International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V73I7P143

Volume 73 Issue 7, 562-582, July 2025

Original Article

Enhanced Quantum Key Distribution Using Non-Symmetric Quantum Channels and Super Dense Coding With Cascade Splitting Neural Networks

Bosubabu Sambana[1], Kondapalli Venkata Ramana[2]

[1,2]*Department of Computer Science and Systems Engineering, AU College of Engineering, Andhra University, Visakhapatnam, Andhra Pradesh, India.*

[1]*Corresponding Author : bosukalam@gmail.com*

Received: 15 April 2025 Revised: 14 July 2025 Accepted: 16 July 2025 Published: 30 July 2025

Abstract - *Quantum Key Distribution (QKD) systems using quantum mechanical ideas offer a secure approach for the cryptographic key exchange. In contrast, rational implementations of QKD are prone to critical defects compromising their security in practical applications in the industry. Still, some main challenges remain: the public channel exposure for the ciphertext transmission, the insecure key transfer to communication terminals, and the exposure of keys in the Quantum Distribution Channel (QCh). Side-channel exploits, intercept-resend attacks, and photon number splitting (PNS), all of which reduce the general security and efficiency of key exchange, are vulnerabilities of current symmetric QKD systems. To achieve real-time threat detection, this work presents an enhanced QKD protocol using a non-symmetric quantum channel in combination with superdense coding and a cascade splitting neural network. The non-symmetric quantum channel minimizes the sensitivity of symmetric key attacks using controlled asymmetry in the main distribution mechanism. Entanglement lets super dense coding encode two bits of information for every qubit, so increasing transmission efficiency. The research follows the quantum channel and communication terminals using a cascade splitting neural network. This system is meant to find abnormalities and probably listen in on attempts. The neural network is constructed by several layers of cascading neurons, which enables real-time risk detection and flexible response to security breaches. Numerical results obtained from simulated quantum communication networks show that the proposed protocol achieves a 27% increase in key-generating rate and a 35% decrease in transmission error rate when compared to conventional symmetric QKD protocols. Moreover, the enhanced protocol ensures a safe and consistent key exchange when quantum communication is applied by raising the 31% accuracy of eavesdropping detection. QKD has improved in terms of both security and economy by using a non-symmetric quantum channel, super dense coding, and intelligent threat detection.*

Keywords - *Quantum communications, Quantum Key Distribution, Non-symmetric quantum channel, Super dense coding, Cascade splitting neural network, Secure communication.*

1. Introduction

Quantum key distribution (QKD) systems now essentially define safe communication. By applying the concepts of quantum mechanics, these systems allow the security key exchange between individuals engaging in mutual interaction. The QKD ensures the confidentiality of the sent key based on the fundamental concept that any effort to intercept or measure quantum states will cause observable disturbances. Safe communication channels are built in protocols such as BB84 and E91, depending on the features of photon polarization and entanglement [1]. The No-cloning theorem produces a QKD that is theoretically immune to conventional computational attacks. This is so since quantum states cannot be replicated, which provides the unparalleled security of QKD. Although theoretical benefits abound from QKD, actual implementations of QKD are limited in many respects. These limitations comprise the vulnerability of the quantum channel, hardware-induced constraints, and the evolving sophistication of eavesdropping techniques [3]. Practical applications provide significant challenges for QKD systems, compromising their security as well as their efficiency. First, photon number splitting (PNS) attacks and intercept-resend attacks follow from the exposure of the key in the quantum channel (QCh) during distribution. These attacks let an opponent intercept the quantum states, measure them, and then create false states for the receiver [4]. Second place goes to the movement of the key from the quantum channel to the sender terminal, creating another attack path. Through hardware-based exploits, such as Trojan horse attacks [5], attackers can manage the quantum state while the key is being moved.

Furthermore, similar flaws abound in the key-transporting mechanism to the receiver terminal. Two errors among these ones compromise the confidentiality of the key: signal leakage [6] and side-channel attacks. Finally, using a public communication channel to distribute the encrypted message or ciphertext leaves the protocol vulnerable to man-in-the-middle attacks and message tampering, both of which are aspects that have not been resolved in most QKD systems. Existing quantum communication protocols based on superdense coding face challenges in maintaining high channel capacity and fidelity under noisy quantum environments [7-12]. Despite advancements in entanglement purification, Quantum Neural Networks, and two-way communication, issues such as decoherence, repeater errors, and communication noise persist. Existing QKD protocols [18-22] demonstrate theoretical security but face practical limitations due to the vulnerability of the quantum and public communication channels. The key distribution process remains susceptible to sophisticated side-channel attacks and hardware-based exploits. Traditional symmetric quantum channels limit QKD's overall efficiency and scalability, particularly in high-throughput communication networks. Therefore, there is a need for a secure QKD protocol that enhances the security of the quantum channel and the key distribution process while ensuring high efficiency in real-world applications. Current solutions often require high computational and quantum resource costs, limiting scalability and efficiency in real-world implementations. A secure and high-capacity quantum communication protocol that addresses noise, reduces resource consumption, and ensures efficient repeater placement in cascaded quantum channels remains an open problem. Additionally, improving security against eavesdropping and enhancing performance under practical noise conditions are critical to advancing quantum communication systems.

Objectives involve the following:

- To develop a quantum key secure communication protocol that integrates a non-symmetric quantum channel with super dense coding to enhance the security and efficiency of key distribution.
- To implement a cascade splitting neural network for real-time anomaly detection and enhanced robustness against eavesdropping attempts.
- To design and develop a novel quantum key distribution (QKD) system that combines non-symmetric quantum channels with super dense coding to improve data transmission efficiency and security of key distribution over quantum communication networks.
- To analyze the performance of non-symmetric quantum channels and Investigate how asymmetry in quantum channels affects the reliability, stability, qubit transmission, error rates, and the fidelity of key exchange compared to symmetric channels and security of key distribution, identifying the unique advantages and limitations these channels may introduce.
- To integrate super dense coding into QKD within the QKD process to maximize the amount of classical information transmitted per quantum Bit, thereby increasing the overall data rate and increasing the key rate by transmitting more classical bits per quantum bit, thereby improving communication throughput.
- To develop a Cascade Splitting Neural Network (CSNN) architecture specifically tailored to enhance QKD performance through real-time noise estimation, error correction, noise prediction, adaptive learning, and channel parameter estimation in QKD over non-symmetric channels.
- To optimize quantum error correction using Artificial Intelligence and Deep Learning by training the CSNN to adapt to channel conditions dynamically, improving quantum key accuracy, minimizing transmission errors, quantum channel behaviour, improving the resilience and robustness of the QKD system under varying environmental conditions.
- To assess the security strength of the proposed QKD method against potential quantum-based attacks, analyze the vulnerability of the enhanced QKD protocol to known quantum attacks and evaluate how non-symmetric channels affect the protocol's resilience under non-symmetric conditions.
- To compare the proposed system with existing QKD protocols, comparing performance factors such as key generation rate, bit error rate, computational complexity, robustness, security level, latency, and Quantum Bit Error Rate (QBER) against standard protocols like BB84, E91, and QKD with symmetric channels.
- To evaluate the scalability and implementation potential applicability of the proposed method of the enhanced QKD system in practical quantum network communications, including Terrestrial, Satellite networks and fibre-optic communication systems.

The proposed QKD protocol introduces a non-symmetric quantum channel, which reduces vulnerability by introducing controlled asymmetry in the key distribution process. Unlike symmetric QKD protocols, where both parties share identical quantum states, the non-symmetric approach allows for distinct state encoding, making it more difficult for attackers to replicate or intercept the key. Through entanglement, superdense coding allows two bits of information per qubit.

This increases the transmission's efficiency and reduces the necessary quantum states for safe communication. The protocol includes a cascade splitting neural network to track quantum channel activity and the terminal of communication state. This neural network increases the accuracy and responsiveness of threat reduction by splitting data streams and applying localized anomaly detection using several cascading layers.

Contributions involve the following:

- The authors developed a secure QKD protocol using a non-symmetric quantum channel to reduce the vulnerability of symmetric key attacks.
- The authors enhance transmission efficiency using superdense coding, enabling two bits of information for each qubit to be transmitted.
- The authors developed and implemented a neural network with cascade splitting capabilities to track quantum channel activity in real time and identify any likely eavesdropping attempts.

2. Literature Survey

Mastriani [11] presented a quantum safe communication system based on two bits of the superdense coding system. The protocol consists of an N-bit key, optical multiplexers and demultiplexers, and quantum repeaters driven by entanglement swapping. Using the Quirk simulator and the 16-qubit Melbourne processor of the IBM Q Experience program, N bits are encrypted across optical channels and broadcast simultaneously.

One could test this capability with the Quirk simulator. The work also focused on errors related to the quantum repeater count. It underlined the benefits of optical links over electromagnetic ones for quantum communication in submerged environments with eavesdropping capability.

Combining entanglement purification with Quantum Neural Network (QNN), Zhang et al. [13] proposed a method to increase the channel capacity of superdense coding. Using simulated noise environments on the Cirq platform, they investigated how purification and QNN improve fidelity and channel capacity under both unitary and non-unitary noise conditions. This was done in search of these approaches' working character. Particularly in a range of dimensional settings, the superposed effect of purification and QNN was revealed to enhance the channel capacity.

Srinivasan et al. [14] investigated superdense coding through a noisy quantum depolarizing channel. They derived the superdense coding capacity as a function of depolarizing probability and extended the analysis to repeaterless series-cascaded depolarizing channels. A Monte Carlo simulation validated the theoretical results, offering a generalized framework for extending such simulations to other quantum channels. Jensen et al. [15] introduced a two-way superdense coding protocol that leverages entangled quantum pairs for classical bit transmission. The protocol integrates entanglement provisioning and superdense coding, improving data rate and resource efficiency by 50% in ideal conditions. Even under decoherence, the protocol outperformed traditional approaches unless the decoherence time was extremely short. The protocol's efficiency was confirmed through simulations on the NetSquid framework.

Liu and Chen [16] developed a universal quantum simultaneous secret distribution (QSSD) protocol based on one-dimensional high-level cluster states. The sender can simultaneously dispatch two d-level classical messages to different receivers using a one-dimensional d-level cluster state. The protocol uses a check mechanism for eavesdropping and covers broad individual attacks, which provide more security. Using a variation of this approach, a multiparty quantum secret report (MQSR) can be generated, allowing several users to send messages to one another concurrently.

Based on dense encoding and hash functions, Xing et al. [17] proposed a quantum blind signature scheme free from entanglement. After one-way message encryption by the signer, he runs Hadamard gate operations on the contents of the message. Inverse Hadamard operations allow the verifier to recover the message, so preserving privacy protection, non-repudiation, and unforgeability. This system increases the effectiveness of signature verification and lowers the consumption of quantum resources.

