prepare a reliable quantum state that can be used for encryption [10]. DP&Comm subsystem uses different technologies for digital processing such as field-programmable gate array (FPGA), and graphical processing unit (GPU), to achieve the algorithm for monitoring Mod-Sch subsystem. It also uses classical communication links [11]. The output of QSP can be modified to drive the DP&Comm signal and then the information-carrying quantum state is conveyed through a quantum private channel.

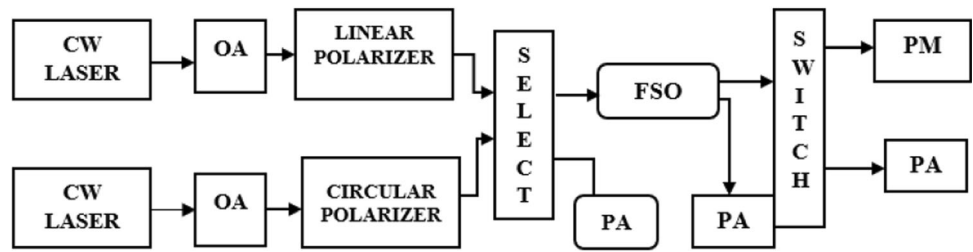
An optical receiver on Bob's side obtains the quantum state and produces an electrical signal that is given into a demodulation scheme (Demod-Sch) with the help of several optical passive devices. Here, Bob has also the same

DP&Comm subsystem as used in Alice. Then the signal passes through Quantum State Determination/Performance Parameters (QSD/PP) subsystem to determine the optical mode established by Bob. It calculates some performance factors obtained such as amplitude, phase, and polarization. Eve, on the other side, needs a variety of subsystems to "listen" the data from Alice and Bob [12]. There are several approaches to achieve QKD over FSO such as protocol-based or entanglement-based.

In this paper, we have used a protocol-based FSO scheme. The QKD protocol specifies the procedure for defining a key, which is divided into three categories: the oldest and most widely used discrete-variable (BB84, B92, E91, SARG04), effective continuous-variable (CV-QKD) protocols, and distributed-phase-reference coding (COW, DPS) [13]. Bennett and Brassard proposed the first and vital protocol, BB84, in 1984, which utilizes four possible quantum modes. Linear polarization or a combination of linear and circular polarizations may be used in polarization-based systems [14].

In the past, Bennett et al. [15] demonstrated the first experimental analysis of quantum cryptography in 1992. Bennett suggested that signal photons interfering with photons communicating over maximum distances across optical fibres could be used to introduce a minimal QKD system, B92, in 1992. But it utilizes two non-orthogonal quantum states i.e., 0 for horizontal and 1 for polarized right circle state. Bennett depicts a hands-on interferometric realization using low-intensity coherent light pulses using two non-orthogonal quantum states. In [16], Brassard and Salvail realized the deficiency in signal transmission using the protocol BB84 where it can allow only a fixed

Fig. 2 Simulation Model for Proposed QKD scheme OA: Optical Attenuator; PA: Polarization Analyzer; PM: Polarization Meter



number of iterations. After the specified number of iterations, there is no certainty that all errors in the frame have been fixed. In [17], Liu et al. proposed a model where a general protocol has been implemented for both information reconciliation and advantage distillation. But due to high transmission overhead, the applications are limited for real-time QKD systems. In [18], Lodewyck et al. demonstrated a coherent-state reverse-reconciliation system using low-density parity-check (LDPC) codes over a 25 km span of fiber. But it produces low throughput. In [13], Scarani et al. discussed about the practical aspects of QKD as well as summarize the used tools to improve the security of data. In [19], Pedersen and Toyran exhibited the use of CASCADE protocol over optical fiber. The result also provides low throughput and low efficiency than LDPC

code. In [20], Kamran et al. presented KMB09 based QKD system and its simulation based on the encrypted bits in higher-order Gaussian beam spatial modes. In [21], Cao et al. described the general network architecture and various protocols used in QKD. The system requirement is analysed in terms of flexibility, reliability, efficiency and interoperability. In [22], Patel et al. compared the existing techniques with the proposed model based on cost of communication and security index. It also explained the secure data transformation between user-device and device to device using an efficient key protocol.

