Quantum Cryptography for Enhanced Cyber Security – A Review

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ABSTRACT

The increasing apprehension regarding internet security has led to the emergence of quantum cryptography as a potentially effective approach for improving the security of networking systems. This study reviews and categorises 20 significant papers from prominent conferences and journals, focussing on diverse aspects of quantum cryptography. The areas of emphasis include key distribution, quantum bit commitment, post-quantum cryptography, and counterfactual quantum key distribution. This study investigates the underlying motivations and obstacles associated with the implementation of quantum cryptography, focussing on security and privacy issues, as well as the current solutions available in the field. The discourse highlights the importance of secure key distribution as an essential element in maintaining the confidentiality and integrity of information transmitted across a network. This study investigates the capabilities of quantum cryptography in facilitating secure key exchange among parties, particularly in scenarios involving eavesdropping, as well as exploring additional applications of quantum cryptography. Furthermore, the manuscript examines the methodologies, results, and constraints of each study under review, identifying trends such as the heightened emphasis on the practical application of quantum cryptography protocols and the rising interest in research pertaining to post-quantum cryptography. Additionally, the survey highlights various challenges and unresolved research enquiries, such as the necessity for enhanced quantum repeater networks, the refinement of security proofs for continuous variable quantum key distribution, and the advancement of quantum-resistant cryptographic algorithms.

Keywords: Quantum Cryptography, Network Security, Quantum Key Distribution

INTRODUCTION

The advent of quantum computing presents a complex landscape characterised by both significant challenges and promising opportunities within the field of cryptography. Quantum computers possess the capability to transform multiple sectors by addressing intricate challenges; nonetheless, they also pose a considerable risk to the security of current cryptographic frameworks [1]. As a result, there has been a significant shift towards the application of quantum cryptography, which leverages the principles of quantum mechanics to establish communication systems that are resilient against both classical and quantum threats. Quantum key distribution (QKD) represents a sophisticated cryptographic methodology that facilitates the secure exchange of encryption keys between two parties via a public channel [2]. Quantum Key Distribution (QKD) protocols leverage the intrinsic characteristics of quantum mechanics, including superposition, entanglement, and the no-cloning theorem, to guarantee the detection of any eavesdropping attempts, thereby offering information-theoretic security [3]. Unlike traditional cryptographic methods that depend on the computational complexity of specific mathematical challenges, quantum key distribution ensures security, even in the presence of adversaries possessing infinite computational capabilities [4]. Throughout the years, quantum key distribution (QKD) has attracted considerable interest from both scholarly and industrial sectors, resulting in the formulation of numerous QKD protocols, including BB84, E91, and continuous variable QKD. The protocols have undergone significant investigation, with considerable focus on enhancing their efficiency, security, and relevance to practical communication networks [7]. A significant focus of investigation within the field of quantum cryptography has been the advancement and refinement of quantum key distribution protocols. Various approaches have been examined to optimise key rates, minimise the quantum bit error rate, and extend the distance over which secure communication is feasible [8]. The advancements in this field have resulted in the introduction of novel protocols, including measurement-device-independent quantum key distribution (MDI-QKD) [9] and twin-field quantum key distribution (TF-QKD) [10], which demonstrate enhanced performance and resilience against a range of attack vectors. Alongside the advancement of novel protocols, there has been a concentrated effort to identify and address potential security vulnerabilities within current QKD protocols [11]. Instances of photon-number-splitting attacks and detector blinding attacks have demonstrated their potential to undermine the security of various quantum key distribution implementations. A range of countermeasures has been proposed and implemented to mitigate these vulnerabilities, including the decoy-state method [12] and the application of secure detectors [13]. Another important element of quantum cryptography investigation is the incorporation of quantum key distribution into current communication infrastructures. One strategy involves the integration of quantum key distribution into optical networks, which constitute the fundamental framework of contemporary communication infrastructure [14]. A number of studies have explored the potential for implementing quantum key distribution (QKD) within wavelength-division multiplexing (WDM) networks and passive optical networks (PONs) [15]. The findings indicate that quantum key distribution (QKD) has the capability to improve the security of optical networks while maintaining their performance levels. The incorporation of Quantum Key Distribution (QKD) into optical networks has resulted in the emergence of innovative service models, including Key-as-a-Service (KaaS) [8]. KaaS facilitates secure key distribution within virtual optical networks (VONs) through the integration of quantum key distribution (QKD) into the foundational optical infrastructure. The provision of security as a service by KaaS facilitates the straightforward deployment of QKD-based security solutions by network operators within their existing infrastructures, which may lead to the broader acceptance of quantum cryptography. Furthermore, with the advancement of quantum computing technology, it is essential to investigate cryptographic methods that can endure the potential risks introduced by quantum computers. The emergence of post-quantum cryptography has been driven by the need to develop cryptographic algorithms that maintain their security in the face of quantum adversaries [16, 17]. Lattice-based cryptography, code-based cryptography, and isogeny-based cryptography represent some of the most promising techniques currently under investigation in the realm of post-quantum cryptography [18]. Quantum cryptography has demonstrated significant potential for improving network security; however, numerous challenges and unresolved research questions persist that require further investigation. The establishment of efficient quantum repeater networks is crucial for extending the range of quantum key distribution systems [19]. Enhanced security proofs for continuous variable quantum key distribution and related protocols are essential to guarantee their resilience against possible attacks [6, 7]. Moreover, the practical application of quantum cryptography systems, encompassing aspects such as miniaturisation, cost reduction, and compatibility with existing infrastructure, represents a significant focus of current research efforts [20].