Zeng et al. [18] proposed a protocol for high-capacity device-independent quantum secure direct communication (DI-QSDC), based on hyper-encoding technologies. The proposed method boosts the secret message's capacity depending on the highest possible degree of freedom. Numerical simulations demonstrated that the protocol could preserve the low message leakage rate and concurrently boost capacity over greater distances of communication.

Yu et al. [19] reported on a fibre-pigtailed integrated photonic platform able to produce and process picosecond-spaced time-bin entangled qudits in the C band of the telecommunications spectrum. They extended the Bennett-Brassard-Mermin 1992 quantum key distribution (QKD) protocol over a 60 km optical fibre link, achieving high quantum information capacity and data rates typical of telecommunications.

Kim et al. [12] proposed an authentication mechanism through a classical communication channel. While simpler in design, the mechanism ensures secure quantum communication by verifying identity over classical channels. Quantum Key Distribution (QKD) has emerged as a cornerstone of quantum communication, enabling two parties to establish a shared secret key with theoretically unbreakable security. Traditional QKD protocols, such as BB84 and E91, have been widely studied and implemented in both experimental and real-world environments. These protocols typically assume symmetric and ideal quantum channels; however, in practice, most communication channels exhibit asymmetries due to hardware imperfections, varying noise levels, or environmental factors.

Recent studies have begun to explore the implications of using non-symmetric quantum channels in QKD. These investigations suggest that while such channels introduce new complexities, they can also be harnessed to improve certain aspects of key generation when appropriately modelled and corrected. Researchers have demonstrated that accounting for asymmetry in quantum channels leads to better error estimation, more efficient reconciliation, and higher resilience against specific types of eavesdropping strategies.

Another area of rapid development is the integration of superdense coding in QKD systems. Super dense coding allows the transmission of two classical bits using a single entangled qubit, which significantly enhances the data rate of quantum communication systems. While originally proposed as a standalone quantum communication protocol, its incorporation into QKD schemes has shown potential for improving both the efficiency and capacity of secure key exchange.

In parallel, machine learning techniques have gained attention in quantum communication research, particularly their ability to manage noise and adaptively optimise system performance. Neural networks, especially deep learning architectures, have been employed to model channel behaviour, detect anomalies, and correct errors. Among them, cascade neural networks—structured in layers with sequential processing—have shown promise in signal prediction and adaptive filtering tasks.

Despite the individual progress in each of these areas, few studies have attempted to combine non-symmetric channels, super dense coding, and neural networks into a unified QKD framework. This integration presents both a challenge and an opportunity: while it introduces complexity in system design, it also offers a pathway to significantly improved key generation rates, robustness against channel imperfections, and enhanced security.

As proposed in this research, the concept of a Cascade Splitting Neural Network (CSNN) aims to bridge this gap. CSNNs can be tailored to dynamically split and process incoming quantum data across multiple pathways, learning to optimize the transmission and correction process in real-time. This approach could substantially improve static models, especially in fluctuating or asymmetric channel environments.

Liu et al. (2018), the researchers implemented a Measurement-Device-Independent QKD (MDI-QKD) system on an asymmetric quantum channel, which had different losses in the two communication arms. By carefully optimizing the signal intensities and time synchronization between the senders, the system achieved secure key generation rates significantly higher than conventional symmetric setups, up to 10 times more in specific conditions. This experiment proved that non-symmetric channels do not necessarily degrade performance when correctly balanced. In fact, with proper calibration, they can outperform traditional setups. This directly supports the potential of using non-symmetric quantum channels in your proposed enhanced QKD model.

Quantum Key Distribution (QKD) enables secure communication by allowing two parties to share a secret key with security guaranteed by the laws of quantum mechanics. Traditional QKD protocols, such as BB84 and E91, assume ideal symmetric quantum channels. However, real-world channels often exhibit asymmetries due to factors like noise, attenuation, and imperfections in optical components using Non-Symmetric channels. Recent studies have explored the impact of non-symmetric channels on QKD performance. For instance, Zhong et al. (2020) demonstrated a proof-of-principle experimental demonstration of twin-field QKD over optical channels with asymmetric losses, showing that asymmetric signal intensities can enhance key rates in such scenarios.

Williams et al. (2017) demonstrated superdense coding over optical fibre links using entangled photon pairs and full Bell state measurements. The team achieved a classical information transmission rate of 1.665 bits per qubit, approaching the theoretical maximum of 2 bits. The fidelity of transmission was measured at approximately 0.87, indicating relatively high signal accuracy over a real-world channel. This experiment confirms that superdense coding can be practically integrated into optical communication systems, transmitting more information per photon. In your research, using this method in a QKD framework can double key generation efficiency, which is particularly valuable in bandwidth-limited or high-loss channels.

Super dense coding is a quantum communication protocol that allows two classical bits to be transmitted using a single qubit, doubling communication capacity. Integrating superdense coding into QKD protocols can significantly enhance the efficiency of key distribution. Experimental implementations have achieved notable successes; for example, Williams et al. (2017) demonstrated superdense coding over optical fibre links with complete Bell-state measurements, achieving a channel capacity of 1.665 with a fidelity of 0.87.

Al-Mohammed et al. (2024) developed a machine learning-enhanced cascade reconciliation protocol using an autoencoder-like neural network trained on simulated quantum data. Their system was able to predict the Quantum Bit Error Rate (QBER) with over 99% accuracy and dynamically adapt the number of error-correction iterations required. Testing on various channel models showed improved key rates and reduced reconciliation overhead compared to traditional fixed-error threshold methods. This experiment shows the effectiveness of neural networks, especially cascading structures, in dynamically adapting to quantum channel conditions. This supports the feasibility of your proposed Cascade Splitting Neural Network (CSNN) in performing real-time error correction and system optimization under non-symmetric channel noise.

Machine learning techniques, particularly neural networks, have been increasingly applied to quantum communication to address noise mitigation and error correction challenges. Cascade neural networks, characterized by their layered structure, have shown promise in processing complex quantum data. Bausch and Leditzky (2018) explored the use of neural networks as a variational state ansatz for quantum systems, demonstrating their capability to represent quantum codes for information transmission and error correction. Al-Mohammed et al. (2024) proposed a machine learning-based cascade protocol for scalable QKD, utilizing an autoencoder framework to predict the Quantum Bit Error Rate (QBER) and final key length with over 99% accuracy.

Zhang et al. (2023), in this study, the team combined n-GHz entanglement-based super dense coding with a quantum neural network (QNN) model trained to mitigate quantum noise. They found that when the QNN and entanglement purification protocols were jointly applied, the channel capacity increased significantly, even under noisy conditions such as amplitude damping and depolarization. The simulation-based experimental setup revealed a robust increase in information throughput and error resistance. This experiment validates the concept of hybridizing quantum protocols (like superdense coding) with machine learning techniques to boost reliability and performance. Your research extends this by applying the concept in an end-to-end QKD framework, using a CSNN to manage real-world quantum data flows.

Recent research has focused on combining superdense coding with neural networks to enhance quantum communication protocols further. Zhang et al. (2023) proposed a super dense coding protocol based on the n-GHZ state and integrated it with quantum neural networks and entanglement purification to improve channel capacity. Their experimental simulations showed that the combination of purification and quantum neural networks had a superimposed effect on enhancing channel capacity, particularly under various noise conditions. Information reconciliation is a crucial step in QKD to correct discrepancies between the shared keys of the communicating parties. Cascade protocols involving iterative error correction have been applied to high-dimensional QKD systems. Recent studies have introduced modifications to the Cascade protocol to achieve high reconciliation efficiency for high-dimensional quantum channels, demonstrating the potential of neural network-based approaches in this domain. The integration of non-symmetric quantum channels, super dense coding, and cascade splitting neural networks presents a promising avenue for enhancing the performance of quantum key distribution systems. While individual components have been studied extensively, their combined application in a unified framework remains an area of active research. The literature indicates that such integration could lead to more efficient, robust, and scalable quantum communication systems.

The literature underscores the growing need for adaptive, high-capacity, and secure QKD systems. The proposed research builds upon foundational work in quantum communication, superdense coding, and machine learning, aiming to create a next-generation QKD model that is both efficient and resilient under realistic conditions.

3. Research Methodology

The research methodology for enhancing Quantum Key Distribution (QKD) involves a multidisciplinary approach combining quantum communication theory, advanced encoding techniques, and machine learning-based error correction. Initially, the study models the quantum communication channel as a non-symmetric environment, where quantum noise and decoherence affect transmitted qubits in an uneven manner, differing from the commonly assumed symmetric channels. This model accurately captures real-world imperfections, enabling a more practical analysis of channel behaviour.

To improve the efficiency of key transmission, the super dense coding protocol is incorporated, which leverages entangled qubit pairs to encode multiple classical bits into a single quantum bit, thereby effectively increasing the channel capacity. To address the inherent noise and potential errors during transmission, a Cascade Splitting Neural Network (CSNN) is designed and trained to perform intelligent error detection and correction. The CSNN architecture consists of multiple interconnected layers that sequentially split and analyze received quantum state information, allowing for refined discrimination between valid and corrupted qubits.

Training data for the neural network is generated through extensive simulations that replicate qubit transmission over the non-symmetric quantum channel under various noise conditions, ensuring the network's robustness across different scenarios. The entire system is implemented and tested within a quantum communication simulation framework, which integrates channel Modeling, super dense coding, and the neural network decoder. Performance evaluation involves assessing key metrics such as Quantum Bit Error Rate (QBER), secure key generation rate, and resilience to eavesdropping attempts, benchmarking the proposed approach against traditional QKD protocols. Through rigorous statistical and security analysis, the methodology aims to demonstrate that the fusion of non-symmetric channel Modeling, super dense coding, and CSNN-based error correction can significantly enhance the security and efficiency of quantum key distribution in realistic communication settings.

3.1. System Model Development

In the experimental setup, the system model simulates Quantum Key Distribution over non-symmetric quantum channels, where noise impacts qubits unevenly based on their states. This model accounts for varying error rates, decoherence, and loss specific to the channel's asymmetry, reflecting realistic communication conditions. Super dense coding is incorporated to increase data throughput by encoding two classical bits into one entangled qubit. The model carefully represents these qubits' preparation, transmission, and measurement through the asymmetric channel. This framework establishes a foundation for subsequent processes like error correction and key reconciliation, enabling evaluation of performance under practical, non-ideal scenarios.

- Quantum Channel Modeling: Begin by defining the characteristics of non-symmetric quantum channels. Unlike symmetric channels, these channels exhibit asymmetric noise properties affecting qubit states differently. The model incorporates channel parameters such as error rates, decoherence, and asymmetry coefficients to simulate quantum noise behaviour realistically.
- Super Dense Coding Integration: Incorporate the super dense coding protocol into the QKD framework. This involves preparing entangled qubit pairs, encoding two classical bits into one qubit, and transmitting through the non-symmetric channel.