The major contributions of this work are summarized in the following.

1. A binary sequence is transmitted from Alice to Bob using linear and circular polarization of photons. The sequence is delivered by encoding 1 s and 0 s in the polarization of photons through FSO channel at various atmospheric turbulence condition.
2. An error reconciliation protocol is used to transmit the sequence and generation of secret key using privacy amplification method.
3. The number of errors remaining in the transmitted sequence, percentage of original sequence lost per number of iterations is calculated.

The rest of the paper is as follows: concept of the reconciliation process and privacy amplification is discussed in Sect. 2. Here, the use of CASCADE as an error reconciliation protocol is explained along with the initial two iterations of the reconciliation process. Section 3 describes the proposed method for the QKD system using simulation tools such as MATLAB and Opti system. The simulation results are analyzed in Sect. 4 and concluded in Sect. 5.

2 Proposed method

In the QKD process, the initial objective of Alice and Bob is to form a secret key of n bits. Hence, an N number of quantum signals are transmitted through a quantum channel and then communicate using a classical channel. Opti system is generally used as an optical simulator to design

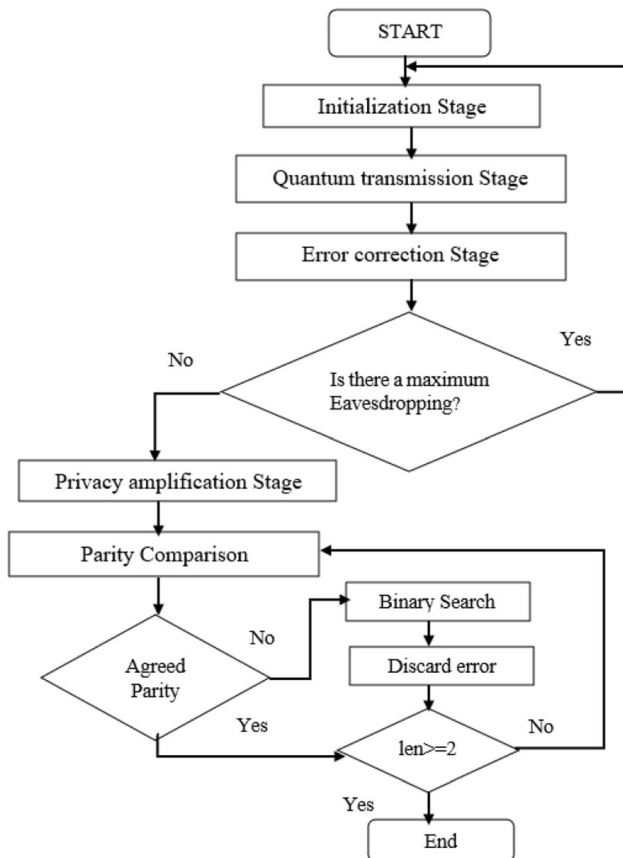


Fig. 3 A simplified Flow chart of the Proposed QKD system

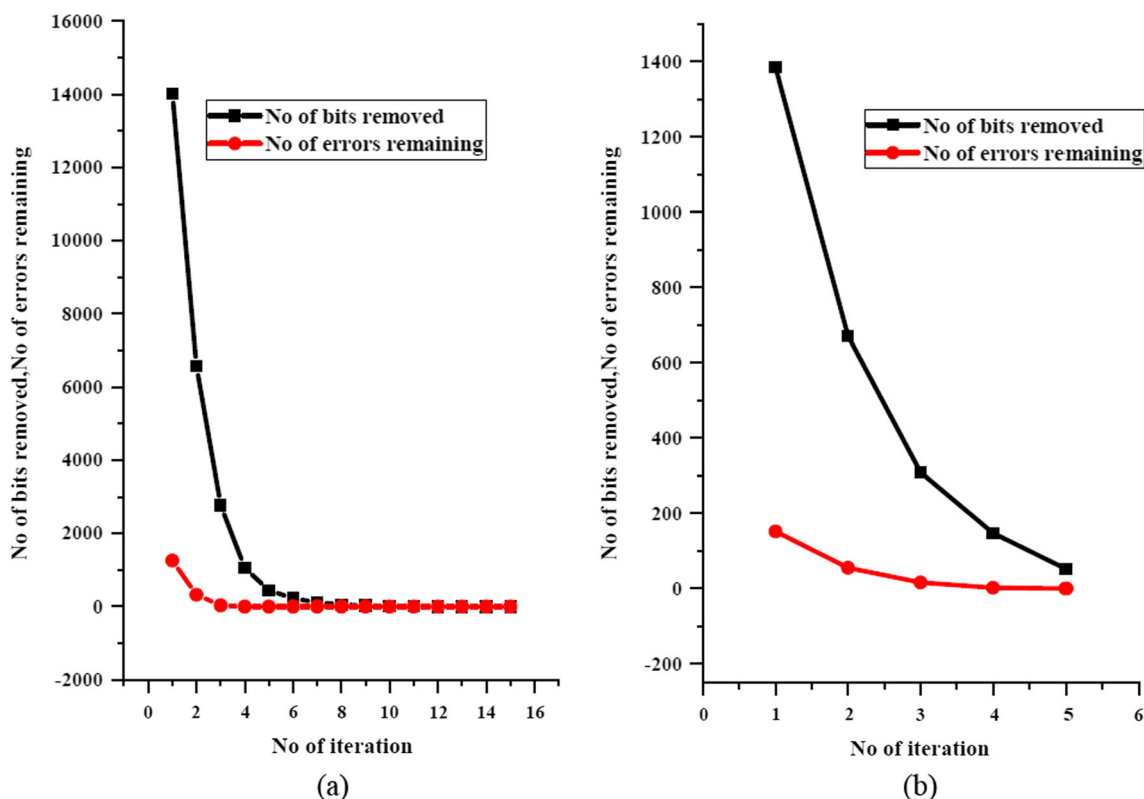


Fig. 4 Measurement of error remaining, number of bits removed **a** at iteration 15 and **b** at iteration 5

Table 1 Error Correction per iterations