RELATED WORK

This literature review examines the progress and obstacles present in the domain of quantum cryptography, with particular emphasis on quantum key distribution (QKD), post-quantum cryptography, and the incorporation of QKD into optical networks. A total of 20 papers, in addition to other pertinent works, were chosen from prominent conferences and journals, encompassing Quantum Key Distribution (QKD) Protocols.

Quantum Key Distribution (QKD) protocols have undergone rigorous examination to facilitate secure key exchange between two entities. The foundational BB84 protocol, proposed by Bennett and Brassard [2], represents one of the earliest and most extensively examined quantum key distribution protocols. Further investigations resulted in the formulation of additional quantum key distribution protocols, including the E91 protocol [5] and continuous variable quantum key distribution [6]. Each protocol utilises the distinct characteristics of quantum mechanics to ensure information-theoretic security [3]. Nurhadi and Syambas [21] present a comprehensive examination of multiple quantum key distribution protocols, such as BB84, E91, BBM92, B92, the Six-State Protocol, DPS, SARG04, COW, and S13. The researchers subsequently perform simulations of three specific protocols: BB84, B92, and BBM92, utilising a quantum simulator for their analysis. The findings indicate that the B92 protocol exhibits the lowest probability of error, whereas the BB84 protocol demonstrates the highest probability of error. Kalra and Poonia [22] introduce a novel protocol that represents a modification of the BB84 protocol, demonstrating that it exhibits double the capacity relative to the original BB84 protocol, while also achieving nearly half the error rate. The proposed protocol employs random bases for modulation and encoding, utilising random bits as its foundation, whereby both the sender and the receiver obtain two keys. Sasaki et al. [23] introduce a quantum key distribution protocol that employs a single-photon source to produce a series of pulses, with each pulse containing either one or zero photons, which are transmitted to a receiver. The protocol's security is fundamentally based on the principles of quantum mechanics, along with the premise that any attempt at measurement or interference by an eavesdropper is detectable. Dirks et al. [24] investigate the technical feasibility of a Geostationary Earth Orbit Quantum Key Distribution (GEOQKD) system that integrates untrusted and trusted mode BBM92 protocols. Their findings indicate a maximum tolerable loss of 41dB per channel, with key rates of 1.1bit/s in untrusted mode and 300bit/s in trusted mode. This research presents a feasible design for the space segment and outlines a system architecture that enables the GEOQKD system to function effectively in both untrusted and trusted modes, achieving high pointing accuracies. In their study, Williams et al. [25] introduce a quantum key distribution protocol that employs time-bin encoding utilising entangled photon pairs to facilitate secure communication. The protocol was executed within a practical framework and subjected to testing to validate its time synchronisation and eavesdropper detection functionalities. Schimpf et al. [26] examined a study focused on the utilisation of a blinking-free source of polarization-entangled photon pairs derived from a GaAs quantum dot for quantum key distribution (QKD). This research investigates the issue of entanglement degradation at elevated temperatures and suggests operating the source at a minimum temperature of 20 K, alongside employing a pulsed two-photon-excitation scheme to