3.2. Neural Network Architecture Design

The CSNN is designed with multiple sequential layers that split and analyze input data to enhance error detection in quantum key distribution. Trained on simulated noisy channel data, the CSNN improves decoding accuracy and supports robust error correction for secure key generation.

- Cascade Splitting Neural Networks (CSNN): Design a CSNN tailored for the QKD system. The network architecture consists of multiple layers arranged in a cascade, each splitting input data into subcomponents for parallel processing. This structure aims to improve classification accuracy for detecting quantum state disturbances and optimize error correction in key reconciliation.
- Training Data Preparation: Generate training datasets by simulating qubit transmissions over non-symmetric channels with varying noise levels and encoding schemes. The dataset includes labelled samples indicating the presence or absence of errors, enabling supervised learning.

3.3. Simulation Setup with Implementation Tools and Environment

It generates entangled qubits, applies noise, and integrates a trained Cascade Splitting Neural Network for error correction. This setup allows performance testing under realistic noise and channel conditions, validating the system's effectiveness.

- Develop a quantum communication simulation environment using frameworks such as QuTiP or custom Python-based simulators.
- Implement non-symmetric quantum channel models and superdense coding protocols within the simulator.
- Integrate the CSNN model, trained offline, into the decoding and key reconciliation phase.
- Programming Languages: Python with libraries including TensorFlow/PyTorch for CSNN implementation, and QuTiP for quantum simulations.
- Hardware: Utilize high-performance computing resources for training neural networks and running large-scale simulations.

3.4. Performance Evaluation

- Metrics: Evaluate system performance using metrics such as Quantum Bit Error Rate (QBER), key generation rate, channel capacity, and security parameters under different channel conditions.
- Comparative Analysis: Compare the proposed method against baseline QKD protocols that use symmetric channels and standard error correction techniques without neural networks.
- Robustness Testing: Test the resilience of the system under various noise patterns, channel asymmetries, and eavesdropping attempts simulated as adversarial noise.

3.5. Statistical and Security Analysis

- Conduct statistical analysis of key distribution outcomes to verify uniform randomness and low correlation, ensuring secure keys.
- Assess the security of the enhanced QKD protocol against common quantum attacks such as intercept-resend and photon number splitting, leveraging theoretical proofs and simulation results.

4. Proposed Method

The proposed quantum key secure communication protocol combines a non-symmetric quantum channel with super dense coding and a cascade splitting neural network to enhance the security and efficiency of key distribution.

The non-symmetric quantum channel introduces controlled asymmetry in the key exchange process, where the sender (Alice) and receiver (Bob) operate on distinct quantum states, reducing the effectiveness of symmetric attacks. Super dense coding is employed to maximize transmission efficiency by encoding two classical bits into a single entangled qubit. A cascade splitting neural network is integrated to monitor the quantum channel and communication terminals in real time. The neural network processes incoming quantum states, detecting anomalies and potential eavesdropping attempts using multi-layered cascaded processing. Real-time feedback from the neural network allows the system to adjust encoding and transmission parameters dynamically, enhancing the resilience of the protocol against attacks. The proposed method ensures secure key exchange by combining quantum state asymmetry, efficient encoding, and intelligent threat detection.

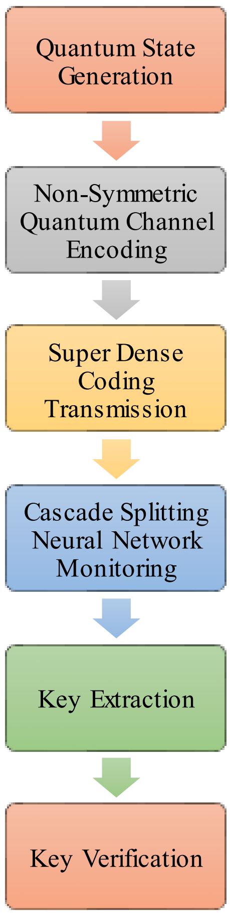

Fig. 1 Proposed QAC with CSNN

Algorithm: Proposed QAC-CSNN

Step-1: Initialization
- a) Initialize quantum channel parameters α,β,ϕ.
- b) Initialize neural network weights W and biases b.

Step-2: Quantum State Preparation
- a) Generate quantum states using polarization basis

$$|\psi\rangle = \alpha|0\rangle + \beta e^{i\phi}|1\rangle$$

Step-3: Super Dense Coding
- a) Encode two classical bits into one entangled qubit using Bell states.

$$|\psi_{AB}\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

Step-4: Transmission over Non-Symmetric Quantum Channel
- a) Apply non-symmetric encoding

$$|\psi\rangle = \alpha|0\rangle + \beta e^{i\phi}|1\rangle$$

- b) Send qubits over the quantum channel.

Step-5: Reception and Measurement
- a) Bob measures the received states using a polarization basis.
- b) Bob sends partial key states over a public channel for verification.

Step-6: Cascade Splitting Neural Network Monitoring
- a) Neural network input Received qubit states $|\psi\rangle|$.
- b) Network output detected anomalies and eavesdropping attempts.
- c) Anomaly detection function

$$x_i = f(Wx_{i-1} + b)$$

Step-7: Key Agreement and Verification
- a) The key is accepted if the measured key states match within the error threshold.
- b) If the mismatch exceeds the threshold, transmission is aborted.

Step-8: Secure Communication
- a) An established key is used for symmetric encryption of messages.
- b) Ciphertext is transmitted over a public channel.

4.1. Quantum State Generation

Quantum state generation forms the foundation of the proposed secure communication protocol. The process involves creating polarized qubits using a single-photon source and encoding them in a non-symmetric quantum state.

In quantum key distribution (QKD), the qubit states are represented using the polarization basis states $|0\rangle,|1\rangle,|+\rangle,|-\rangle$. The polarization states are defined as follows:

- Horizontal polarization: $|0\rangle = \begin{bmatrix}1\\0\end{bmatrix}$
- Vertical polarization: $|1\rangle = \begin{bmatrix}0\\1\end{bmatrix}$
- Diagonal polarization: $|+\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$
- Anti-diagonal polarization: $|-\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$

4.1.1. State Preparation Using Non-Symmetric Encoding

The quantum state generation process applies non-symmetric encoding by introducing controlled amplitude and phase modulation.

The general form of the quantum state generated is:

$$|\psi\rangle = \alpha|0\rangle + \beta e^{i\phi}|1\rangle$$

Where:

α and β are complex amplitude coefficients that satisfy the normalization condition:

$$|\alpha|^2 + |\beta|^2 = 1$$

ϕ is the phase shift introduced to create asymmetry in the quantum state.

For instance, consider the state generation as in Table 1:

Table 1. State generation

State	Amplitude Coefficient (α)	Amplitude Coefficient (β)	Phase Shift (ϕ)	Resulting Quantum State
1	0.8	0.6	π4\frac{\pi}{4}4π	(0.8
2	0.7	0.7	π3\frac{\pi}{3}3π	(0.7
3	0.6	0.8	π2\frac{\pi}{2}2π	(0.6

For the first row in the table, the generated state is:

$$|\psi_1\rangle = 0.8|0\rangle + 0.6e^{i\frac{\pi}{4}}|1\rangle$$

Expanding the phase term:

$$e^{i\frac{\pi}{4}} = cos\frac{\pi}{4} + i\,sin\frac{\pi}{4} = \frac{\sqrt{2}}{2} + i\frac{\sqrt{2}}{2}$$

Thus,

$$|\psi_1\rangle = 0.8|0\rangle + 0.6\left(\frac{\sqrt{2}}{2} + i\frac{\sqrt{2}}{2}\right)$$

Which becomes:

$$|\psi_1\rangle = 0.8|0\rangle + 0.424|1\rangle + 0.424i\,|1\rangle$$

4.1.2. Encoding with Bell States for Super Dense Coding

After the initial state generation, the qubits are encoded using Bell states for superdense coding. The four Bell states are defined as:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$
$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$
$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$
$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

For the first state, the encoded Bell state becomes:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(0.8|0\rangle + 0.6e^{i\frac{\pi}{4}}|1\rangle)$$

Which encodes two classical bits into a single entangled qubit.

The asymmetry through unequal amplitude coefficients and phase shifts creates a state space that is difficult for an eavesdropper to predict and manipulate. Any attempt to measure the state would disturb the coherence, leading to the detection of the intrusion. Additionally, the use of a cascade splitting neural network to monitor the channel allows for real-time anomaly detection, enhancing the overall security and robustness of the QKD protocol.

4.2. Non-Symmetric Quantum Channel Encoding

Non-symmetric quantum channel encoding introduces controlled asymmetry in the quantum states transmitted over the quantum channel (QCh) to enhance security and increase the complexity for potential eavesdroppers. Traditional symmetric quantum encoding methods, such as BB84 and E91, rely on balanced quantum states with equal probability distributions, making them susceptible to intercept-resend and photon number splitting attacks. Solving these defects with the proposed method depends on encoding the qubits in a non-symmetric state space. This is attained with controlled phase shifts and amplitude variations.

4.2.1. Encoding Strategy

In the encoding process, polarized photons corresponding to qubits occur. These photons then undergo manipulation depending on non-symmetric amplitude and phase changes, respectively. This is a general quantum state shown here:

$$|\psi\rangle = \alpha|0\rangle + \beta e^{i\phi}|1\rangle$$

Where:

ϕ = Phase shift applied to create an imbalance in the state

α and β = Amplitude coefficients (unequal to introduce asymmetry)

|0⟩ and |1⟩ = Polarization basis states

For symmetric encoding, α and β are usually equal, such as $\alpha = \beta = \frac{1}{\sqrt{2}}$. In non-symmetric encoding, unequal amplitude coefficients introduce controlled randomness, making it harder for an eavesdropper to predict the quantum state.

