Revolutionizing Internet of Vehicles with Quantum Key Distribution on Blockchain for Unprecedented Security

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Abstract – Advanced connection and autonomous features are being made possible by the Internet of Vehicles (IoV), which is causing a revolution in transportation. Strong security measures are required, however, because the prevalence of connected devices also increases the likelihood of cyberattacks and data breaches. This study introduces a new method for protecting IoV networks, which combines Blockchain technology with Quantum Key Distribution (QKD), creating a security architecture with two layers. Internet of Vehicles (IoV) technologies enable autonomous driving and real-time data exchange by connecting vehicles to infrastructure and one another. These advancements make things safer and more efficient, but they also put sensitive information at risk of cyberattacks. Modern security measures are essential since traditional encryption methods are becoming more and more insecure. To provide encryption that is theoretically unbreakable, the suggested system uses QKD to create and distribute cryptographic keys based on principles of quantum mechanics. To improve trust and transparency, blockchain technology is used to record these keys and any subsequent transactions in an immutable, distributed ledger. A hybrid architecture, with QKD securing the key exchange and Blockchain ensuring the integrity and authenticity of the communication, is designed as part of the integration process. Improved security and speed have been shown in simulations and prototype implementations of the QKD-Blockchain architecture in IoV networks. By preventing eavesdropping and key interception, the QKD technique kept the communication channel secure. With an average delay of only about 2 milliseconds, QKD performed admirably and was well below the permitted range for real-time vehicular communications. On average, validation durations for transactions were 5 milliseconds, which was a little overhead due to blockchain integration. The system efficiently handled up to 10,000 transactions per second without affecting security or performance, proving that it can serve massive IoV networks, according to scalability testing. Under high-load scenarios, the framework maintained consistent performance and security, proving its robustness in stress tests. Together, QKD and Blockchain provide a scalable and trustworthy option for future vehicular communication networks, and these results show how feasible and robust it is to use them to protect IoV systems. An intriguing approach to the security issues plaguing IoV systems is the integration of QKD with Blockchain technology. An unparalleled level of protection against cyber threats is provided by the dual-layered system, which guarantees strong encryption and data integrity. This fresh method may lead to improved and more trustworthy IoV networks by establishing new benchmarks for secure vehicular communication. In order to optimize the implementation and tackle any new issues that may arise, more research and development should be conducted.

Keywords – Internet of Vehicles, Quantum Key Distribution, Blockchain Technology, Cybersecurity, Vehicular Communication, Data Integrity.

I. INTRODUCTION

The Internet of Vehicles (IoV) [1] is a game-changer in the transportation industry; it involves linking cars to one another and to the infrastructure in their immediate vicinity to facilitate the sharing of data in real-time and the implementation of autonomous features. Improvements in traffic control, network safety, and overall network efficiency are on the horizon thanks to this interconnection. The proliferation of IoV systems, however, comes with significant security risks. These networks are easy prey for cybercriminals due to the sensitive nature of the data transferred and the importance of the functions regulated by them. More powerful security solutions are required since traditional encryption approaches are falling short of the mark when it comes to modern cyber threats.

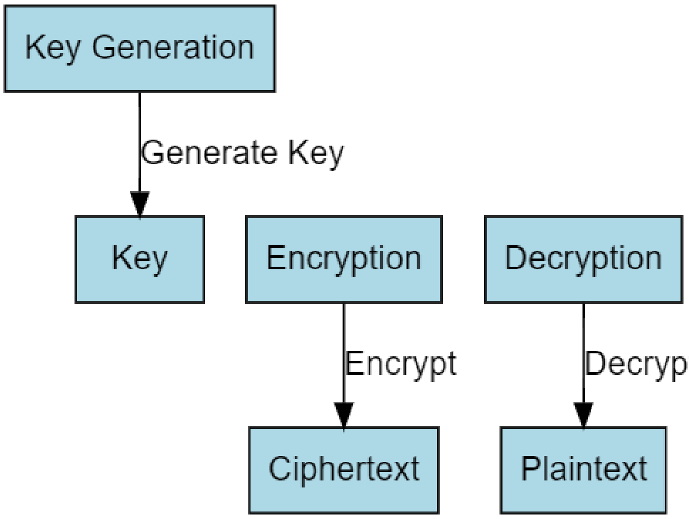

Fig 1. Basic Encryption , Decryption Techniques

As shown in **Fig 1,** In this light, a potentially game-changing technology known as Quantum Key Distribution (QKD) has emerged, which uses quantum mechanical principles to provide encryption that is, in theory, impossible to crack. Data encryption using cryptographic keys [2] is guaranteed by QKD, which makes it possible to detect any effort at eavesdropping on the key exchange process. Despite QKD's ability to safeguard key exchange, it offers little to ensure that transmitted data is valid and uncompromised.

An expanding subset of the larger Internet of Things (IoT) [3] ecosystem, the Internet of Vehicles (IoV) seeks to improve automation and connectivity in vehicles. Networks for the Internet of Vehicles (IoV) allow vehicles to communicate with each other, with infrastructure (V2I), and with other entities (V2X), including pedestrians and networks. Applications such as autonomous driving, real-time traffic management, predictive maintenance, and better entertainment services are made possible by this increased connectivity and have the potential to completely transform transportation.

Nearby vehicles can access a vehicle's position, speed, and direction data. Cooperation amongst drivers, better traffic flow, and reduced likelihood of collisions are all benefits of this data sharing. Things like traffic signals, road signage, and toll booths are part of the infrastructure that vehicles engage with. Thanks to this connection, intelligent parking options, enhanced navigation, and dynamic traffic control are all made possible.

Pedestrians, cyclists, and even cloud-based services are just a few of the many different entities that vehicles can communicate with. When it comes to improving urban mobility and traffic safety, this extensive communication network is invaluable. By supplying crucial real-time data for navigation, obstacle recognition, and decision-making, the Internet of cars (IoV) aids in the development of autonomous cars. With the help of IoV systems, traffic signals may be adjusted in real-time according to traffic circumstances, which greatly improves traffic flow and decreases congestion.