preserve fidelity to the Bell state. Amer et al. [27] conducted a study examining the performance of quantum repeater QKD grid networks, specifically focussing on the impact of incorporating a minority of trusted nodes. The examination further reveals constraints within these networks, especially concerning the success probability of BSM and the rate of decoherence, and proposes the incorporation of trusted nodes, even in the presence of optimal repeater technology. Ding et al. [28] introduced an innovative methodology aimed at optimising the parameters of practical quantum key distribution (QKD) systems through the application of the random forest (RF) algorithm. The proposed method demonstrates significant potential for application within practical quantum key distribution networks and plays a crucial role in advancing the field of quantum communication technologies. Dhoha et al. [29] conducted a comprehensive literature review focussing on quantum key distribution (QKD) and quantum bit commitment (QBC) protocols. This paper examines the practical implementation of the BB84 quantum key distribution protocol, considering scenarios both in the presence and absence of an eavesdropper. The results indicate that BB84 serves as an efficient quantum key distribution protocol. Yao et al. [30] examine the application of quantum random number generators (QRNGs) and quantum key distribution (QKD) protocols within the field of cryptography, offering a theoretical assessment of their security grounded in entropic uncertainty relations. The authors employ Theorem II.1 to demonstrate that by selecting appropriate classical sampling strategies, it is possible to examine the behaviour of ideal states that consistently conform to the specified strategy, and that the actual state is closely approximated, in terms of trace distance, to these ideal states.

Post-Quantum Cryptography:

Mujdei et al. [31] conducted an investigation into side-channel attacks targeting the post-quantum cryptographic schemes Kyber, Sabre, and NTRU. The researchers introduced a novel attack strategy and provided evidence of its efficacy in overcoming countermeasures such as randomisation techniques. This research underscores the significance of incorporating considerations for side-channel attacks within the design and implementation of post-quantum cryptography. Imana et al. [32] introduced two optimised architectures for executing arithmetic operations within the framework of InvBRLWE-based encryption, resulting in enhancements in area-time complexities and power efficiency. The authors conducted a theoretical analysis and implemented a solution based on FPGA, demonstrating its potential applicability in cryptoprocessor applications utilising BRLWE/InvBRLWE. Prakasan et al. [33] examined security challenges within the classical channel of Quantum Key Distribution (QKD) by introducing an authenticated-encryption scheme that utilises NTRU and Falcon algorithms. The proposed scheme improves security while maintaining performance levels, presenting a feasible approach to address concerns related to QKD security. Sajimon et al. [34] conducted an evaluation of post-quantum cryptography algorithms specifically for Internet of Things devices, identifying Kyber, Sabre, Dilithium, and Falcon as the most effective implementations. The research findings additionally suggested the utilisation of LightSaber-KEM and Dilithium2 to enhance quantum resistance. The methodology employed in this study utilised the Raspberry Pi 4 to conduct performance evaluations, with the potential for extension to the assessment of quantum-resistant TLS and DTLS protocols in the context of IoT.

