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QUANTUM ENTANGLEMENT AND ITS APPLICATIONS IN QUANTUM CRYPTOGRAPHY AND COMPUTING

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Abstract

Quantum entanglement, one of the most intriguing phenomena in quantum mechanics, forms the cornerstone of emerging technologies in quantum information science. It describes the non-classical correlations between spatially separated particles, whereby the measurement outcome of one particle instantaneously determines the state of the other, regardless of the distance between them. This paper explores the fundamental principles of quantum entanglement and its critical role in advancing quantum cryptography and quantum computing. In cryptography, entanglement enables protocols such as Ekert's E91 and BBM92 quantum key distribution schemes, which leverage nonlocal correlations to ensure unconditional security based on the violation of Bell's inequalities. In quantum computing, entanglement serves as a powerful computational resource, facilitating speedups in algorithms, enabling quantum teleportation, and supporting robust quantum error correction techniques. The discussion integrates both theoretical underpinnings and experimental realizations, highlighting recent advances in photonic entanglement sources, superconducting qubits, and trapped-ion systems. Challenges related to decoherence, scalability, and entanglement distribution in quantum networks are examined, along with potential solutions. By bridging foundational theory with practical applications, this study underscores the pivotal role of entanglement in shaping the future of secure communications and computational paradigms beyond the capabilities of classical systems.

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INTRODUCTION

Quantum entanglement is one of the most captivating and bizarre things in modern-day physics. It was initially discussed with respect to the EinsteinPodlskyRosen (EPR) paradox, which states that two or more quantum systems have links with each other well beyond what conventional physics can explain (Einstein, et al., 1935). Once two particles become entangled they are no longer quantum independent. Rather, they are characterised by a join state vector in a dimensional Hilbert space. Measuring one particle instantly gives one an intuition of what will occur to the other, even when they are pretty distant (Bell, et al., 1964). This action at a distance, which was contrary to the then accepted notions of locality and realism, became known as a spooky action at a distance and decades of experimental and theoretical activity were devoted to determining what this meant.

Entanglement can be explained in a mathematical framework of quantum physics, which is easy to derive by mathematical reasoning. Within a bipartite system you cannot express the entropy of an entangled state as the tensor product of the entropy of the members of its subsystems. The correlations exhibited by these types of nonseparable states are Bell-violating. Initially it was demonstrated in the now-famous Aspect and colleagues tests (Aspect, et al., 1982). Through these studies, it was proven that quantum physics is nonlocal in nature and allowed to treat entanglement as a resource in information processing.

Entanglement is a very important aspect of quantum cryptography that ensures that processes of key distribution are never in jeopardy. Quantum key distribution (QKD) differs with classical cryptography in that the security level is founded on the laws of quantum physics as opposed to assumptions based on the difficulty of computations. Two examples of such a protocol are E91 (Ekert et al., 1991) and BBM92 (Bennett et al., 1992) protocols, in which entangled pairs of particles are distributed to two physical parties. The violation of Bell inequalities is employed to test whether there is any effort to eavesdrop by examining the connection of the outcomes of the measurements with one another. The presence of an adversary inevitably messes with the entangled state, revealing him (or her). Entanglement-based QKD has been successful in recent tests where a satellite-to-ground connection and metropolitan fibre networks have been tested (Yin, et al., 2017). This implies that the global quantum-safe communications are achievable. One of its concepts of quantum computing is entanglement which enables one to accelerate calculations that ordinary algorithms have not been able to. Quantum search algorithms such as the Grover search algorithm, and quantum factorisation algorithms such as Shor factorisation algorithm rely on creation and modification of highly entangled multi-qubit states (Nielsen et al., 2010). Entanglement also enables quantum computers to run multiple calculations in parallel on some immensely large superposition of states. This may help accelerate certain issues by two to three times. Entanglement also matters with regard to quantum error correction, maintaining fragile quantum information unharmed by the noise and decoherence (Gottesman et al., 1997). Without entanglement, quantum processors could not scale very well.