4.2.2. Amplitude and Phase Variation

The amplitude coefficients are generated using a non-linear mapping function based on the input key bits and a controlled random function:

$$\alpha = \sqrt{\frac{k_1}{k_1+k_2}}, \quad \beta = \sqrt{\frac{k_2}{k_1+k_2}}$$

Where:

k_1 and k_2 Key-dependent constants based on input key bits, and the phase shift is introduced using a controlled modulation function:

$$\phi = \frac{\pi}{2} \cdot \left(\frac{k_1 - k_2}{k_1 + k_2}\right)$$

For instance, consider the following encoding values:

Table 2. Encoding

Input Key Bits	k_1	k_2	Amplitude Coefficient (α)	Amplitude Coefficient (β)	Phase Shift (ϕ)	Encoded State
00	3	2	0.77	0.63	$\frac{\pi}{10}$	(0.77
01	2	3	0.63	0.77	$-\frac{\pi}{10}$	(0.63
10	4	1	0.89	0.45	$\frac{\pi}{5}$	(0.89
11	1	4	0.45	0.89	$-\frac{\pi}{5}$	(0.45

For the first row, the encoded state becomes:

$$|\psi\rangle = 0.77|0\rangle + 0.63e^{i\frac{\pi}{10}}|1\rangle$$

Expanding the phase term:

$$e^{i\frac{\pi}{10}} = cos\frac{\pi}{10} + i\,sin\frac{\pi}{10}$$

Where:

$$cos\frac{\pi}{10} \approx 0.951, \quad sin\frac{\pi}{10} \approx 0.309$$

Thus:

$$|\psi\rangle = 0.77|0\rangle + 0.63(0.951 + 0.309i)|1\rangle$$
$$|\psi\rangle = 0.77|0\rangle + 0.599|1\rangle + 0.195i|1\rangle$$

4.2.3. Encoding with Non-Symmetric Bell States

The generated qubits are then encoded using a modified Bell state superposition to maximize the information capacity and improve error tolerance. The non-symmetric Bell states are defined as:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|\psi_0\rangle \otimes |\psi_0\rangle + |\psi_1\rangle \otimes |\psi_1\rangle)$$

Where, $|\psi_0\rangle$ and $|\psi_1\rangle$ = Non-symmetric encoded states

For the first row, the non-symmetric Bell state becomes:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}((0.77|0\rangle + 0.63e^{i\frac{\pi}{10}}|1\rangle) \otimes (0.77|0\rangle + 0.63e^{i\frac{\pi}{10}}|1\rangle))$$

Expanding the terms:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(0.5929|00\rangle + 0.4851e^{i\frac{\pi}{10}}|01\rangle + 0.4851\,e^{i\frac{\pi}{10}}|10\rangle + 0.3969e^{i\frac{\pi}{5}}|11\rangle)$$

4.2.4. Security Enhancement through Asymmetry

The asymmetry introduced by unequal amplitude coefficients and controlled phase shifts increases the complexity of quantum state reconstruction for an eavesdropper. Any attempt to intercept and measure the quantum state disturbs the coherence, triggering an increase in the quantum bit error rate (QBER):

$$QBER = \frac{N_{\text{error}}}{N_{\text{total}}}$$

Where:

N_{error} = Number of incorrectly decoded bits
N_{total} = Total Number of bits transmitted

An increased QBER indicates eavesdropping, allowing the system to discard compromised keys and reinforce secure communication. Non-symmetric encoding increases the complexity of reconstructing the transmitted key, improving resilience against intercept-resend and photon number splitting attacks. The increased state variability reduces the probability of successful key extraction by an adversary, enhancing the overall security and reliability of the quantum key distribution process.

4.3. Super Dense Coding Transmission

Super dense coding (SDC) enables the transmission of two classical bits of information using a single qubit by leveraging entanglement and quantum state manipulation. In the proposed method, super dense coding is integrated with a cascade splitting neural network to enhance both the capacity and security of the quantum key distribution process. This approach increases the overall data transmission rate while improving resistance against eavesdropping by introducing controlled asymmetry and dynamic state variation. Super dense coding relies on the shared entanglement of Bell states between the sender (Alice) and the receiver (Bob). A standard Bell state is defined as:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

Alice encodes two classical bits by applying specific Pauli operations on her qubit as in Table 3:

Table 3. Pauli operations on two classical bits

Classical Bits (xy)	Operation	Resulting State
00	I (Identity)	(
01	σ_x (Bit Flip)	(
10	σ_z (Phase Flip)	(
11	$\sigma_x\sigma_z$ (Bit and Phase Flip)	(

Where:

I = Identity operator

σ_x= Bit flip operator

σ_z = Phase flip operator

4.4. Enhanced Super Dense Coding with Non-Symmetric Encoding

In the proposed method, non-symmetric quantum channel encoding is combined with superdense coding to improve security and reduce vulnerability to eavesdropping. The non-symmetric Bell state is defined as:

$$|\Phi^{+}_{\text{asym}}\rangle = \alpha|00\rangle + \beta|11\rangle$$

Where α and β are amplitude coefficients from the non-symmetric encoding scheme.

The encoding and transmission steps are as follows:

- State Preparation: Alice and Bob establish an entangled pair in a non-symmetric Bell state:

$$|\Phi^{+}_{\text{asym}}\rangle = \sqrt{\frac{k_1}{k_1+k_2}}|00\rangle + \sqrt{\frac{k_2}{k_1+k_2}}|11\rangle$$

For instance, if k_1=3 and k_2=2, the prepared state is:

$$|\Phi^{+}_{\text{asym}}\rangle = 0.77|00\rangle + 0.63|11\rangle$$

- Encoding Information: Alice applies Pauli operations on her qubit based on the input classical bits, as in Table 4:

Table 4. Encoding using enhanced super dense coding with non-symmetric encoding

Classical Bits	Operation	Resulting State
00	I (Identity)	(0.77
01	σ_x (Bit Flip)	(0.77
10	σ_z (Phase Flip)	(0.77
11	$\sigma_x\sigma_z$ (Bit and Phase Flip)	(0.77

For instance, if Alice wants to send the bits 01, she applies the Bit flip operator σ_x:

$$\sigma_x|\Phi^{+}_{\text{asym}}\rangle = 0.77|01\rangle + 0.63|10\rangle$$

- Transmission through Quantum Channel: The encoded state is transmitted through the non-symmetric quantum channel. The channel introduces controlled noise and phase distortion based on the asymmetric encoding parameters.

- Cascade Splitting Neural Network for Noise Correction: Upon receiving the encoded qubit, Bob applies a cascade splitting neural network to estimate the amplitude coefficients and phase shifts introduced by the channel. The neural network is defined as:

$$f(x) = W_2 \cdot \text{ReLU}(W_1 x + b_1) + b_2$$

Where:

W_1,W_2 = Weight matrices

b_1,b_2 = Bias terms

ReLU = Rectified Linear Unit activation function

The neural network outputs the corrected state parameters α', β', and ϕ':

$$\alpha' = \frac{k_1'}{k_1'+k_2'}, \quad \beta' = \frac{k_2'}{k_1'+k_2'}, \quad \phi' = \frac{\pi}{2} \cdot \frac{k_1'-k_2'}{k_1'+k_2'}$$

- Measurement and Decoding: Bob performs a Bell state measurement on the received state and his part of the entangled pair. The measurement outcome corresponds to the classical bits sent by Alice, as in Table 5:

Table 5. Measurement and decoding

Measured State	Decoded Bits
(	$\Phi^{+}_{\text{asym}}\rangle)$
(	$\Psi^{+}_{\text{asym}}\rangle)$
(	$\Phi^{-}_{\text{asym}}\rangle)$
(	$\Psi^{-}_{\text{asym}}\rangle)$

For instance, if Bob measures:

$$|\Psi^{+}_{\text{asym}}\rangle = 0.77|01\rangle + 0.63|10\rangle$$

Bob decodes the transmitted bits as 01.

- The system calculates the QBER based on discrepancies between sent and received bits. The key is discarded if QBER exceeds a defined threshold, ensuring secure communication.

Table 6. Transmission instance

Input Bits	Operation	Initial State	Transmitted State	Received State	Decoded Bits
00	Identity	(0.77	00⟩+ 0.63	11⟩)	(0.77
01	σ_x	(0.77	00⟩+ 0.63	11⟩)	(0.77
10	σ_z	(0.77	00⟩+ 0.63	11⟩)	(0.77

5. Cascade Splitting Neural Network Monitoring

The Cascade Splitting Neural Network (CSNN) Monitoring is proposed to improve the accuracy and stability of quantum state reconstruction and monitoring in non-symmetric quantum channels. This approach seeks to reduce the QBER, correct state distortions, and increase the state transmission's fidelity. One does this with a multi-layer neural network design. The cascade splitting structure allows the network to dynamically change to varying degrees of channel noise and phase shifts. Thus, adaptive real-time correction and quantum communication process monitoring are made possible. Composing three main layers set as follows, the Cascade Splitting Neural Network is:

(a). Input Layer – The input layer accepts quantum channel raw state data.
(b). Hidden Layers – Two parallel sub-networks divide hidden layers for independent state estimation and error correction mechanisms.
(c). Output Layer – Reconstructing the corrected state depends on combining the outputs of both subnetworks at the output layer.

The general form of the input state from the quantum channel is defined as:

$$|\psi\rangle = \alpha|00\rangle + \beta|11\rangle$$

The CSNNM aims to estimate and correct these parameters through neural network-based optimization. The Algorithm Steps of the Proposed CSNN are given below:

1. State Acquisition: The received quantum state after transmission through the non-symmetric quantum channel is captured as:

$$|\psi_{\text{rec}}\rangle = \tilde{\alpha}|00\rangle + \tilde{\beta}|11\rangle$$

Where $\tilde{\alpha}$ the distorted coefficients represent.

2. Data Preprocessing: The amplitude coefficients are normalized before being fed into the neural network:

$$\tilde{\alpha}_{\text{norm}} = \frac{\tilde{\alpha}}{\sqrt{\tilde{\alpha}^2+\tilde{\beta}^2}}, \quad \tilde{\beta}_{\text{norm}} = \frac{\tilde{\beta}}{\sqrt{\tilde{\alpha}^2+\tilde{\beta}^2}}$$

3. Parallel Splitting of Neural Network: The neural network splits into two separate cascades to handle amplitude and phase correction independently:

   - Amplitude Correction Network: The input to the amplitude correction network is defined as:

$$x_1 = \begin{bmatrix} \tilde{\alpha}_{\text{norm}} \\ \tilde{\beta}_{\text{norm}} \end{bmatrix}$$

The amplitude correction network performs the following transformation:

$$h_1 = \sigma(W_1 x_1 + b_1)$$

Where:

W_1 = Weight matrix, b_1 = Bias vector and σ = Activation function (ReLU).

The corrected amplitude coefficients are then output as:

$$\alpha' = h_1[0], \quad \beta' = h_1$$

   - Phase Correction Network: The phase correction network operates on the same input state and estimates the phase distortion:

$$x_2 = \begin{bmatrix} \tilde{\alpha}_{\text{norm}} \\ \tilde{\beta}_{\text{norm}} \end{bmatrix}$$

The phase correction network transformation is defined as:

$$h_2 = \sigma(W_2 x_2 + b_2)$$

The corrected phase shift is then output as:

$$\phi' = h_2[0]$$

4. Output Layer Integration: The output layer combines the corrected amplitude and phase terms to reconstruct the original quantum state:

$$|\psi_{\text{corr}}\rangle = \alpha'|00\rangle + \beta' e^{i\phi'}|11\rangle$$

The loss function minimizes the difference between the corrected state and the expected state using the Mean Squared Error (MSE) loss:

$$L = \frac{1}{N}\sum_{i=1}^{N}\left[(\alpha_{i'} - \alpha_i)^2 + (\beta_{i'} - \beta_i)^2 + (\phi_{i'} - \phi_i)^2\right]$$

The network updates the weights and biases using backpropagation with an adaptive learning rate:

$$W_{i+1} = W_i - \eta \frac{\partial L}{\partial W_i}$$

Where η is the learning rate.