Examination of Security Challenges and Mitigation Strategies:

Abidin et al. [35] examined the application of quantum cryptography and quantum key distribution (QKD) within the DARPA Quantum Network to facilitate secure virtual private network (VPN) communication. The research detailed the protocols and algorithms associated with quantum key distribution (QKD) and examined their implementation in conjunction with IPsec. The article emphasises the potential of quantum cryptography in enhancing cybersecurity measures and tackling issues related to internet security. Kumar et al. [36] conducted an investigation into multiple post-quantum cryptographic methodologies aimed at enhancing the security of IoT networks. This study analysed contemporary research within this domain and determined that the development of lightweight and secure post-quantum cryptography tailored for small devices is anticipated to occur in the foreseeable future. Ahn et al. [37] conducted an analysis of the potential implications of quantum computing on distributed energy resource (DER) networks, proposing the implementation of post-quantum cryptography (PQC) and quantum key distribution (QKD) as protective measures. The investigation proposed examining the ideal cost and network configuration to achieve both cost-effectiveness and high performance in quantum-safe networks within distributed energy resource systems. Gupta et al. [38] investigated the application of blockchain technology within e-voting systems and put forth a double-layered security framework that incorporates a QKD algorithm to ensure secure communication. This investigation underscores the possibilities for subsequent enquiries into blockchain technology in conjunction with quantum computing countermeasures. Lin et al. [39] conducted an analysis of security vulnerabilities in CV-QKD and suggested enhancements to the current protocols. The investigation indicated the necessity for additional research aimed at formulating security proofs that take into account collective attacks as well as practical source and channel loss. Cao et al. [40] introduced a KaaS framework aimed at the integration of quantum key distribution (QKD) within optical networks, thereby improving their security measures. The performance evaluation indicated the framework's viability as an effective approach for integrating quantum key distribution within optical networks. Su et al. [41] provided a straightforward information-theoretic demonstration of the security associated with the BB84 QKD protocol. The results present a definitive and unambiguous demonstration of security, contributing novel perspectives on security challenges within the realm of quantum key distribution.

Quantum Key Distribution

Quantum Key Distribution (QKD) represents a sophisticated approach to secure communication, leveraging the principles of quantum mechanics to facilitate the distribution of cryptographic keys between two entities. The fundamental concept posits that the measurement of a quantum system induces a disturbance that can be detected, thereby ensuring that any eavesdropper attempting to intercept the key would inevitably leave a discernible trace. Alice and Bob establish a shared key through the exchange of quantum states, specifically utilising photons, and by employing a specific measurement methodology. Through the comparison of their measurements, it is possible to identify any instances of attempted eavesdropping, thereby allowing the utilisation of the remaining key bits to create a secret key for the purposes of encrypting and decrypting messages. Quantum Key Distribution (QKD) provides an unparalleled level of secrecy, ensuring that the encrypted message remains impervious to interception by eavesdroppers. However, it is important to note that QKD is constrained by limitations regarding the distance over which it can operate effectively and the speed of communication it can achieve.

Motivation and Challenges

The rising reliance on digital technologies has resulted in an escalating need for cryptographic protocols that ensure security and preserve privacy. Quantum cryptography has surfaced as a viable approach to tackle these challenges, especially within the domain of cryptocurrency. The field of quantum cryptocurrency encompasses the implementation of quantum cryptography protocols, which are designed to ensure secure transactions that can withstand potential threats posed by quantum computing technology. Nevertheless, the execution of these protocols presents various challenges, necessitating a thorough examination of security and privacy concerns. The implementation of quantum cryptocurrency faces significant challenges, particularly in the advancement of secure quantum key distribution (QKD) protocols. Quantum Key Distribution (QKD) protocols offer a robust mechanism for the generation of shared secret keys between two entities, which can subsequently be utilised in various cryptographic applications. A number of quantum key distribution protocols have been introduced, such as BB84, E91, and B92. Nonetheless, these protocols exhibit susceptibility to assaults from quantum computing systems, indicating a necessity for the advancement of more resilient protocols. One additional challenge in the implementation of quantum cryptocurrency involves the advancement of post-quantum cryptographic algorithms. Post-quantum cryptography encompasses cryptographic algorithms designed to withstand attacks from both classical and quantum computational systems. Although numerous post-quantum cryptographic algorithms have been introduced, including lattice-based, code-based, and hash-based cryptography, their adoption remains limited. Further investigation is required to validate their security and efficiency.