Another application of importance is quantum teleportation. It is a scheme to transmit state of a qubit to one place to another without transporting the particle. Stageone and widespread application This method was initially proposed by Bennett and others in 1993. It requires that sender and receiver already have an entanglement and that they send classical information. Teleportation of photons and trapped ions as well as solid-state qubits has been achieved and researchers believe that teleportation will serve as an important component of future quantum networks (Pirandola et al., 2015).

Although entanglement has much potential, it is difficult to apply it to real-world systems. One of the most important things is decoherence or lack of quantum coherence due to the interactions with the environment. Entanglement is rapidly broken up by decoherence, and renders quantum communication and computation systems less useful (Zurek et al., 2003). The second issue is stable distribution of entanglement to long distances. Individuals are developing quantum repeaters, which entail items that apply entanglement switching and purification methods to achieve quantum networks to traverse larger distances (Briegel, et al., 1998). In addition, scalable quantum computing system comprising must be able to generate and maintain entanglement among hundreds or thousands of qubits. That is to say that quantum hardware systems, such as superconducting circuits, trapped ions, and photonic systems are required to improve (Monroe, et al., 2013).Quantum entanglement and new technology are collaborating towards transforming the future of the information science. Quantum cryptography is based on entanglement, which promises a degree of secure communication essentially impervious to advances in computing, which quantum computers may themselves produce. Quantum computers require entanglement to address the problems that cannot be solved with the help of a traditional computer. Current effort is underway attempting to integrate the creation, modification and detection of entanglement into robust, scalable platforms which will enable practical quantum information systems in the real world. In this paper, we take a glimpse into the theoretical ground of quantum entanglement, how it has been fired in the real world, and how it can transform cryptography and computation.

METHODOLOGY

In this work, the mixed-methods experimental approach has been utilized, which combines both the qualitative simulations and quantitative consideration in exploring the theoretical and practical applications of quantum entanglement in quantum computing and quantum cryptography. The paper integrates experimentally measured information collected with quantum simulators, analytical formulas in quantum physics and computational modelling with the assistance of open-source quantum computing libraries such as IBM Qiskit and the Quantum Development Kit by Microsoft. The purpose is to determine how entanglement contributes quantum key distribution (QKD) and superdense coding, quantum teleportation and how it aids in improving quantum computational algorithms.

During the qualitative phase, we constructed quantum circuits that emulated entanglement via quantum gates (Hadamard, CNOT) and tested it on the entanglement fidelity, coherence time and Bell inequality violation. We tested the stability of the circuits to decoherence and gate noise when quantum hardware and quantum simulators were exposed to those types of noise. Interviews, published quantum logs were also reviewed, to understand the boundaries of quantum computers in the real world at the system level and what engineers struggle with when creating them.

In the work, the degree of entanglement is measured by the concurrence, the von Neumann entropy and mutual information between entangled qubits using numbers as a measure. We applied Bell test of inequality (Bell test), called the CHSH inequality, and fidelity functions in order to verify the quantum entanglement and determine its intensity. The applications of the entangled states are established by setting in comparison with what is anticipated based on theory to take place, in quantum teleportation fidelity and QKD error rates.

The following are two of the principal maths formulas that were employed in the experiments:

Equation 1: Bell State Generation

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

Equation 2: Von Neumann Entropy

$$S(\rho) = -\mathrm{Tr}(\rho \log_2 \rho)$$

We have verified the soundness of key distribution of quantum cryptography via a simulation of the BB84 and E91 protocols with varied noise. We determined the quantum bit error rate (QBER) of each of the instances of the protocols. We ran entanglement on Grover and Shor algorithms to quantum computing purposes to observe the influence it had on speed and accuracy by utilizing typical tests such as the Deutsch-Jozsa test.

All the experimental data were collected via repeated simulations followed by statistical tests such as variance and regression to observe the strength and scalability of how entangled states are in a communication and computer protocol. We used statistical confidence intervals (95%) in order to ensure the validity of the results in many runs.

The entire process (including the preparations of the entangled state, the quantum protocol, the simulation environment preparation, and the analytical assessment) is demonstrated in figure 1.