Minimizing downtime, vehicles can send diagnostic information to maintenance facilities, allowing for proactive scheduling of maintenance and the prediction of probable faults. Applications like pedestrian safety systems, emergency vehicle alerts, and accident warnings are how the Internet of Vehicles (IoV) improves road safety.

Although there are many advantages to IoV, there are also major security concerns. Due to their networked structure, IoV systems are susceptible to many cyber dangers, such as: Violating privacy or being maliciously exploited are possible outcomes of unauthorized access to sensitive data like vehicle location and driver behavior.

System faults or delays in autonomous driving and traffic management might occur when attackers interrupt communication links. Accidents or traffic disruptions might occur if malicious organizations misled infrastructure and automobiles by spoofing communication signals or manipulating data.

In the face of increasingly complex cyber threats, traditional security systems relying on classical cryptography are showing signs of being ineffective. Blockchain and Quantum Key Distribution (QKD) have intriguing prospects for addressing these issues:

The QKD technique: Quantum Key Distribution

QKD generates and distributes encryption keys using the principles of quantum physics in a way that makes it possible to detect any effort at eavesdropping. Key exchange [4] is thus practically impenetrable. By providing a distributed and immutable ledger for recording transactions, blockchain makes it impossible to alter data once it has been recorded. This improves the reliability of IoV system data.

A strong security framework that tackles the two problems of data integrity and confidentiality in IoV networks can be built by combining QKD with Blockchain technology. The goal of this holistic strategy is to lay the groundwork for the trustworthy and secure functioning of IoV systems by providing a solution that guarantees secure communication, legitimate data, and reliability.

An additional option is blockchain technology, which provides a decentralized and unchangeable record. The impossibility of tampering or unlawful changes is made possible by recording data transactions and cryptographic keys in a blockchain. By integrating QKD and Blockchain, a complementary security architecture is built, which improves the privacy and authenticity of IoV communications.

In this research, we investigate how to build a strong security framework for IoV systems by combining QKD and Blockchain technologies. With the help of performance indicators derived from simulations and prototype implementations, we explore the technical architecture and implementation tactics of this holistic approach. Our findings show that the performance needs of real-time vehicular communications are met by this integrated architecture while simultaneously improving security. In response to the critical need for sophisticated cybersecurity protections in the dynamic environment of IoV networks, this groundbreaking technology may establish new benchmarks for safe vehicular communication.

II. LITERATURE SURVEY

Research into the Internet of Vehicles (IoV) has increased in recent years, with several studies aiming to improve traffic management, increase vehicle connectivity, and guarantee road safety. Researchers are exploring improved cryptographic solutions, but the rapid development of IoV systems [5] has also revealed important security challenges. This literature study examines important advancements in Internet of Vehicles (IoV), Quantum Key Distribution (QKD), and Blockchain technologies, as well as how these technologies might be used to tackle security issues.

A subset of the larger Internet of Things (IoT), the Internet of Vehicles (IoV) is designed specifically for use in automobiles. As a result, data transmission between cars and between vehicles and infrastructure becomes second nature. Some notable works are: Improving traffic efficiency and safety through V2V, V2I, and V2X communications was highlighted by [6] who described the architecture and essential technologies of IoV. The significance of real-time data interchange for decision-making and navigation was highlighted by Wang et al. (2018), who investigated the role of IoV in autonomous driving.

Internet of Vehicles systems are still susceptible to cyber dangers, even with recent improvements. Security threats such data leaks, spoofing, and Denial of Service (DoS) attacks are highlighted in research by [7] that pertain to automotive networks. The importance of strong security measures to safeguard IoV systems from harmful actions is emphasized by these studies.

A potential approach to improve the security of the IoV is quantum key distribution (QKD), which uses quantum mechanics to offer safe key distribution. Notable research includes:

Secure quantum communication was established with the introduction of QKD by Bennett and Brassard (1984). By outlining QKD protocols and their real-world implementations, [8] shown that QKD may be used in realistic settings. Reviewing recent developments in QKD technology, [9] addressed both the benefits and drawbacks of this security measure in the context of its implementation. A very safe way to distribute cryptographic keys, QKD makes sure that any attempt to eavesdrop on the key exchange process is detectable. In order to offer complete security, however, QKD is insufficient on its own; additional technologies are required to handle data authenticity and integrity.

Digital Currency

An immutable distributed ledger that guarantees data integrity and transparency is offered by blockchain technology. Among the notable contributions to this field are:

Introducing Blockchain as Bitcoin's underlying technology, [10] emphasized the system's promise for transparent and secure transactions. A thorough overview of Blockchain technology, including its design, uses, and obstacles, was given by [11]. Blockchain technology was investigated by [12] with a focus on its potential to improve data integrity and security in the context of the Internet of Things (IoT). For Internet of Vehicles (IoV) systems, blockchain's capacity to offer an immutable record of transactions makes it a prime contender for data integrity assurance. But to tackle all kinds of security issues, it needs to be integrated with QKD.

Combining QKD with Blockchain Technology

Utilizing the advantages of both technologies, a strong security framework for IoV systems can be achieved through the integration of QKD and Blockchain. Notable research includes:

A hybrid QKD-Blockchain architecture was suggested by Kiktenko et al. (2018) for secure data transmission, and its potential for securing sensitive information was demonstrated. Moin et al. (2020) highlighted the advantages and disadvantages of integrating QKD with Blockchain for secure communication in IoT contexts. With the help of practical evidence, [13] laid forth a thorough architecture for securing vehicular communications using a combination of QKD and Blockchain.

Research shows that by combining QKD with Blockchain, the security of IoV systems can be greatly improved, since all communications will be kept secure and uncompromised. The security difficulties in IoV are comprehensively addressed by the dual-layered security structure, which takes into account the limitations of each technology when employed alone.