The implementation of quantum cryptocurrency necessitates a thorough examination of security and privacy concerns. The potential for quantum hacking represents a significant security concern within the realm of quantum cryptocurrency. Quantum hacking entails the interception and manipulation of qubits utilised in quantum cryptography protocols, potentially undermining the security of the system. A variety of countermeasures have been suggested to mitigate the risks associated with quantum hacking, including decoy state techniques and protocols based on entanglement for quantum key distribution. Privacy represents a significant factor in the realm of quantum cryptocurrency. Although quantum cryptography protocols offer a significant level of security, it is important to note that they do not inherently guarantee privacy. In quantum key distribution protocols, the confidentiality of the communication is contingent upon the capacity of the two parties to maintain the security of the secret key. In the event that the system of one party is compromised, it follows that the privacy of the communication may also be at risk. Proposed resolutions to these challenges encompass privacy amplification protocols and quantum coin flipping protocols. A number of scholarly articles have been released concerning the subject of quantum cryptocurrency, suggesting diverse approaches to address the challenges and issues outlined previously. The overview presented in Table 1 summarises the reviewed papers within this survey, detailing their focus, methodology, findings, and limitations. The articles encompass a variety of subjects, such as quantum key distribution, post-quantum cryptography, counterfactual quantum key distribution, and key management strategies. The survey seeks to deliver an in-depth examination of the existing landscape of research in quantum cryptocurrency, while also pinpointing significant challenges and prospective avenues for future inquiry.

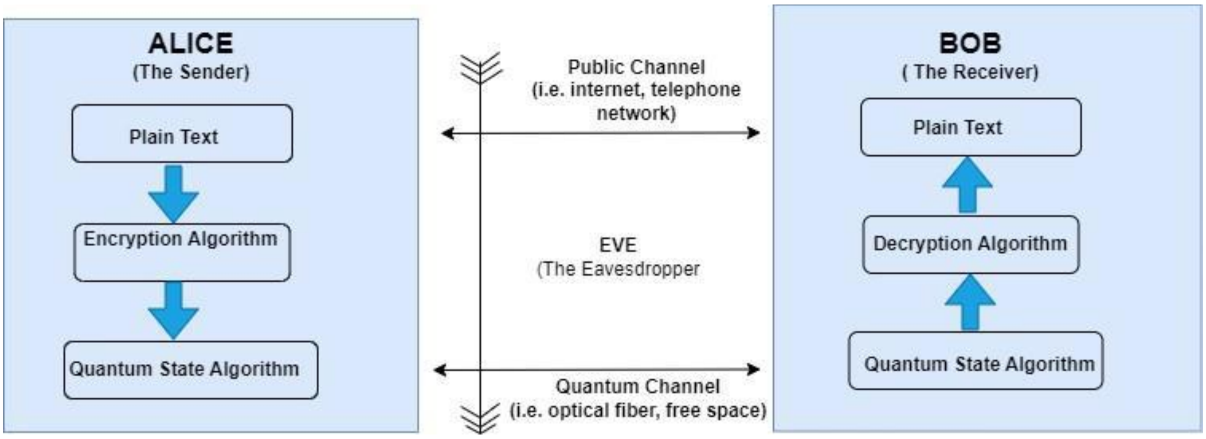

Fig. 1: Basic Block Diagram of QKD System

RESULTS AND DISCUSSION

The examination of existing literature concerning quantum cryptography, particularly focussing on quantum key distribution (QKD), post-quantum cryptography, and their incorporation into optical networks, has yielded several noteworthy conclusions and identified topics warranting additional exploration.