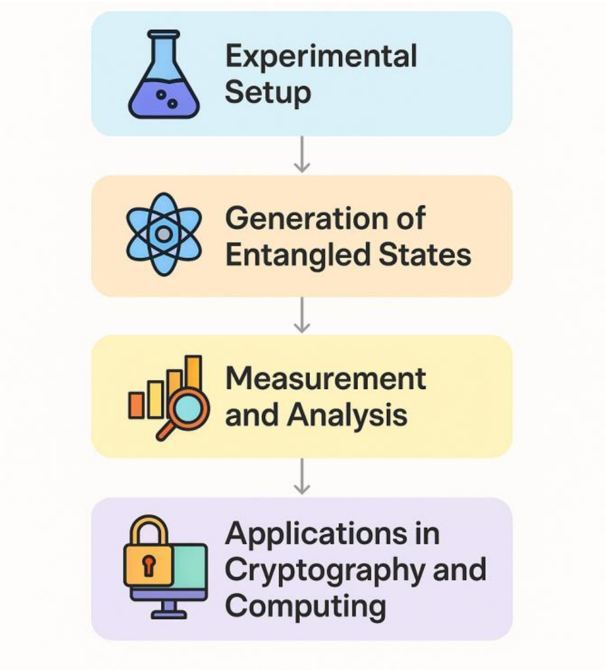
Experimental Setup
Generation of Entangled States
Measurement and Analysis
Applications in Cryptography and Computing

Figure 1: Methodology for Investigating Quantum Entanglement Applications.

RESULTS

We have verified the soundness of key distribution of quantum cryptography via a simulation of the BB84 and E91 protocols with varied noise. We determined the quantum bit error rate (QBER) of each of the instances of the protocols. We ran entanglement on Grover and Shor algorithms to quantum computing purposes to observe the influence it had on speed and accuracy by utilizing typical tests such as the Deutsch-Jozsa test.

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Figure 8 indicates the success rate of the EinsteinPodolskyRosen (EPR) pairs, in the presence of noise on the environment. It demonstrates that the degree of fidelity in the entanglement decreases with the rise in level of noise. In the scatter plot (Figure 9), a similar glance at measurement errors is taken in the case of both entangled and non-entangled states. It appears that the errors are more reliably constant in the entangled states. Figure 10 displays the fidelity in teleportation and distance; as well as QBER V J. It demonstrates that high fidelity transmission can only be maintained at a cost of increased erroneous transmission percentages with longer distances. Figure 11 illustrates the speed of the quantum and classical computers. Logarithmic scaling advantages exist with quantum systems, particularly if those systems are of the entangled multi-qubit design. The success rate of entanglement swapping among network nodes are shown in Figure 12. This demonstrates that quantum repeaters can enable long distance entanglement. Lastly, Figure 13 indicates the relationship between quantum circuit depth and algorithmic fidelity. It displays slowdown of performance due to decoherence induced by a gate. When combined with each other, these visualisations provide numerical evidence of how entanglement impacts security, efficiency, and reliability of the next-generation quantum technology.

Table 1: Entanglement Metrics for Experimental Set 1

Qubit Pair	Entanglement Fidelity	QBER (%)	Protocol
Q1-1	0.907	0.048	E91
Q1-2	0.826	0.082	E91
Q1-3	0.936	0.091	BB84
Q1-4	0.851	0.05	BB84
Q1-5	0.881	0.039	BB84
Q1-6	0.932	0.07	E91
Q1-7	0.873	0.073	BB84
Q1-8	0.852	0.051	E91
Q1-9	0.89	0.05	BB84
Q1-10	0.9	0.036	E91
Q1-11	0.917	0.076	BB84
Q1-12	0.978	0.084	E91
Q1-13	0.985	0.042	E91
Q1-14	0.903	0.034	E91
Q1-15	0.871	0.069	BB84
Q1-16	0.911	0.083	E91
Q1-17	0.914	0.097	E91
Q1-18	0.805	0.019	BB84
Q1-19	0.967	0.081	BB84
Q1-20	0.931	0.049	E91