Iterations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Corrected errors (in %)	94.5	91.9	90.8	90.3	90	89.9	89.2	88.4	86.8	83.6	77.1	51.4	0	0	0

Table 2 Comparison table

Iterations	Ours				Ref [30]				Improvement			
	1	2	3	4	1	2	3	4	1	2	3	4
Corrected errors (In %)	94.5	91.9	90.8	90.3	54.522	45.347	0.451	0.002	39.978	46.553	90.349	90.298

different optical networks. It can be used to simulate the QKD system with different photonics components [23]. The schematic diagram of the proposed QKD system is presented in Fig. 2, where two continuous-wave lasers with the operating frequency of 193.1 THz released light beams with an optical power of 10dBm into the channel. The signal is passing through an optical attenuator with an attenuation value of 0.1 dB to have a single photon. To ensure the state of polarization (SOP) linear and circular polarizers are used at the end of Alice. The ‘select’ component can be used as a polarized beam splitter(PBS) to select the incoming photons randomly. Here, the Free space optic link acts as a quantum channel. In the real

world, when the signal transmission is performed by Eve then it introduces attenuation and errors as compared to the original signal [24]. The light beam propagating through the channel encounters the fluctuation known as turbulence [25]. Here, various atmospheric conditions are considered which affect the signal propagation from Alice to Bob. Two polarization analyzers (PA) are implemented to observe the trajectory of SOP on the Poincare sphere for secret key extraction at the transmitter and receiver side respectively. The switch is used to produce randomness in transferring the polarization of photons during transmission and reception using rectilinear or diagonal basis detection [26].