Quantum Key Distribution Protocols: A range of quantum key distribution protocols, including BB84, E91, B92, among others, have been established to facilitate secure key exchange between parties. Each protocol utilises the distinct characteristics of quantum mechanics to achieve information-theoretic security; however, they encounter challenges related to performance, efficiency, and possible vulnerabilities. Additional investigation and refinement of these protocols are necessary to improve their practical application in quantum communication systems.

Post-Quantum Cryptography: A variety of post-quantum cryptographic techniques, such as lattice-based cryptography, code-based cryptography, and isogeny-based cryptography, are currently under investigation to formulate cryptographic algorithms that maintain their security against quantum adversaries. The algorithms demonstrate potential; however, further investigation is required to ascertain their security, efficiency, and broader acceptance in light of quantum threats. The incorporation of quantum key distribution (QKD) into optical networks, exemplified by Key-as-a-Service (KaaS) frameworks, has resulted in the emergence of innovative service models and has enabled the implementation of QKD-driven security solutions within pre-existing network infrastructures. This development facilitates the potential for extensive implementation of quantum cryptography. Nonetheless, there are ongoing challenges in practical implementation that must be addressed, such as miniaturisation, cost reduction, and compatibility with existing infrastructure.

Examination of Security Challenges and Mitigation Strategies: Quantum hacking, side-channel attacks, and various vulnerabilities present significant challenges to the security of quantum cryptography systems. Proposed countermeasures include decoy state methods, entanglement-based QKD protocols, privacy amplification protocols, and quantum coin flipping protocols, all aimed at mitigating these threats. Additional investigation is essential to establish resilient security protocols capable of enduring the changing threat environment.

Quantum Cryptocurrency: The integration of quantum cryptography within the realm of cryptocurrency introduces distinct challenges, such as the establishment of secure quantum key distribution protocols, the development of post-quantum cryptographic algorithms, and the consideration of privacy issues. Although investigations have been undertaken to tackle these challenges, further efforts are required to create secure and efficient quantum cryptocurrency systems.

Quantum cryptography presents considerable promise for improving network security and privacy. Notwithstanding the advancements achieved in the discipline, numerous challenges and unresolved research enquiries persist. Addressing these challenges and advancing the state of inquiry in quantum cryptography will contribute to the development of secure communication technologies and pave the way for practical applications, such as quantum cryptocurrency.

Challenges and Open Research Questions:

Our review of the literature on quantum cryptography and quantum cryptocurrency has led to the identification of several challenges and open research questions.

1. The advancement of practical, efficient, and resilient quantum key distribution protocols is essential for the broader implementation of quantum cryptography. Additional investigation is required to enhance current protocols, identify potential weaknesses, and develop novel protocols capable of resisting sophisticated attacks, particularly those posed by quantum adversaries.
2. Development and Standardisation of Post-Quantum Cryptographic Algorithms: With the progression of post-quantum cryptography, it is imperative to conduct further investigations to guarantee the security, efficiency, and interoperability of post-quantum cryptographic algorithms. Moreover, the establishment of standardised cryptographic algorithms and protocols that can be broadly embraced by both industry and government is essential for safeguarding communication systems from quantum threats.
3. Quantum-Resistant IoT Devices: Given the growing ubiquity of IoT devices, it is imperative to create lightweight and efficient cryptographic solutions suitable for implementation on resource-constrained devices. The focus of research should be on the optimisation of post-quantum cryptographic algorithms specifically designed for IoT devices, as well as the exploration of efficient quantum key distribution solutions that are tailoredto the unique requirements of IoT environments.
4. The integrity of quantum cryptography systems is contingent upon the effective management and secure storage of cryptographic keys. Investigations should focus on innovative methodologies for key management, distribution, and storage that can uphold security in the context of potential quantum threats.
5. The security and privacy challenges inherent in quantum cryptocurrency necessitate a focused examination and analysis. The investigation should concentrate on the advancement of secure and private quantum

cryptocurrency systems, encompassing the incorporation of privacy-preserving methodologies and innovative protocols that can safeguard user privacy while ensuring the security of transactions.