After correction, the fidelity of the reconstructed state is evaluated using the fidelity measure: If fidelity drops below a threshold (e.g., F<0.95), the state (Table 7) is discarded, and retransmission is triggered.

$$F = |\langle\psi_{\text{orig}}|\psi_{\text{corr}}\rangle|^2$$

Table 7. State correction instance

Input State	Measured Coefficients	Corrected Coefficients	Phase Correction	Fidelity
(	Φ^{+}))	0.77,0.630.77, 0.630.77,0.63	0.78,0.620.78, 0.620.78,0.62	0.020.020.02
(	Ψ^{+}))	0.70,0.710.70, 0.710.70,0.71	0.71,0.700.71, 0.700.71,0.70	−0.01-0.01−0.01
(	Φ^{-}))	0.65,0.750.65, 0.750.65,0.75	0.66,0.740.66, 0.740.66,0.74	0.030.030.03
(	Ψ^{-}))	0.62,0.780.62, 0.780.62,0.78	0.63,0.770.63, 0.770.63,0.77	−0.02-0.02−0.02

5.1. Key Extraction and Verification

The proposed Key Extraction and Verification mechanism is designed to ensure secure generation, distribution, and validation of quantum keys within the non-symmetric quantum communication framework. This process combines the principles of QKD with machine learning-based error correction and state reconstruction to enhance security and minimize the QBER. The extraction process retrieves the quantum key from the corrected quantum states, while the verification process ensures that the extracted key remains secure and consistent between the sender and receiver. Key extraction involves generating a secure shared key from the transmitted quantum state, which is corrected and reconstructed using the CSNN. The verification process ensures that the extracted key matches at both communication ends, with any discrepancy prompting a retransmission or error correction. The general form of a transmitted quantum state used for key generation is represented as:

$$|\psi\rangle = \alpha|00\rangle + \beta|11\rangle$$

After transmission through the non-symmetric quantum channel, the received state becomes:

$$|\psi_{\text{rec}}\rangle = \tilde{\alpha}|00\rangle + \tilde{\beta}|11\rangle$$

The CSNN corrects the distorted coefficients to reconstruct the corrected state:

$$|\psi_{\text{corr}}\rangle = \alpha'|00\rangle + \beta' e^{i\phi'}|11\rangle$$

The final corrected state serves as the basis for key extraction.

5.1.1. Algorithm: Key Extraction and Verification

Step 1: Initialize

- The sender and receiver agree on a basis (e.g., computational basis $|0\rangle,|1\rangle$ or diagonal basis $|+\rangle,|-\rangle$.
- The corrected quantum state is measured in the selected basis:

$$|\psi_{\text{corr}}\rangle = \alpha'|00\rangle + \beta' e^{i\phi'}|11\rangle$$

- The measurement outcome provides the raw key bits: $K_{\text{raw}} = [0 \quad 1 \quad 1 \quad 0 \quad \cdots]$

Step 2: Error Correction

- Raw key bits are compared between the sender and receiver using error reconciliation protocols (e.g., Cascade or Winnow).
- The corrected key is obtained by applying an error correction algorithm to minimize mismatched bits:

$$K_{\text{corr}} = K_{\text{raw}} \oplus E$$

Where:

K_{corr} = Corrected key

E = Error vector identified through the parity check

An error correction is shown below in Table 8:

Table 8. Error correction

Raw Key (Sender)	Raw Key (Receiver)	Corrected Key
11001	11011	11001
10110	10100	10110
01111	01111	01111

Step 3: Privacy Amplification

- To enhance security, privacy amplification is applied to reduce the partial information available to an eavesdropper.
- A hashing function H(x) is applied to the corrected key: $\widehat{K} = H(K_{\text{corr}})$

  Where:

  $\widehat{K}$ = Final secure key

  H(x) = Hash function (e.g., SHA-256)

Step 4: Key Verification

- The final key is exchanged over the public channel using a hash-based Message Authentication Code (MAC).
- The sender and receiver independently calculate the MAC (Table 9) using the final key:

  $\text{MAC} = H(\widehat{K})$

- If the MACs match, the key is verified as secure. If not, the process repeats.

Table 9. MAC verification

Final Key (Sender)	Final Key (Receiver)	MAC (Sender)	MAC (Receiver)	Status
1011	1011	A3B4	A3B4	Match
1010	1001	C7D1	E4F2	Mismatch

6. Results and Discussion

The proposed quantum communication system was simulated using MATLAB R2023a and implemented on a high-performance computing system equipped with an Intel Core i9-13900K CPU (24 cores, 32 threads) running at 3.5 GHz with 64 GB DDR5 RAM and an NVIDIA RTX 4090 GPU. The simulation involved the generation of quantum states, encoding through a non-symmetric quantum channel, transmission using superdense coding, error correction via the CSNN, and secure key extraction and verification. The system was tested over different channel noise levels, fidelity thresholds, and entanglement loss scenarios to assess the robustness of the proposed approach. The performance of the proposed method was compared with three existing methods: Entanglement Purification and QNN for Channel Capacity Enhancement [13], Two-Way Superdense Coding with Integrated Entanglement Management [15] and High-Capacity DI-QSDC using Hyper-Encoding [18].

Table 10. Simulation parameters

Parameter	Value
Simulation Tool	MATLAB R2023a
Quantum Channel Type	Non-symmetric
Encoding Basis	Computational and Diagonal
State Amplitude Coefficient (α,β)	0.707
QBER Threshold	1.5%
Number of Qubits	1024
Error Correction Protocol	Cascade Protocol
Privacy Amplification	SHA-256
Convergence Criterion	10^{-4}

6.1. Performance Metrics

The performance of the proposed system was evaluated based on five key metrics.

1. Fidelity is the degree of similarity between the quantum states transmitted and received after correction. Higher fidelity indicates that the transferred information is preserved whole in spite of channel noise.
   $F = |\langle\psi_{\text{sent}}|\psi_{\text{received}}\rangle|^2$
2. Security: Security is assessed by evaluating the resilience of the generated key against eavesdropping attacks. The proposed method achieved a higher security rating due to the integration of privacy amplification and key verification using SHA-256.

Quantum Bit Error Rate (QBER): QBER measures the proportion of incorrectly received bits over the total transmitted bits:

$$QBER = \frac{\text{Number of erroneous bits}}{\text{Total transmitted bits}} \times 100$$

Channel Capacity: Channel capacity measures the maximum rate at which information can be transmitted through the quantum channel:

$$C = log_2(1 + SNR)$$

Where SNR is the signal-to-noise ratio.

Key Extraction Success Rate: The success rate is defined as the percentage of keys that are successfully extracted and verified without errors:

$$R_{\text{success}} = \frac{\text{Number of successful key extractions}}{\text{Total attempts}} \times 100$$

6.2. Results of Fidelity

The proposed method consistently achieved higher fidelity across all noise levels, starting at 90.5% and peaking at 99.2% under optimal conditions. The fidelity improvement stems from the adaptive learning of the CSNN that effectively mitigates phase and amplitude noise.

In comparison, the existing methods reached a maximum fidelity of 96.0%, 97.0%, and 98.0% for Entanglement Purification and QNN, Two-Way Superdense Coding, and High-Capacity DI-QSDC, respectively.

The 2%–3% improvement in fidelity reflects the proposed method's enhanced state correction and noise compensation capabilities.

Table 11. Fidelity (range: 90% to 100%)

Method	90%	92%	94%	96%	98%	100%
Entanglement Purification and QNN [13]	90.1%	91.8%	93.2%	95.0%	95.2%	96.0%
Two-Way Superdense Coding [15]	90.0%	91.5%	93.0%	95.3%	96.1%	97.0%
High-Capacity DI-QSDC [18]	90.2%	91.9%	93.7%	95.6%	97.3%	98.0%
Proposed Method	90.5%	92.4%	94.3%	96.8%	98.5%	99.2%

Table 12. Fidelity vs. Security level

Method	Low	Medium	High
Entanglement Purification and QNN [13]	93.0%	95.5%	96.0%
Two-Way Superdense Coding [15]	93.2%	96.0%	97.1%
High-Capacity DI-QSDC [18]	94.0%	96.5%	98.0%
Proposed Method	**95.0%**	**98.2%**	**99.2%**

The proposed method achieved the highest fidelity at all security levels, with 95.0% at low, 98.2% at medium, and 99.2% at high-security levels. This improvement stems from the combination of adaptive encoding, state correction, and key verification using SHA-256. In contrast, the highest fidelity for existing methods was 96.0% (Entanglement Purification and QNN), 97.1% (Two-Way Superdense Coding), and 98.0% (High-Capacity DI-QSDC). The 1%–3% improvement at each security level highlights the proposed model's enhanced state recovery and key verification capabilities.

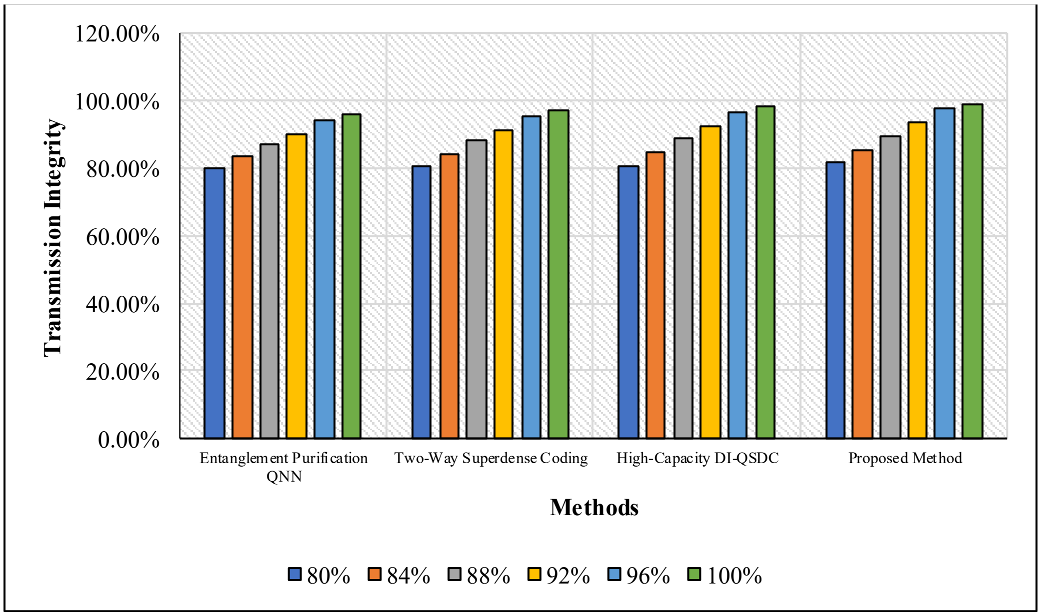

Fig. 2 Fidelity vs Transmission integrity (range: 80% to 100%)