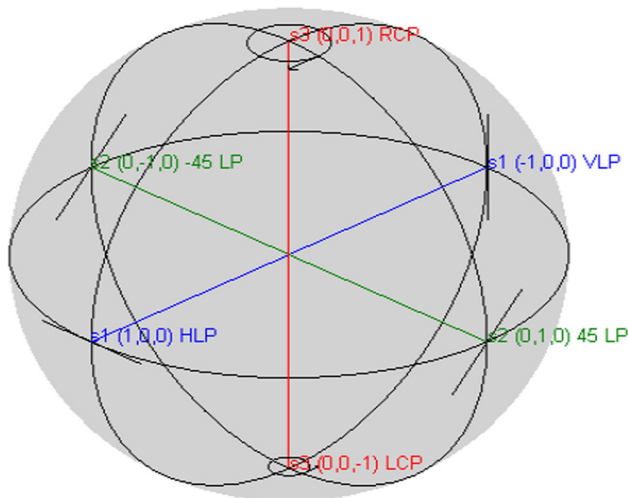


Fig. 5 Poincare Sphere at FSO link distance of 1 km

A simulation is a significant way in the study of communication networks. The simulation environment enables researchers to create complex network topologies, as well as a high level of control and repeatable studies, allowing them to perform experiments and validate their findings [27]. Hence, this proposed algorithm is programmed using MATLAB and Optisystem-15 software. The procedure of this proposed method is demonstrated as follows:

1. Alice sends a sequence of random photon to Bob (Recipient).
 - Let $n = \{n_0, n_1 \dots n_l\}$ where n – number of quantum states and record the sequence of the states.
2. Bob measures each state with probability of 50% after getting the quantum states.
3. After transmission of N bits, Quantum transmission is stopped and then error reconciliation protocol is applied on both.
4. Then Alice and Bob compute error Percentage using information reconciliation process. Let number of iterations is represented as iter. It follows these steps:
 - a. Initialize iter, P
 - b. For i in $(1: \text{iter})$
 - Find num, the number of P-blocks
 - For j in $(1:\text{num})$
 - Conduct parity check on Alice and Bob’s respective blocks. If they match, remove the same bit from each block. Else, conduct a binary search to find an erroneous bit and remove it. For each iteration of the binary search, remove one bit as well.
 - Generate a random shuffling order, which is used to shuffle Alice and Bob’s sequences.

- Double P

5. Both sides perform privacy amplification, to produce a series of final secret key.

A simplified flow chart is represented in Fig. 3 which describes the steps to follow the error correction using CASCADE protocol.

Again, the feasibility of the proposed model is demonstrated for a 1 km FSO channel at a various attenuation of 20 dB/km(haze), 30 dB/km (rain), and 40 dB/km (snow). The input polarization has been given as both linear and circular polarization to calculate the state of polarization (SOP) S_0 .