6. Scalability and Interoperability: The practical implementation of quantum cryptography solutions necessitates the development of scalable and interoperable systems capable of seamless integration with current communication infrastructure. Investigation should concentrate on the advancement of scalable quantum cryptography systems and protocols that can be seamlessly deployed and integrated with current networks and technologies.
7. Experimental Demonstration and Deployment: Although numerous quantum cryptography protocols and algorithms have been theoretically proposed and analysed, there exists a significant requirement for further experimental demonstrations and practical implementations in real-world settings. Research efforts should prioritise the validation and optimisation of protocols, algorithms, and countermeasures within realistic environments to enhance the understanding of their performance and inherent limitations.
8. An Examination of Quantum Hacking and Associated Countermeasures: With the progression of quantum computing, there is an increasing potential for the emergence of quantum hacking and various other advanced forms of cyber attacks. The investigation should concentrate on pinpointing and mitigating possible security weaknesses within quantum cryptography frameworks, as well as formulating resilient countermeasures capable of enduring advancing threats.

Investigating these challenges and unresolved research enquiries will facilitate the advancement of secure and feasible quantum cryptography solutions, thereby laying the groundwork for applications like quantum cryptocurrency, which aim to improve the security and privacy of digital communication in the context of quantum technology.

Future work

The advancement and refinement of resilient quantum key distribution protocols capable of enduring sophisticated attacks, alongside the investigation of secure and efficient post-quantum cryptographic algorithms, with a focus on their interoperability and standardisation. The increasing prevalence of IoT devices necessitates the development of lightweight and efficient cryptographic solutions specifically designed for resource-constrained devices. This endeavour will encompass the optimisation of post-quantum cryptographic algorithms and quantum key distribution solutions specifically tailored for Internet of Things environments. Furthermore, investigations ought to delve into innovative methodologies for key management, distribution, and storage within quantum cryptography frameworks to ensure security against emerging quantum threats. The advancement of secure and private quantum cryptocurrency systems represents a significant domain for investigation, necessitating the incorporation of privacy-preserving methodologies and innovative protocols aimed at safeguarding user confidentiality while ensuring the integrity of transaction security. The scalability and interoperability of quantum cryptography systems are critical for practical implementation. Therefore, future investigations should focus on developing systems that can be seamlessly deployed and integrated with current networks and technologies. Empirical demonstrations and practical implementations of quantum cryptography protocols and algorithms are essential for assessing their efficacy and constraints. In conclusion, it is imperative to examine potential security vulnerabilities inherent in quantum cryptography systems, including the phenomenon of quantum hacking. Furthermore, the formulation of effective countermeasures will be crucial to safeguarding digital communication as we transition into the quantum era.

CONCLUSIONS

This study emphasises the considerable promise of quantum cryptography in transforming the security and privacy landscape of digital communication within the context of the quantum era. Nonetheless, various challenges and unresolved research enquiries need to be tackled in order to completely leverage this potential. In-depth investigation into the advancement of resilient quantum key distribution protocols, secure post-quantum cryptographic algorithms, and effective solutions for Internet of Things devices is crucial for facilitating secure and practical applications of quantum cryptography, such as quantum cryptocurrency. Furthermore, experimental demonstrations and real-world implementations will be essential for the validation and refinement of the proposed protocols and algorithms. Ongoing investigation and partnership are expected to address these challenges, resulting in improved security and privacy in digital communication, while promoting the broader implementation of quantum cryptography solutions across multiple sectors. This paper presents insights and research directions intended to inform future endeavours in this dynamic and swiftly advancing domain, thereby contributing to a transformative period of secure communication within the context of quantum technology.

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