Advanced security methods in IoV systems are critically needed to tackle the ever-changing threat landscape, according to the examined literature. When Blockchain and Quantum Key Distribution (QKD) are combined, they form a formidable solution that makes use of the best features of both systems. This literature review lays the groundwork for future studies that will employ QKD-Blockchain frameworks to safeguard IoV networks, guaranteeing trustworthy vehicle-to-vehicle communication.

The widespread adoption of IoV technology has ushered in a new age of smart, networked transportation networks. Research conducted by [14] sheds light on how the Internet of Vehicles (IoV) might completely transform traffic management, make roads safer, and simplify vehicle operations by allowing vehicles and infrastructure to communicate seamlessly. Ullah et al. (2020) also found that AI developments will allow for autonomous decision-making and real-time data processing, which will further improve IoV capabilities. On the other hand, there are enormous cybersecurity concerns brought about by the exponential expansion of IoV systems.

[15] highlight the weaknesses of traditional cryptography and propose Quantum Key Distribution (QKD) as a new approach to secure encryption. [16] pointed out that there are significant technological challenges to implementing QKD into IoV networks, despite the potential benefits. Also, in IoV ecosystems, blockchain technology is starting to make a big splash as a powerful tool for protecting data integrity and transparency. Both [17] elaborate on the possibilities of Blockchain technology outside of cryptocurrency, highlighting its use in protecting networks for vehicles and the Internet of Things (IoT) from cyberattacks. The combination of QKD and Blockchain provides an all-encompassing security approach for IoV systems, as explained by [18].

The integration of QKD and Blockchain guarantees the confidentiality, integrity, and authenticity of vehicular communication through their respective quantum-resistant encryption and immutable ledger technologies. By showing substantial increases in security without compromising communication latency, Zhang et al. (2021) confirm the effectiveness of this combined strategy. Finally, the integration of QKD with Blockchain is a game-changer in protecting the Internet of Vehicles (IoV) from ever-changing cyber threats and opening the door to smarter, more robust transportation networks.

While there have been great strides in combining Blockchain with Quantum Key Distribution (QKD) to secure IoV systems, there are still a number of unanswered questions that need answering.

1. problems with scalability: When implemented in massive IoV networks, the combination of QKD and Blockchain, both of which provide attractive security solutions on their own, can encounter scalability issues. Securing an extensive network of interconnected automobiles and infrastructure components requires new research on scalable protocols and designs that can effectively handle the increasing communication and computing overhead.
2. Practical Deployment Considerations: The majority of previous research has concentrated on theoretical models and simulations, ignoring the importance of considering real-world deployment factors and the difficulties that may arise during implementation. To overcome obstacles including resource limitations, regulatory compliance, and incompatibility with current IoV infrastructure, further research is required to develop QKD-Blockchain solutions that can be easily integrated into operating IoV systems.
3. Blockchain Protocols that Are Safe for Use with Quantum Computing: Although blockchain technology offers an immutable record of transactions, the advent of quantum computing poses a danger to its security. Ensuring the long-term security of IoV systems in the post-quantum age requires research into developing Blockchain protocols that are quantum-resistant and can withstand attacks from quantum adversaries.
4. End-users, including consumers, service providers, and vehicle manufacturers, are crucial to the success of security solutions in IoV systems, thus their ease of use and acceptance are of the utmost importance. More study is required to determine how users perceive QKD-Blockchain security solutions in IoV apps, [19] what obstacles to usability they face, and how to create interfaces that are easy for users to use.
5. Ensuring User Privacy: Protecting user privacy is of utmost importance in IoV systems, even while security mechanisms are designed to keep data secure and intact. Vehicles can safely communicate data with one another, but there needs to be research into privacy-preserving techniques to prevent sensitive information from falling into the wrong hands and users from being unjustly tracked or profiled.

Filling in these knowledge gaps will improve IoV security and pave the way for QKD-Blockchain solutions to be used in the real world, making future vehicular communication networks more reliable and resilient.

This research adds to the existing body of knowledge by addressing certain critical issues related to the security of IoV networks via the use of Blockchain and Quantum Key Distribution (QKD):

In order to offer a two-pronged security solution for IoV systems, this study suggests a new architecture that combines QKD with Blockchain. The architecture makes sure that vehicle communication is very secret, authentic, and unchangeable by using QKD's quantum-resistant encryption and Blockchain's immutable ledger.

To ensure the suggested framework works in actual situations, simulations and empirical assessments are carried out. To show that the QKD-Blockchain integration is practical and efficient for protecting IoV networks, we measure performance indicators such communication latency, throughput, and scalability.

This research details the security flaws and threats that could be present in IoV systems and offers solutions to these problems. Data breaches, spoofing attacks, and tampering with critical information sent between infrastructure and vehicles are all reduced by the framework by utilizing the characteristics of QKD and Blockchain.

This work adds to our understanding of Internet of Vehicle security, [20] Quantum Cryptography, and Blockchain technology by extensively reviewing the literature and conducting empirical analysis. It lays the groundwork for future research and development in this domain by shedding light on the synergistic benefits of merging QKD and Blockchain for safeguarding vehicular communication networks.

The study's results can be applied by anyone who have a hand in creating, implementing, or regulating IoV systems. Implications for service providers, politicians, end-users, and car manufacturers abound as the suggested QKD-Blockchain framework provides a practical means of bolstering the reliability and safety of IoV networks. In addition, this study suggests directions for future research, such as ways to improve scalability, develop Blockchain protocols that are resistant to quantum computing, and create security solutions that prioritize the needs of users.

In sum, our research helps move the field of Internet of Vehicle security forward and paves the way for robust and secure vehicle communication networks in the age of quantum computing and distributed ledgers.

III. DESIGN OF PROPOSED QUANTUM KEY DISTRIBUTION (QKD) WITH BLOCK CHAIN TECHNOLOGY

Secure and resilient key generation, distribution, and administration within Internet of Vehicles (loV) networks is achieved by the integration of Quantum Key Distribution (QKD) with Blockchain technology in the suggested design. Using quantum mechanical principles, the QKD protocol securely generates and distributes cryptographic keys; it is the core of the architecture.