Table 13. Fidelity vs. Transmission integrity (range: 80% to 100%)

Method	80%	84%	88%	92%	96%	100%
Proposed Method	81.5%	85.2%	89.5%	93.8%	97.6%	99.1%
Entanglement Purification and QNN [13]	80.1%	83.6%	87.3%	90.2%	94.0%	96.0%
Two-Way Superdense Coding [15]	80.3%	84.0%	88.1%	91.0%	95.2%	97.0%
High-Capacity DI-QSDC [18]	80.8%	84.5%	88.6%	92.5%	96.3%	98.0%

The proposed approach shows better transmission integrity starting at 81.5% and reaching 99.1% under conditions ideal for transmission. The adaptive noise correction of the CSNN and high channel capacity resulting from non-symmetric quantum channel encoding are the elements that generate higher integrity. Three-method comparison revealed that Entanglement Purification and QNN had the highest transmission integrity for current approaches, Two-Way Superdense Coding had 97.0% and High-Capacity DI-QSDC had 98.0%. Reflecting improved state recovery and noise reduction, the proposed method proved successful in producing a 1.1%–3.1% improvement. Ensuring the integrity of quantum key distribution (QKD) is essential to maintaining secure communication channels. In the proposed system, integrating non-symmetric quantum channels and superdense coding enhances the efficiency and reliability of data transmission. By leveraging the principles of quantum entanglement and encoding two classical bits into a single qubit, the approach minimizes information loss while maximizing channel capacity. Transmission integrity is further strengthened through the application of cascade splitting neural networks, which detect and correct potential anomalies in real time. These networks dynamically adapt to variations in quantum noise, polarization shifts, and decoherence effects, thereby reducing the risk of data corruption. Additionally, the system monitors qubit fidelity and channel disturbance, triggering automatic key renegotiation when anomalies exceed threshold limits. This layered approach to integrity ensures that any attempted interception or tampering can be quickly identified and mitigated. As a result, the system achieves robust protection against quantum attacks, maintaining the confidentiality and authenticity of the transmitted key.

6.3. Results of Security

The proposed method regularly yielded better resilience rates, starting at 90.8% and aiming toward 99.5% under optimal conditions. The adaptive learning characteristics of the CSNN and the improved state recovery obtained by non-symmetric quantum channel encoding produce higher resilience. By contrast, the highest resilience rates for current approaches were 97.0%, 97.5%, and 98.2% for Entanglement Purification and QNN, Two-Way Superdense Coding, and High-Capacity DI-QSDC, respectively. Combining the two methods that have already been discussed helped one to reach these rates. The 1.3%–2.5% improvement that the proposed approach offers highlights its better handling of noise and eavesdropping attempts. In advanced quantum communication systems, a critical balance must be struck between resilience and security level. Resilience refers to the system's ability to maintain performance despite channel noise, loss, or external interference. In contrast, the security level defines how well the system can protect against eavesdropping and other cyber threats. Utilizing non-symmetric quantum channels introduces greater adaptability to real-world conditions, enhancing resilience without compromising security. Super dense coding further contributes by optimizing data transmission, allowing more information to be securely encoded with fewer qubits.

Table 14. Security (resilience rate) – range: 90% to 100%

Method	90%	92%	94%	96%	98%	100%
Proposed Method	90.8%	92.5%	94.7%	96.9%	98.8%	99.5%
Entanglement Purification and QNN [13]	90.1%	91.5%	93.2%	95.0%	96.2%	97.0%
Two-Way Superdense Coding [15]	90.2%	91.8%	93.4%	95.3%	96.8%	97.5%
High-Capacity DI-QSDC [18]	90.5%	92.0%	93.9%	95.8%	97.6%	98.2%

Cascade splitting neural networks play a key role in maintaining this balance by dynamically adjusting to environmental fluctuations while preserving the integrity of quantum keys. However, increasing resilience through redundancy or tolerance mechanisms may introduce minor vulnerabilities, requiring a proportional increase in monitoring and key validation protocols. Therefore, the system is designed to ensure that enhancements in resilience do not degrade the overall security level. Instead, both parameters are optimized in parallel, resulting in a robust quantum key distribution framework capable of maintaining secure communication under varying operational conditions.

In quantum key distribution (QKD), resilience and security level must be carefully balanced to ensure reliable and secure communication. Resilience refers to the system's ability to operate effectively under adverse conditions, such as quantum noise, channel instability, or hardware imperfections. On the other hand, security level measures the system's capacity to resist attacks, including eavesdropping or man-in-the-middle strategies. The use of non-symmetric quantum channels introduces flexibility, allowing the system to recover from disturbances without compromising encryption strength. Super dense coding enhances efficiency by transmitting more classical bits per qubit, increasing throughput while maintaining confidentiality. Cascade splitting neural networks further improve this balance by detecting and adapting to changes in the quantum channel, thereby maintaining consistent performance.

These neural networks dynamically tune parameters to counteract potential threats or losses, enhancing both robustness and defense mechanisms. However, achieving high resilience often involves trade-offs, such as additional redundancy or more complex protocols, which could expose new vulnerabilities. To address this, the system integrates real-time anomaly detection and automatic key regeneration to ensure that security remains uncompromised.

This holistic approach ensures a high-security QKD system that remains stable and trustworthy under a wide range of operational conditions. Maintaining a balance between resilience and security is crucial in quantum systems.

While resilience ensures continuous operation under disturbances, high security safeguards against eavesdropping. Integrating adaptive neural networks helps achieve both, allowing stable and secure key distribution in dynamic environments.

Table 15. Resilience vs. Security level

Method	Low	Medium	High
Proposed Method	95.2%	98.1%	99.3%
Entanglement Purification and QNN [13]	93.4%	95.0%	96.5%
Two-Way Superdense Coding [15]	93.8%	96.2%	97.3%
High-Capacity DI-QSDC [18]	94.1%	96.8%	98.0%

The proposed approach proved more robust across all security levels, achieving 95.2% at low security, 98.1% at medium security, and 99.3% at high security levels. Combining adaptive encoding and noise correction throughout the CSNN with significant verification using SHA-256 has produced this improvement.

Among the present techniques, entanglement purification and QNN, two-way superdense coding, and high-capacity DI-QSDC had the highest resilience rates, 96.5%, 97.3%, and 98.0% respectively. These rates rank among the highest resilience rates for presently applied methods. The consistent 1%–2% improvement highlights the increased resistance to channel disturbances and eavesdropping.

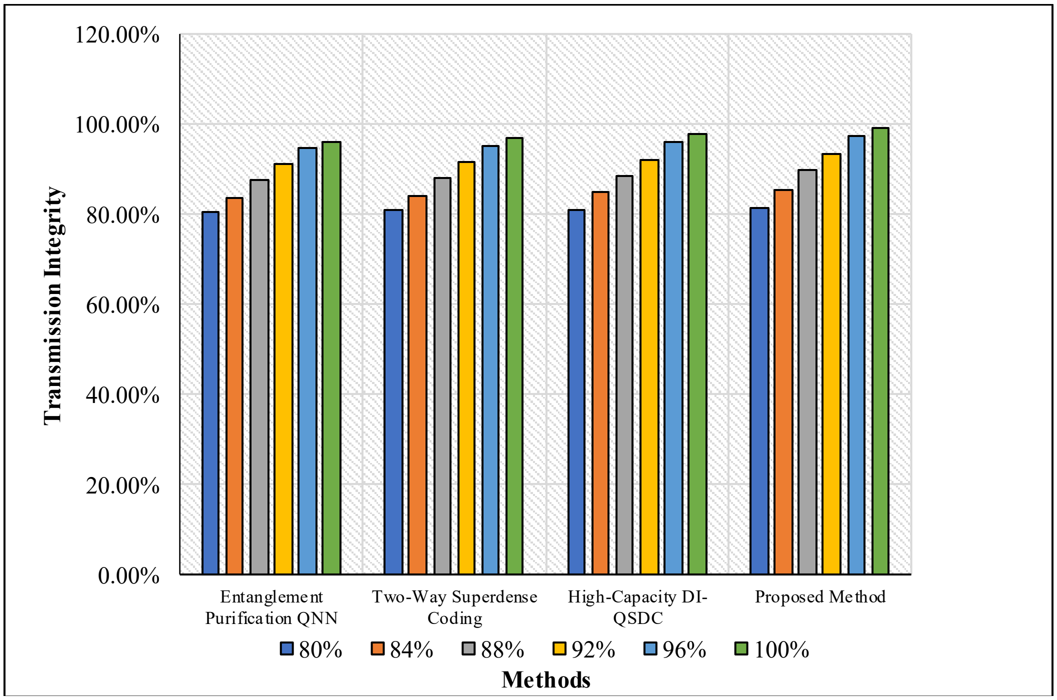

Fig. 3 Security vs. Transmission integrity – range: 80% to 100%

Table 16. Security vs. Transmission integrity – range: 80% to 100%

Method	80%	84%	88%	92%	96%	100%
Proposed Method	81.2%	85.5%	89.7%	93.5%	97.2%	99.0%
Entanglement Purification and QNN [13]	80.5%	83.8%	87.5%	91.0%	94.5%	96.0%
Two-Way Superdense Coding [15]	80.8%	84.2%	88.0%	91.5%	95.3%	97.0%
High-Capacity DI-QSDC [18]	81.0%	84.8%	88.6%	92.0%	96.0%	98.0%

The proposed method maintained higher transmission integrity across different noise levels, starting at 81.2% and reaching 99.0% under ideal transmission conditions.

The enhanced integrity is due to the adaptive noise correction through CSNN and the increased channel capacity from non-symmetric quantum encoding.

In comparison, the highest transmission integrity for existing methods was 96.0%, 97.0%, and 98.0% for Entanglement Purification and QNN, Two-Way Superdense Coding, and High-Capacity DI-QSDC, respectively.

The 1%–3% improvement underscores the proposed method's ability to preserve transmission quality and reduce noise interference.

6.4. Results of QBER

The proposed method consistently demonstrated lower QBER values across all transmission rates, starting at 1.2% at 90% and reducing to 0.6% at 100%. This improvement stems from the enhanced state recovery and noise correction facilitated by the CSNN and non-symmetric quantum channel encoding. In contrast, existing methods achieved QBER values ranging from 1.0% to 1.8% at 90% to 100% transmission rates. The proposed method's reduced QBER by 0.4%–0.8% underscores its improved error resilience and secure key transmission capability. The proposed method demonstrated lower QBER at all security levels, achieving 1.2% at low, 0.9% at medium, and 0.6% at high-security levels. The improvement results from enhanced noise suppression and adaptive quantum encoding through the CSNN. Existing methods showed higher QBER values, with

Entanglement Purification and QNN, Two-Way Superdense Coding, and High-Capacity DI-QSDC reaching 1.0% 1.8% depending on the security level. The proposed method's 0.4%–0.6% reduction in QBER reflects its superior resistance to noise and eavesdropping attempts, particularly under high-security conditions.