3 Simulation results

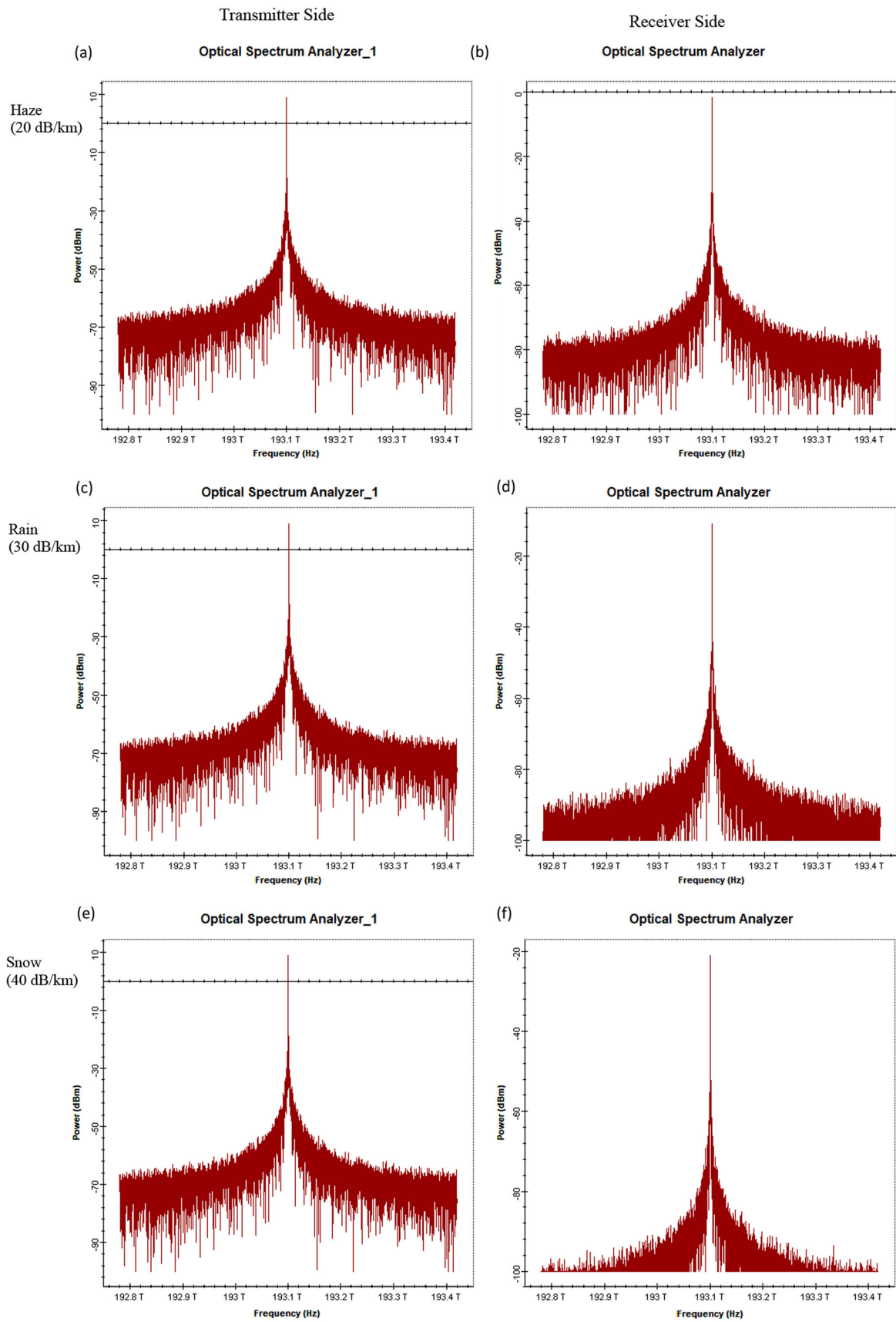
The performance of an error correction can be computed using different methods. The system parameters are estimated error rate, change in error estimation, reconciliation efficiency, bits exposed, percent bits exposed [28]. The used base frame length $n = 10^4$ bits. In the proposed method, the system efficiency is evaluated based on the number of errors remaining in the transmitted sequence, percentage of original sequence lost, number of bits removed per number of iterations. The comparison between the number of bits removed and the number of errors remaining is shown in Fig. 4 per iteration.

From the graph in Fig. 4a, b the black line presents number of bits removed and red line represents the remaining error. It can be visualized from the above results that, with each iteration, the number of remaining errors is reduced. In [29], the author proposed the modification depend on the length of the initial key and computed the error percentage. The use of the forward error correction method has been illustrated by [30] [31]. Here, the error correction per iteration using cascade protocol is evaluated in Table 1.

In [30], the author considered the error correction method using cascade protocol only for 4 iteration. But we proposed the error correction for the iteration of 15 and achieved the better result. Table 2 presents a comparative analysis of our work relative to [30].

The Poincaré sphere analyzes the effect of eve on the signal transmission. On this sphere, each point represents a specific SOP. The SOP on the North pole represents the R-SOP and the South pole the L-SOP, while the equator line represents various linear SOPs such as H, V, D, and A [32]. The evolution of SOP and its corresponding parameter S_0 concerning the FSO link is observed in Fig. 5. Here, the state of circular and linear polarizations is located at the poles and on the equator, respectively.

In Fig. 5, the parameter S_0 calculated by considering the haze condition with attenuation of 20 dB/km. But the



◀ **Fig. 6** The transmitter and receiver power spectrum obtained in various turbulence conditions

output is influenced by outdoor features such as attenuation, temperature variation, scattering [33]. The designed model provides stokes parameter value of 9.689 dBm, 9.499 dBm, and 8.921 dBm at haze, rain, and snow condition. It is observed that the SOP varied in different elliptical-polarized states as per the atmospheric turbulence condition. As the attenuation value increases, the value of stokes parameter reduces.

In addition, the frequency spectrum at the transmission side and receiver side are illustrated in Fig. 6 at various attenuation levels. A spectrum analyzer is a precision measuring tool that shows the power dispersion of a light source over a specific wavelength value. On the vertical scale, it shows power (dBm), and on the horizontal scale, it shows frequency (THz) [34]. The spectral components are derived at the center frequency of 193.1 THz. Because of the versatility of various spectral components, any spectral chip can be used as the center wavelength for modulating the user data stream [35]. The security of user information in conventional optical networks is enhanced because of this property of the optical spectrum.