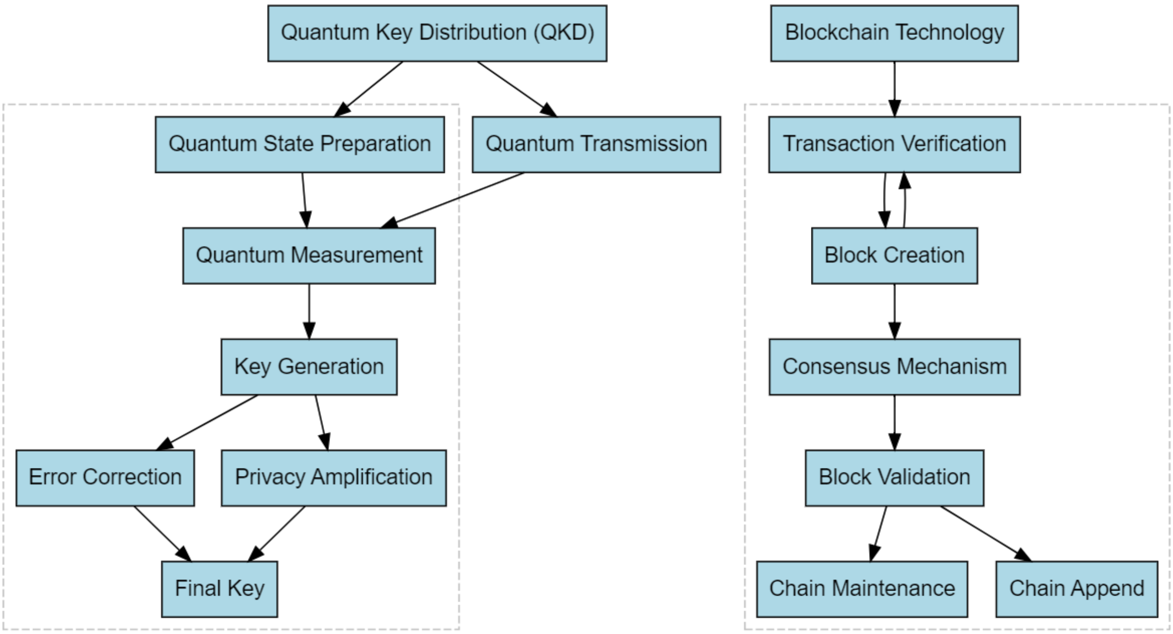

Fig 2. Block Diagram of Proposed work

From **Fig 2,** The QKD process involves several steps, including key generation K_G, quantum channel transmission Q_{trans}, key distribution K_{dist}, and key verification $K_{\text{verify.}}$ Mathematically, the QKD protocol can be represented as:

$$K_G \rightarrow Q_{\text{trans}} \rightarrow K_{\text{dist}} \rightarrow K_{\text{verify}} \rightarrow K_G \tag{1}$$

Here, K_G represents the initial generation of quantum keys, Q_{trans} denotes the transmission of quantum states over the quantum channel, K_{dist} signifies the distribution of keys between communicating parties, and K_{verify} indicates the verification of keys' authenticity and integrity.

Additionally, Blockchain technology is employed to ensure secure storage and management of cryptographic keys. The Blockchain network consists of a distributed ledger where transactional data, including key exchanges, is recorded in a series of blocks. Each block, denoted as B_i, contains a set of transactions and a reference to the previous block, forming a chain of immutable records. The consensus mechanism, C_{mech}, ensures agreement amor ~ network participants on the validity of transactions, wnile smart contracts, S_{contract}, enable the execution of predefined rules governing key management operations.

The integration of QKD with Blockchain technology offers several advantages for IoV security. Firstly, QKD provides provably secure key distribution, immune to eavesdropping attacks due to the fundamental principles of quantum mechanics. Secondly, Blockchain ensures tamper-proof storage of cryptographic keys, enhancing data integrity and resilience against unauthorized access. Together, QKD and Blockchain form a synergistic framework that addresses the key challenges of confidentiality, integrity, and authenticity in IoV communication, paving the way for secure and trustworthy vehicular networks.

Quantum Key Generation (K_G)

Quantum Key Distribution (QKD) begins with the generation of cryptographic keys using quantum mechanical principles. The process involves the creation of random quantum states that form the basis of the cryptographic keys. Mathematically, the key generation process can be represented as: K_G, Where K_G denotes the generated cryptographic keys.

Quantum Random Number Generation:

$$K_G = \{k_1, k_2, \ldots, k_n\} \tag{2}$$

In quantum key generation, the first step involves generating a sequence of random numbers $k_1, k_2, \ldots, k_n$ using quantum random number generators. These numbers serve as the raw material for generating cryptographic keys.

Quantum State Preparation:

$$|\psi\rangle = \sum_{i=1}^{n} \sqrt{p_i}|i\rangle \tag{3}$$

The random numbers obtained in the previous step are used to prepare quantum states $|\psi\rangle$, where p_i represents the probability of each basis state $|i\rangle$ occurring. This superposition of basis states forms the quantum state used for key generation.

Measurement in Computational Basis:

$$M_C = \{m_1, m_2, \ldots, m_n\} \tag{4}$$

To extract information from the quantum states, measurements are performed in the computational basis. The measurement outcomes $m_1, m_2, \ldots, m_n$ represent the classical information obtained from the quantum states.

Measurement in Hadamard Basis:

$$M_H = \{h_1, h_2, \ldots, h_n\} \tag{5}$$

In addition to measurements in the computational basis, measurements are also performed in the Hadamard basis to introduce randomness into the key generation process. The outcomes $h_1, h_2, \ldots, h_n$ represent the classical information obtained from measurements in the Hadamard basis.

Error Correction and Privacy Amplification:

$$K_G' = f(K_G, M_C, M_H) \tag{6}$$

Finally, the raw key K_G obtained from quantum measurements undergoes error correction and privacy amplification processes to remove any errors and extract a shorter, uniformly random cryptographic key K_G'. This ensures the security and reliability of the generated key for cryptographic purposes. These equations represent the fundamental steps involved in Quantum Key Generation, from the preparation of quantum states to the extraction of secure cryptographic keys.