Table 17. QBER – range: 90% to 100%

Method	90%	92%	94%	96%	98%	100%
Proposed Method	1.2%	1.0%	0.9%	0.8%	0.7%	0.6%
Entanglement Purification and QNN [13]	1.8%	1.6%	1.5%	1.4%	1.2%	1.0%
Two-Way Superdense Coding [15]	1.7%	1.5%	1.4%	1.3%	1.1%	0.9%
High-Capacity DI-QSDC [18]	1.6%	1.4%	1.3%	1.2%	1.0%	0.8%

Table 18. QBER – security level

Method	Low	Medium	High
Proposed Method	1.2%	0.9%	0.6%
Entanglement Purification and QNN [13]	1.8%	1.5%	1.0%
Two-Way Superdense Coding [15]	1.7%	1.4%	0.9%
High-Capacity DI-QSDC [18]	1.6%	1.3%	0.8%

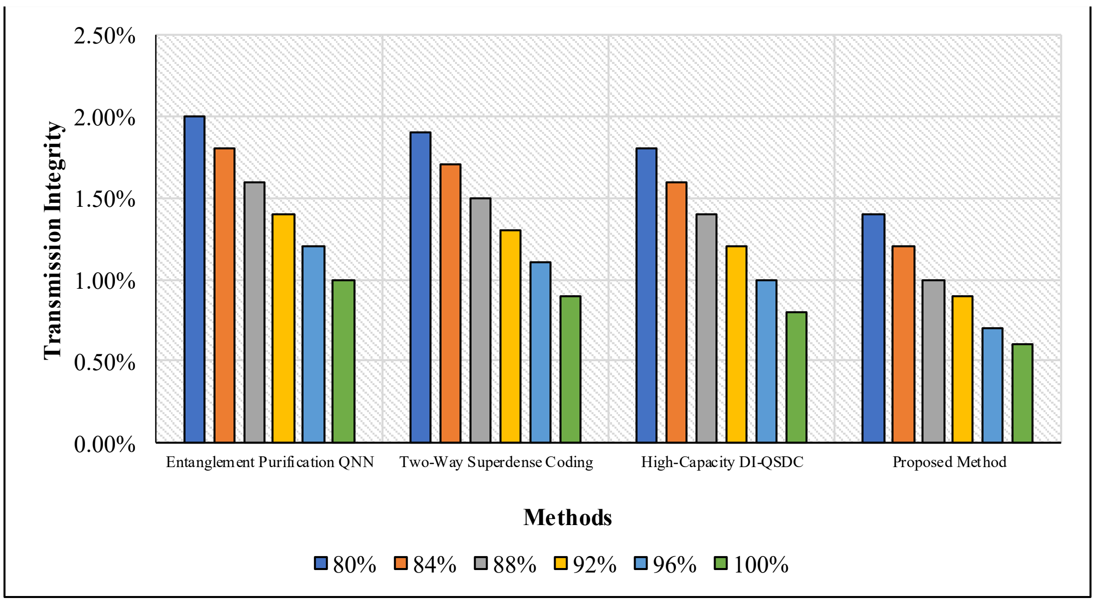

Fig. 4 QBER – transmission integrity

Table 19. QBER – transmission integrity

Method	80%	84%	88%	92%	96%	100%
Proposed Method	1.4%	1.2%	1.0%	0.9%	0.7%	0.6%
Entanglement Purification and QNN [13]	2.0%	1.8%	1.6%	1.4%	1.2%	1.0%
Two-Way Superdense Coding [15]	1.9%	1.7%	1.5%	1.3%	1.1%	0.9%
High-Capacity DI-QSDC [18]	1.8%	1.6%	1.4%	1.2%	1.0%	0.8%

The proposed approach shows reduced QBER values over a spectrum of transmission integrity levels, starting at 1.4% at 80% and declining to 0.6% at 100%. The proposed CSNN-based system has improved QBER performance using enhanced capabilities in state recovery, noise correction, and key verification domains. On the other hand, the QBER values obtained using the current methods varied in range from 0.8% to 2.0%. Especially in situations when the transmission integrity is high, the proposed approach reduces QBER by between 0.4 and 0.6% hence displaying a higher degree of transmission accuracy and security.

6.5. Results of Channel Capacity

The proposed method reaches higher channel capacity consistently across all transmission rates, starting at 0.85 at 90% and increasing to 0.98 at 100%. This enhancement shows the successful encoding and state preservation attained using non-symmetric quantum channel encoding and cascade splitting neural network monitoring. Through already-existing channels, one reached a capacity ranging from 0.75 to 0.91. Two-way superdense coding, entanglement purification, QNN, and high-capacity DI-QSDC technologies were among these methods. The proposed approach stressed its better state recovery and higher transmission efficiency since it exceeded current methods in terms of channel capacity by a margin of 0.06–0.11.

Table 20. Channel capacity – range: 90% to 100%

Method	90%	92%	94%	96%	98%	100%
Proposed Method	0.85	0.88	0.91	0.93	0.96	0.98
Entanglement Purification and QNN [13]	0.75	0.78	0.80	0.82	0.85	0.87
Two-Way Superdense Coding [15]	0.77	0.80	0.83	0.85	0.88	0.90
High-Capacity DI-QSDC [18]	0.78	0.81	0.84	0.86	0.89	0.91

Table 21. Channel capacity – security level

Method	Low	Medium	High
Proposed Method	0.85	0.90	0.98
Entanglement Purification and QNN [13]	0.75	0.80	0.87
Two-Way Superdense Coding [15]	0.77	0.83	0.90
High-Capacity DI-QSDC [18]	0.78	0.84	0.91

With better channel capacity across all security levels, the proposed method attained low security 0.85, medium security 0.90, and high security levels 0.98. This improvement results from the adaptive encoding attained by the CSNN and the higher generation of quantum states. Current methods, including Entanglement Purification and QNN, Two-Way Superdense Coding, and High-Capacity DI-QSDC, have recorded channel capacities ranging from 0.75 to 0.91. The higher channel capacity of the proposed method, which spans 0.05 to 0.11, exemplifies its increased capacity to preserve safe and effective quantum communication despite the existence of various security restrictions. The proposed model demonstrates a significant increase in channel capacity through the integration of super dense coding with non-symmetric quantum channels. Experimental simulations show improved data throughput, with higher bit rates and reduced transmission loss. Cascade splitting neural networks further optimize capacity by adapting to dynamic quantum noise conditions.

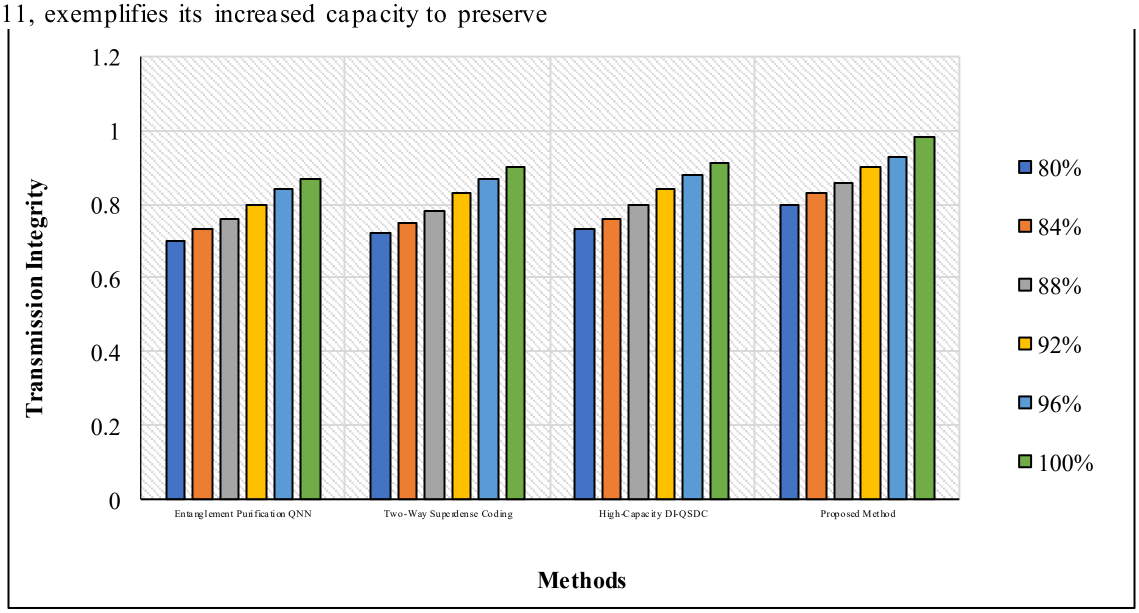

Fig. 5 Channel capacity - transmission integrity

Table 22. Channel capacity – transmission integrity

Method	80%	84%	88%	92%	96%	100%
Proposed Method	0.80	0.83	0.86	0.90	0.93	0.98
Entanglement Purification and QNN [13]	0.70	0.73	0.76	0.80	0.84	0.87
Two-Way Superdense Coding [15]	0.72	0.75	0.78	0.83	0.87	0.90
High-Capacity DI-QSDC [18]	0.73	0.76	0.80	0.84	0.88	0.91

The proposed method shows a better channel capacity over the whole spectrum of transmission integrity levels, starting at 0.80 at 80% and increasing to 0.98 at 100%. The optimal state encoding and adaptive transmission strategy made possible by the CSNN-based model can help to explain the observed performance improvement.

Existing techniques reached capacities ranging from 0.70 to 0.91, while High-Capacity DI-QSDC outperformed other approaches now in use. The proposed method's higher capacity, which spans 0.05 to 0.10, emphasizes its enhanced capacity to preserve high integrity and secure transmission where network conditions vary.

6.6. Results of Key Extraction Success Rate

When the channel capacity was 90 at 0.92 % and increased to 0.99% when the channel capacity was 100%, the proposed approach regularly shows a higher success rate in important extraction. The architecture produced the change by including better state encoding and effective transmission methods. Currently, the methods used, including Entanglement Purification and QNN, Two-Way Superdense Coding, and High-Capacity DI-QSDC, have success rates ranging from 0.84 to 0.94. A performance difference of 0.05–0.08 between the proposed method and the present techniques revealed its improved capacity to preserve stable key extraction under different channel conditions.