Figure 6a, c, e represent the signal power is the same at transmission side that is 9.9 dBm. However, the spectral components as in Fig. 6b, d, f shows the decrease in signal power after the signal are attenuated by 20 dB/km, 30 dB/km, and 40 dB/km. It can be envisioned that the spectrum at the transmission and received side is highly correlated at 20 dB/km (Haze). However, with the increase in atmospheric turbulence the signal power reduces.

4 Conclusion

In this work, we have showed a quantum key distribution model using CASCADE protocol under the FSO channel. The system performance is analysed by evaluating the percentage of error correction in the transmitted signal, frequency spectra between sender and recipient. However, CASCADE is a standard for the error reconciliation phase in maximum QKD system but due to large binary search method, the efficiency can be further improved using LDPC and Winnow protocols. The capability of the network can be improved by reducing the information leakage and having low interaction between two parties. In future work, the improvements to the proposed idea can be implemented using Multi-Input-Multi-Output (MIMO) and Wavelength Division Multiplexing (WDM).

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Mrs. Bandana Mallick has completed her B. Tech and M. Tech in Electronics and Communication Engineering from Biju Patnaik Technical University, Odisha. Presently she is pursuing her Ph.D. in GIET University, Gunupur, and Odisha. She has also 11 years of teaching experience. Her interest field includes wireless communication and application of fiber optic communication in dispersion management.



Dr. Priyadarsan Parida is an accomplished Associate Professor at GIET University, where he has dedicated his career to both academic and research pursuits. Dr. Parida received his Ph.D. from Veer Surendra Sai University of Technology, Burla, and has since acquired over 10 years of experience in teaching and 5 years of research experience. In his capacity at GIET University, Dr. Parida has been actively engaged in academic activities, including

teaching various undergraduate and postgraduate courses related to electronics and communication engineering. Moreover, he has made substantial contributions to research in his field, with his work being recognized in different international journals and conferences of repute. Dr. Parida's research interests are focused on developing innovative computer vision applications to biomedical images. His expertise and contributions in this area have made him a respected figure in the field. Dr. Parida's dedication to teaching and research is a testament to his commitment to the advancement of knowledge and scientific progress. Overall, Dr. Parida's contributions to his field, both in teaching and research, have made him an esteemed member of the academic community at GIET University and beyond. His work is recognized as having significant potential to drive forward scientific progress in the area of computer vision applications to biomedical images, channel equalization and secured communication.



Dr. Chittaranjan Nayak received a Ph.D. degree in engineering from the National Institute of Technology, Agartala, India, in 2017. He is currently working as an associate professor in the Department of Communication Engineering, Vellore Institute of Technology, Vellore, India, and an active member of IEEE, OSA, and IETE. Chittaranjan does research in Optical Engineering, Biomedical Engineering, and Electronic Engineering. His current research interests

include computational photonics, 1-D photonic multilayers, and the

formation of photonic nanojets for different optoelectronics applications.



Dr. Pritam Keshari Sahoo received his M.Tech. Degree in electronics and communication engineering from IIT Kharagpur, India in 2012 and Ph.D. degree from Motilal Nehru national Institute of Technology, Allahabad, Uttar Pradesh, India. He has 10 years of teaching experience and his area of interest includes Cellular Wireless Communication, Optical wireless communication. He has remained member of several Professional Bodies including

IEEE, ISTE, and ISRD. Currently he holds Assistant Professor position in the Dept. of ECE at ITER, Siksha 'O' Anusandhan University Bhubaneswar, Odisha.



Dr. Gopinath Palai completed his UG from Utkal University and P.G. from IIT, KGP and Ph.D. from BU in the field of quantum electronics. Currently, he is working as professor and Head of the Department of ECE in GITA Autonomous College Bhubaneswar, Affiliated to BPUT, Odisha. His research interest includes Quantum Electronics and optical devices, Machine Learning with sensor technology and Corona virus disease. He has published more

than 200 research papers in various international (179) journals and conferences (24). Two books and 4 book chapters have been credited to his research account. Moreover, 8 number of students has been awarded (Ph.D.) under the supervision of Prof. Palai