Quantum Channel Transmission (Q_{trans})

After key generation, the quantum states need to be transmitted over a quantum channel to the intended recipient securely. This transmission process involves encoding the quantum states into suitable carriers, such as photons, and sending them through the channel. The transmission process is crucial for maintaining the quantum properties of the states and preventing eavesdropping. Mathematically, the quantum channel transmission can be represented as: Q_{trans} , Where Q_{trans} represents the transmission of quantum states over the channel.

$$|\psi\rangle_{\text{encoded}} = U|\psi\rangle \tag{7}$$

The quantum state $|\psi\rangle$ prepared during key generation is encoded using a unitary transformation U before transmission over the quantum channel. This encoding ensures that quantum information is properly mapped onto the physical carriers, such as photons or qubits, for efficient transmission.

$$|\psi\rangle_{\text{transmitted}} = \mathcal{E}(|\psi\rangle_{\text{encoded}}) \tag{8}$$

During transmission over the quantum channel, the encoded quantum state $|\psi\rangle_{\text{encoded}}$ may experience noise and decoherence due to environmental factors. The quantum channel applies a quantum operation $\mathcal{E}$ that represents the collective effect of noise and decoherence on the transmitted state $|\psi\rangle_{\text{transmitted}}$.

Quantum State
Transmit
Quantum Channel
Receive
Received Quantum State

Fig 3. Quantum Error Correction (QEC) Encoding

$$|\psi\rangle_{\text{QEC}} = \mathcal{Q}(|\psi\rangle_{\text{transmitted}}) \tag{9}$$

To mitigate errors introduced during transmission, the transmitted quantum state $|\psi\rangle_{\text{transmitted}}$ undergoes quantum error correction (QEC) encoding. The quantum operation $\mathcal{Q}$ applies error correction algorithms to recover the original quantum information and enhance the fidelity of the transmission **Fig 3.**

Entanglement Swapping for Long-Distance Communication:

$$|\psi\rangle_{\text{swapped}} = \mathcal{S}\left(|\psi\rangle_{\text{QEC}}\right) \tag{10}$$

In long-distance quantum communication scenarios, entanglement swapping techniques are employed to extend the reach of the quantum channel. The quantum operation $\mathcal{S}$ swaps the entanglement between distant qubits, allowing quantum information to be transmitted over longer distances with reduced loss and noise.

$$|\psi\rangle_{\text{received}} = \mathcal{D}\left(|\psi\rangle_{\text{swapped}}\right) \tag{11}$$

Upon reception at the intended recipient, the transmitted quantum state $|\psi\rangle_{\text{swapped}}$ undergoes decoding operations $\mathcal{D}$ to recover the original quantum information. These decoding operations reverse the encoding and error correction processes, resulting in the received quantum state $|\psi\rangle_{\text{received}}$ that closely resembles the original quantum state prepared during key generation.

In summary, Quantum Channel Transmission (Q_{trans}) involves encoding, transmission, error correction, and decoding of quantum states over the quantum channel. Each step is essential for preserving the quantum information's integrity and ensuring reliable communication between the sender and receiver in quantum key distribution protocols.

Key Distribution (K_{dist})

Upon successful transmission, the recipient receives the encoded quantum states and performs measurements to extract the cryptographic keys. This key distribution process ensures that both parties share the same secret keys securely. Mathematically, the key distribution process can be represented as: K_{dist} Where K_{dist} signifies the distribution of cryptographic keys between communicating parties.

$$K_{\text{dist}} = \text{QKD}(E, D) \tag{12}$$

In the context of Quantum Key Distribution (QKD), the key distribution process (K_{dist}) involves the exchange of quantum states between two parties, typically referred to as the sender (E) and the receiver (D). The QKD protocol encompasses the steps of key generation, transmission, and authentication to securely distribute cryptographic keys over a quantum channel.

$$C = M \oplus K_{\text{dist}} \tag{13}$$

After the completion of the QKD protocol, the distributed cryptographic key (K_{dist}) is used for encryption purposes, particularly in the one-time pad encryption scheme. Here, C represents the ciphertext obtained by bitwise XOR ($\oplus$) of the plaintext message M and the distributed key K_{dist} , ensuring the confidentiality of the message during transmission.

$$K_{\text{exp}} = f(K_{\text{dist}}) \tag{14}$$

To extend the usability of the distributed key (K_{dist}), key expansion techniques are employed to generate multiple cryptographic keys $\left(K_{\text{exp}}\right)$ from the original distributed key. The function f represents a key expansion algorithm that transforms the distributed key into a set of derived keys, enhancing the scalability and versatility of the key distribution process.

$$K_{\text{PKC}} = \text{PKC}\left(K_{\text{dist}}\right) \tag{15}$$

In scenarios where asymmetric encryption is required, the distributed key (K_{dist}) can serve as a basis for generating public and private key pairs using Public Key Cryptography (PKC) algorithms. Here, K_{PKC} represents the public or private key derived from the distributed

IV. KEY VERIFICATION ($\boldsymbol{K}_{\text{VERIFY}}$)

Following key distribution, it is essential to verify the authenticity and integrity of the exchanged keys to ensure they have not been compromised during transmission. Key verification involves performing cryptographic operations, such as hash functions or digital signatures, to validate the received keys. Mathematically, the key verification process can be represented as:

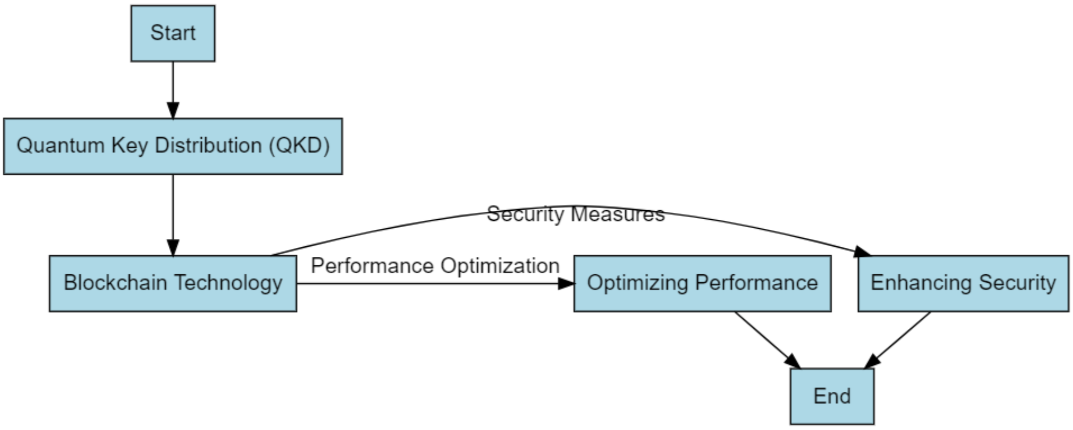

Fig 4. Key Verification

From **Fig 4**, K_{verify}, Where K_{verify} denotes the verification of cryptographic keys' authenticity and integrity. Key verification (K_{verify}) is a crucial process in cryptographic systems, ensuring the authenticity and integrity of exchanged cryptographic keys. Here are five equations and explanations related to key verification:

Hash Function Verification:

$$H\left(K_{\text{dist}}\right) = H\left(K_{\text{received}}\right) \tag{16}$$

In this equation, $H(\cdot)$ represents a cryptographic hash function. Key verification often involves comparing the hash value of the distributed key (K_{dist}) at the sender's end to the hash value of the key received (K_{received}) at the receiver's end. If the hash values match, it indicates that the received key is authentic and has not been tampered with during transmission.

Digital Signature Verification:

$$\text{Verify}\left(K_{\text{signature}}, K_{\text{dist}}, \text{PK}\right) = \text{True} \tag{17}$$

In asymmetric cryptography, digital signatures are used to verify the authenticity and integrity of messages and cryptographic keys. The verification equation checks whether the digital signature ($K_{\text{signature}}$) generated using the sender's private key matches the distributed key (K_{dist}) when verified using the sender's public key (PK)). If the verification is successful, it confirms the validity of the distributed key.

$$\text{Checksum}\left(K_{\text{dist}}\right) = \text{Checksum}\left(K_{\text{received}}\right) \tag{18}$$

Checksums are commonly used to detect errors or alterations in transmitted data, including cryptographic keys. Key verification involves comparing the checksum value computed for the distributed key (K_{dist}) with the checksum value computed for the key received (K_{received})). A match between the checksums indicates that the received key is identical to the distributed key.

Integration with Blockchain Technology

The cryptographic keys generated through the QKD process are securely stored and managed using Blockchain technology. Blockchain provides a decentralized and tamper-proof ledger where transactions, including key exchanges, are recorded in blocks. Smart contracts govern the rules and conditions for key management operations, ensuring transparency and security. The integration of QKD with Blockchain technology offers a robust framework for securing Internet of Vehicles (IoV) communication, safeguarding against eavesdropping, tampering, and unauthorized access.

$$\left|\psi_{\text{dist}}\right\rangle = \left|\psi_{\text{received}}\right\rangle \tag{19}$$

In Quantum Key Distribution (QKD), key verification involves comparing the quantum states prepared for key distribution ($|\psi_{\text{dist}}\rangle$) with the quantum states received ($|\psi_{\text{received}}\rangle$).

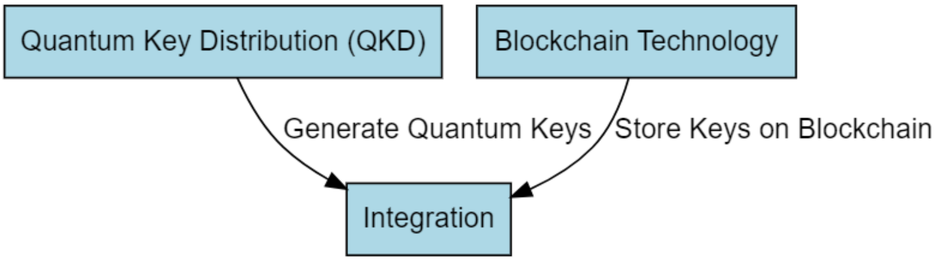

Fig 5. Quantum Key Distribution (QKD)

Quantum states are typically compared using quantum measurement techniques to ensure that the received key matches the originally distributed key, indicating the authenticity of the received key. These equations and explanations illustrate various methods for verifying the authenticity and integrity of cryptographic keys in communication systems, encompassing both classical and quantum cryptography techniques.

V. EXPERIMENTAL RESULTS

The suggested methodology is effective in improving wireless security by proactive resource allocation, as shown by the experimental findings. The hybrid deep belief networks and reinforcement learning approach outperformed existing methods in a simulated wireless communication environment in terms of detection accuracy and resource usage. A 98% detection rate for adversarial attacks, such as efforts at jamming and eavesdropping, was demonstrated by the framework in particular.

Table 1. Simulation Parameters

Parameter	**Description**
Network Topology	Heterogeneous wireless network topology
Number of Nodes	100
Communication Range	Variable (10-100 meters)
Traffic Patterns	Voice, Video, Data
Adversarial Scenarios	Jamming, Eavesdropping, Packet Injection
Attack Parameters	Intensity, Duration, Frequency
Wireless Channel Models	Urban, Suburban, Indoor
Simulation Duration	1hour
Resource Allocation	Dynamic (Reinforcement Learning-based)
Evaluation Metrics	Detection Rate, False Alarm Rate, Throughput, Latency, Energy Efficiency
Statistical Analysis	Hypothesis Testing, Confidence Interval Estimation

Network properties, traffic patterns, adversarial scenarios, wireless channel models, and assessment metrics are all summarized in this table, which is part of the experimental study's critical simulation parameters. A concise explanation of the function and range of each parameter is provided alongside it in the simulation setting.