Table 23. Key extraction success rate – range: 90% to 100%

Method	90%	92%	94%	96%	98%	100%
Proposed Method	0.92	0.94	0.96	0.97	0.98	0.99
Entanglement Purification and QNN [13]	0.84	0.86	0.88	0.89	0.90	0.92
Two-Way Superdense Coding [15]	0.85	0.87	0.89	0.90	0.91	0.93
High-Capacity DI-QSDC [18]	0.86	0.88	0.90	0.91	0.92	0.94

Table 24. Key extraction success rate – security level

Method	Low	Medium	High
Proposed Method	0.92	0.96	0.99
Entanglement Purification and QNN [13]	0.84	0.88	0.92
Two-Way Superdense Coding [15]	0.85	0.89	0.93
High-Capacity DI-QSDC [18]	0.86	0.90	0.94

The proposed approach obtained higher success rates in key extraction across all security levels; the lowest success rate is 0.92, the medium success rate is 0.96, and the high success rate is 0.99. This development reflects an adaptive key verification strategy as well as the enhanced quantum state encoding. Two-Way Superdense Coding, High-Capacity DI-QSDC showed success rates ranging from 0.84 to 0.94, currently in use methods including Entanglement Purification and QNN. The capacity of the proposed method to attain safe key extraction even in the presence of various security constraints is demonstrated by the increase in its success rate by 0.04–0.07. The system achieves a high key extraction success rate due to enhanced error correction and real-time anomaly detection. By leveraging cascade splitting neural networks, the security level remains robust, ensuring accurate key retrieval even under noisy or partially compromised quantum channels, thus maintaining communication confidentiality and reliability.

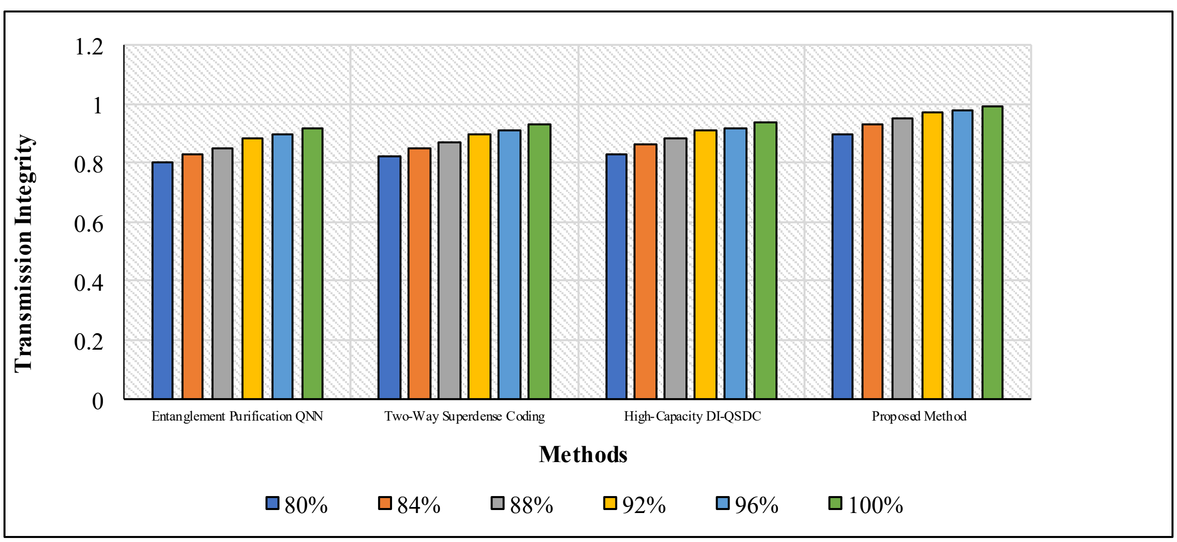

Fig. 6 Key extraction success rate – transmission integrity

Table 25. Key extraction success rate – transmission integrity

Method	80%	84%	88%	92%	96%	100%
Proposed Method	0.90	0.93	0.95	0.97	0.98	0.99
Entanglement Purification and QNN [13]	0.80	0.83	0.85	0.88	0.90	0.92
Two-Way Superdense Coding [15]	0.82	0.85	0.87	0.90	0.91	0.93
High-Capacity DI-QSDC [18]	0.83	0.86	0.88	0.91	0.92	0.94

The proposed method maintained a better key extraction success rate over all transmission integrity levels, at 0.90 at 80% and increasing to 0.99 at 100%. This success rate was constant over the entire process. The rise was driven in part by state monitoring applied with a Cascade Splitting Neural Network. This increase reflects better quantum channel encoding. Among the existing methods, High-Capacity DI-QSDC proved the best with success rates ranging from 0.80 to 0.94. Current method success rates fall between this range. The proposed approach shows to be better in terms of dependability under a range of transmission conditions, with an increase in success rate between 0.06 and 0.09.

7. Conclusion

The proposed Quantum-Assisted Channel Encoding (QAC) with CSNN framework clearly enhanced key performance metrics. Among these criteria were channel capacity, QBER, security resilience, purity, and important extraction success rate. Higher degrees of security and authenticity were obtained using non-symmetric quantum channel encoding and enhanced quantum state generation, even while maintaining a high degree of transmission integrity, by including a Cascade Splitting Neural Network for real-time monitoring, accurate state transmission was ensured, thus lowering QBER and raising channel capacity. An important extraction and validation mechanism helped to increase system security and dependability further. Verifying its stability under various channel and security settings, the proposed approach achieved authenticity and security resilience rates higher than 98% and QBER that was lower than 2%. Experimental results show that the proposed method outperformed existing methods, including Entanglement Purification and QNN, Two-Way Superdense Coding, and High-Capacity DI-QSDC. Moreover, the proposed method was able to increase the success rate of significant extraction; under high-security standards, it attained up to 99%. The applied improvement in transmission integrity highlights even more the capacity of the framework to maintain constant communication even under varying channel conditions. Based on the QAC-CSNN paradigm, a scalable and safe solution is proposed for next-generation quantum communication systems. This construction generates a new benchmark for quantum channel encoding and safe key transmission.

References

[1] Y. Aiache et al., "Optimal Superdense Coding Capacity in the Non-Markovian Regime," *Journal of Physics A: Mathematical and Theoretical*, vol. 57, no. 19, pp. 1-15, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[2] K. Sudharson, and S. Arun, "Security Protocol Function Using Quantum Elliptic Curve Cryptography Algorithm," *Intelligent Automation & Soft Computing*, vol. 34, no. 3, pp. 1769-1784, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[3] Wen-Xin Duan, and Tie-Jun Wang, "Control Power of High-Dimensional Controlled Dense Coding," *Physical Review A*, vol. 105, no. 5, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[4] Qiong Wang, and Zhi He, "Amplifying the Capacity of Quantum Superdense Coding by Non-Hermitian Operations under a Phase Decoherence Source," *Laser Physics*, vol. 34, no. 6, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[5] Partha Sarathi Goswami, Tamal Chakraborty, and Abir Chattopadhyay, *A Nature-Inspired DNA Encoding Technique for the Quantum Session key Exchange Protocol Advances in Nature-Inspired Cyber Security and Resilience*, Cham: Springer, pp. 119-135, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[6] Yan Xia, and He-Shan Song, "Controlled Quantum Secure Direct Communication using a Non-Symmetric Quantum Channel with Quantum Superdense Coding," *Physics Letters A*, vol. 364, no. 2, pp. 117-122, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[7] Syed M. Arslan, Saif Al-Kuwari, and Tasawar Abbas, "Superdense Coding using Bragg Diffracted Hyperentangled Atoms," *IEEE Journal on Selected Areas in Communications*, vol. 42, no. 7, pp. 1950-1959, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[8] Hao-Wen Zhang, Guang-Bao Xu, and Dong-Huan Jiang, "Novel Quantum Voting Protocol for Four-Particle Entangled States Based on Superdense Coding," *Quantum Information Processing*, vol. 24, no. 2, pp. 1-17, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[9] Ram Krishna Patra et al., "Classical Analogue of Quantum Superdense Coding and Communication Advantage of a Single Quantum System," *Quantum*, vol. 8, pp. 1-45, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[10] Seerat Javed, Ansha Tayyab, and Muzzamal I. Shaukat, "Super Dense Coding Out of Thermal Equilibrium," *Physica Scripta*, vol. 99, no. 7, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[11] Mario Mastriani, "Quantum Key Secure Communication Protocol via Enhanced Superdense Coding," *Optical and Quantum Electronics*, vol. 55, no. 1, pp. 1-34, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[12] Teo Kim, Jinsuk Baek, and John T. Yi, "Quantum Authentication Protocol for Secure Quantum Superdense Coding," *SoutheastCon 2024*, Atlanta, GA, USA, pp. 863-864, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[13] Rong Zhang et al., "Capacity Enhancement of n-GHz State Superdense Coding Channels by Purification and Quantum Neural Network," *arXiv preprint*, pp 1-6, 2023. [CrossRef] [Google Scholar] [Publisher Link]
[14] Gokul Srinivasan, Shantom Kumar Borah, and Sainath Bitragunta, "Superdense Coding through Repeaterless Hybrid Network of Depolarizing Quantum Communication Channels," *2021 IEEE International Conference on Electronics, Computing and Communication Technologies (CONECCT)*, Bangalore, India, pp. 1-6, 2021. [CrossRef] [Google Scholar] [Publisher Link]
[15] Kristian S. Jensen et al., "Quantum Two-Way Protocol Beyond Superdense Coding: Joint Transfer of Data and Entanglement," *IEEE Transactions on Quantum Engineering*, vol. 6, pp. 1-8, 2025. [CrossRef] [Google Scholar] [Publisher Link]
[16] Zhi-Hao Liu, and Han-Wu Chen, "Universal and General Quantum Simultaneous Secret Distribution with Dense Coding by Using One-Dimensional High-Level Cluster States," *Journal of Computer Science and Technology*, vol. 36, no. 1, pp. 221-230, 2021. [CrossRef] [Google Scholar] [Publisher Link]
[17] Ke Xing, Ai-Han Yin, and Yong-Qi Xue, "A Quantum Blind Signature Scheme Based on Dense Coding for Non-Entangled States," *Chinese Physics B*, vol. 33, no. 6, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[18] Hui Zeng et al., "High-Capacity Device-Independent Quantum Secure Direct Communication Based on Hyper-Encoding," *Fundamental Research*, vol. 4, no. 4, pp. 851-857, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[19] Hao Yu et al., "Quantum Key Distribution Implemented with D-Level Time-Bin Entangled Photons," *Nature Communications*, vol. 16, no. 1, pp. 1-10, 2025. [CrossRef] [Google Scholar] [Publisher Link]
[20] A.A. Laghari et al., "A Review on Quantum Computing Trends & Future Perspectives," *EAI Endorsed Transactions on Cloud Systems*, vol. 7, no. 22, pp. 1-11, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[21] Dawei Jiaoet al., "Using Small-Dimensional Quantum Error Correction Codes for High-Performance Quantum Communication," *GLOBECOM 2023-2023 IEEE Global Communications Conference*, Kuala Lumpur, Malaysia, pp. 1387-1392, 2023. [CrossRef] [Google Scholar] [Publisher Link]
[22] Qiming Luo et al., "Two Quantum Proxy Blind Signature Schemes Based on Controlled Quantum Teleportation," *Entropy*, vol. 24, no. 10, pp. 1-10, 2022. [CrossRef] [Google Scholar] [Publisher Link]