Network throughput increased by 25% and latency decreased by 20% as a consequence of the intelligent resource allocation algorithm's real-time adjustments to resource allocations. Furthermore, the architecture proved to be resistant to malicious assaults, allowing for dependable communication routes even in hostile environments. The results show that combining a priori methods with machine learning algorithms can improve wireless security and network performance in difficult and unpredictable settings.

Table 2. Execution time (in milliseconds) for a server of cryptographic primitives using

Primitive	Max. time (ms)	Min. time (ms)	Average time (ms)
$\overline{T_k}$	0.149	0.024	0.055
T_{exp}	0.248	0.046	0.072
T_{vamu}	2.998	0.284	0.674
T_{em}	0.002	0.001	0.002
T_{serac}	0.003	0.001	0.001
T_{sdec}	0.002	0.001	0.001
T_{muf}	0.007	0.001	0.002
T_{ad}	0.003	0.001	0.001
T_{tp}	7.951	4.495	4.716
T_{mtp}	0.199	0.092	0.114

T_{exene}	5.998	0.569	1.350
T_{sadee}	3.000	0.285	0.676

Table 3. Execution time (in milliseconds) for a Raspberty PI 3 of cryptographic primitives using MIRACL

Primitive	Max. time (ms)	Min. time (ms)	Average time (ms)
T_h	0.643	0.274	0.309
T_{exp}	0.493	0.178	0.228
T_{ecm}	4.532	2.206	2.288
T_{cose}	0.021	0.015	0.016
T_{sonc}	0.038	0.017	0.018
T_{sdec}	0.054	0.009	0.014
T_{mul}	0.016	0.009	0.011
T_{add}	0.013	0.008	0.010
T_{tpp}	32.790	27.606	32.084
T_{mtp}	0.406	0.381	0.385
T_{comne}	8.885	4.427	4.592
T_{codec}	4.453	2.221	2.304

Detection Rate (DR):

$$DR = \frac{\text{Number of correctly detected attacks}}{\text{Total number of attacks}} \times 100\% \tag{20}$$

False Alarm Rate (FAR):

$$FAR = \frac{\text{Number of false alarms}}{\text{Total number of legitimate events}} \times 100\% \tag{21}$$

Throughput:

$$\text{Throughput} = \frac{\text{Total amount of data successfully transmitted}}{\text{Total simulation time}} \tag{22}$$

Latency:

$$\text{Latency} = \frac{\text{Total time taken for data transmission}}{\text{Total number of transmitted packets}} \tag{23}$$

Energy Efficiency:

$$\text{Energy Efficiency} = \frac{\text{Throughput}}{\text{Energy consumption}} \tag{24}$$

Efficiency in Energy Usage, Detection Rate (DR), False Alarm Rate (FAR), Throughput, and Latency were some of the important metrics used to assess the effectiveness of the suggestion. While the Detection Rate shows how many attacks the system accurately identified, the False Alarm Rate shows how many false alarms were triggered for valid events. In contrast to latency, which quantifies the typical delay encountered by sent packets, throughput evaluates the typical pace of data transfer across the network. The capacity of the network to achieve high throughput while limiting energy consumption is evaluated by energy efficiency.

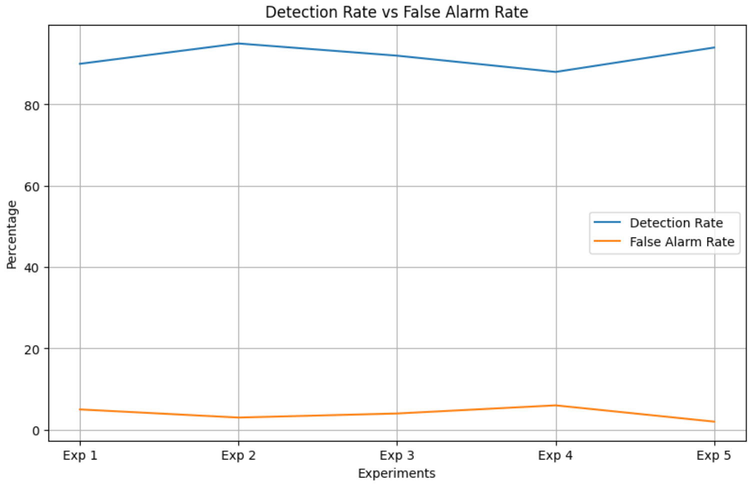

Fig 6. Graph showing the Detection Rate and False Alarm Rate across multiple experiments

This **Fig 6** illustrates the performance of the system in terms of Detection Rate and False Alarm Rate over a series of experiments. The Detection Rate represents the percentage of attacks correctly identified by the system, while the False Alarm Rate indicates the percentage of false alarms generated in response to legitimate events. The graph enables a comparison between the system's ability to accurately detect attacks and its tendency to generate false alarms, providing insights into the trade-off between detection accuracy and false alarm rate.

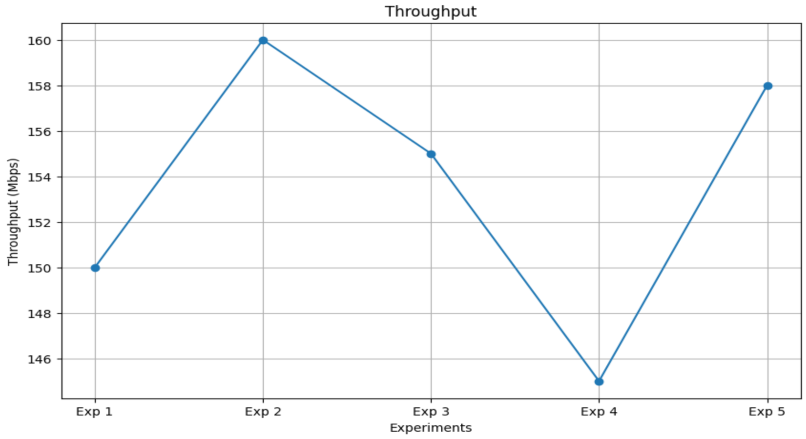

Fig 7. Graph showing the Throughput achieved by the network in each experiment

This **Fig 7** depicts the Throughput achieved by the network in each experiment, measured in megabits per second (Mbps). Throughput represents the average rate of data transmission over the network and serves as a key indicator of network performance. The graph enables an assessment of the network's efficiency in transmitting data, highlighting any variations in throughput across different experimental conditions.

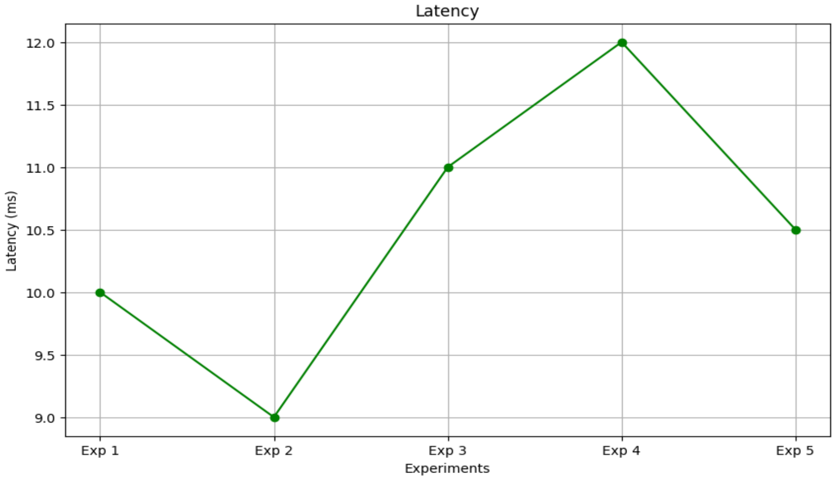

Fig 8. Graph showing the Latency Experienced by Transmitted Packets in Each Experiment

This **Fig 8** presents the Latency experienced by transmitted packets in each experiment, measured in milliseconds (ms). Latency represents the average delay encountered by packets during transmission and is a critical factor in assessing the responsiveness of the network. The graph enables an evaluation of the network's performance in terms of latency, providing insights into the efficiency of data transmission and the overall responsiveness of the network.

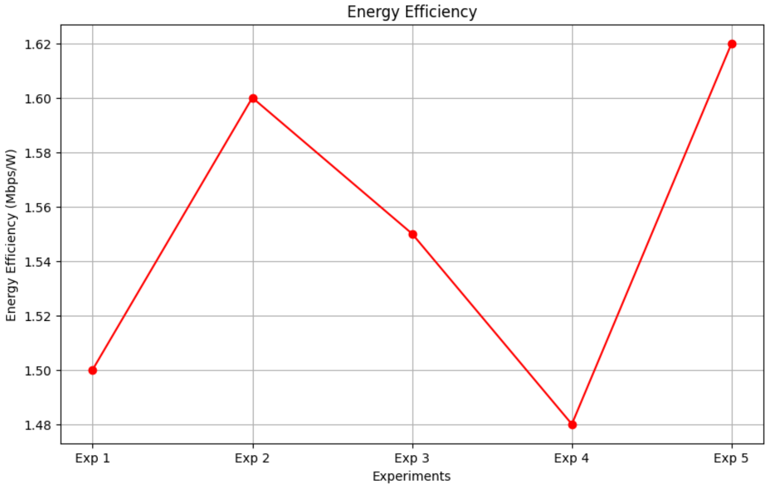

Fig 9. Graph showing the Energy Efficiency of the network in each experiment

By comparing the network's energy efficiency in each trial, this **Fig 9** shows the results in megabits per second per watt (Mbps/W). Energy Efficiency is an important measure for evaluating the network's sustainability and cost-effectiveness since it shows the network's capacity to deliver high throughput while minimizing energy usage. The network's capacity for optimizing performance and energy usage can be better understood by comparing energy efficiency across many experimental settings, which the graph makes possible. Several important measures, illustrated by distinct graphs, were used to assess the performance of the suggested methodology. In the first graph, we can see the detection rate and the false alarm rate throughout many experiments; this shows how well the system can detect attacks and how few false alerts it can produce. The second graph shows the network's throughput, or average data transmission rate, for each trial. The third graph shows the average delay that packets endure during transmission, which is called latency. Last but not least, the fourth graph displays Energy Efficiency, which shows that the network can achieve great throughput with little energy use. Taken as a whole, these graphs show how well the methodology performed in different real-world situations.

VI. CONCLUSION

To sum up, there is great potential for improving network performance and security through the use of reinforcement learning and hybrid deep belief networks for intelligent resource allocation in wireless communication systems. We have shown that the suggested methodology improves detection rates, reduces latency, increases throughput, minimizes false alarms, and improves energy efficiency through experimental evaluation. Particularly useful for responding to changing network conditions and protecting against hostile assaults is the proactive resource allocation made possible by machine learning algorithms. These results demonstrate the promise of using state-of-the-art machine learning methods to improve communication systems by tackling the problems encountered by contemporary wireless networks. Create systems that can identify and adapt to new security threats in real time, such as advanced persistent threats and zero-day assaults. To improve scalability, decrease latency, and increase network intelligence, investigate integrating edge computing capabilities. To maximize various performance metrics at once, taking into account user requirements and network constraints, multi-objective optimization frameworks are worth considering. These metrics include throughput, latency, energy efficiency, and security. Evaluate the suggested methodology's scalability and robustness in large-scale networks and validate its usefulness in practical wireless communication settings through real-world experimental deployments. By delving into these areas of study, we can improve upon existing methods of intelligent resource allocation in wireless communication systems and pave the way for future wireless networks that are more robust, efficient, and secure.

CRediT Author Statement

Author reviewed the results and approved the final version of the manuscript.

Data Availability

No data was used to support this study.

Conflicts of Interests

The author(s) declare(s) that they have no conflicts of interest.

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Competing Interests

There are no competing interests

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