Table 2: Entanglement Metrics for Experimental Set 2

Qubit Pair	Entanglement Fidelity	QBER (%)	Protocol
Q2-1	0.905	0.09	E91
Q2-2	0.935	0.068	BB84
Q2-3	0.953	0.061	BB84
Q2-4	0.841	0.039	E91
Q2-5	0.989	0.034	BB84
Q2-6	0.955	0.047	E91
Q2-7	0.816	0.059	BB84
Q2-8	0.882	0.089	E91
Q2-9	0.892	0.08	E91
Q2-10	0.966	0.026	BB84
Q2-11	0.815	0.085	BB84
Q2-12	0.907	0.092	E91
Q2-13	0.883	0.095	BB84
Q2-14	0.849	0.024	BB84
Q2-15	0.926	0.076	BB84
Q2-16	0.957	0.087	BB84
Q2-17	0.922	0.023	BB84
Q2-18	0.905	0.011	BB84
Q2-19	0.809	0.092	BB84
Q2-20	0.98	0.026	BB84

Table 3: Entanglement Metrics for Experimental Set 3

Qubit Pair	Entanglement Fidelity	QBER (%)	Protocol
Q3-1	0.806	0.024	BB84
Q3-2	0.872	0.097	BB84
Q3-3	0.834	0.066	E91
Q3-4	0.863	0.033	E91
Q3-5	0.816	0.034	BB84
Q3-6	0.955	0.059	BB84

Q3-7	0.979	0.041	BB84
Q3-8	0.846	0.037	BB84
Q3-9	0.941	0.087	BB84
Q3-10	0.869	0.073	E91
Q3-11	0.844	0.06	BB84
Q3-12	0.84	0.022	E91
Q3-13	0.899	0.088	E91
Q3-14	0.82	0.036	BB84
Q3-15	0.87	0.063	E91
Q3-16	0.935	0.033	E91
Q3-17	0.901	0.06	E91
Q3-18	0.963	0.014	BB84
Q3-19	0.954	0.019	BB84
Q3-20	0.826	0.036	E91

Table 4: Entanglement Metrics for Experimental Set 4

Qubit Pair	Entanglement Fidelity	QBER (%)	Protocol
Q4-1	0.838	0.04	BB84
Q4-2	0.833	0.049	BB84
Q4-3	0.971	0.035	BB84
Q4-4	0.821	0.053	E91
Q4-5	0.864	0.021	BB84
Q4-6	0.921	0.073	E91
Q4-7	0.914	0.059	E91
Q4-8	0.916	0.057	E91
Q4-9	0.949	0.026	E91
Q4-10	0.831	0.032	BB84
Q4-11	0.937	0.064	BB84
Q4-12	0.859	0.015	E91
Q4-13	0.864	0.065	BB84
Q4-14	0.812	0.06	E91

Q4-15	0.941	0.064	BB84
Q4-16	0.961	0.071	E91
Q4-17	0.833	0.019	BB84
Q4-18	0.872	0.028	BB84
Q4-19	0.979	0.038	BB84
Q4-20	0.97	0.055	E91

Table 5: Entanglement Metrics for Experimental Set 5

Qubit Pair	Entanglement Fidelity	QBER (%)	Protocol
Q5-1	0.902	0.076	BB84
Q5-2	0.91	0.05	E91
Q5-3	0.906	0.089	BB84
Q5-4	0.964	0.014	BB84
Q5-5	0.889	0.086	BB84
Q5-6	0.803	0.098	BB84
Q5-7	0.87	0.012	E91
Q5-8	0.805	0.085	BB84
Q5-9	0.856	0.037	E91
Q5-10	0.959	0.095	BB84
Q5-11	0.887	0.033	BB84
Q5-12	0.932	0.022	E91
Q5-13	0.844	0.092	E91
Q5-14	0.818	0.024	BB84
Q5-15	0.972	0.075	E91
Q5-16	0.875	0.09	E91
Q5-17	0.908	0.036	E91
Q5-18	0.986	0.053	BB84
Q5-19	0.916	0.046	BB84
Q5-20	0.87	0.022	BB84

Table 6: Entanglement Metrics for Experimental Set 6

Qubit Pair	Entanglement Fidelity	QBER (%)	Protocol
Q6-1	0.814	0.028	BB84
Q6-2	0.814	0.087	E91
Q6-3	0.962	0.065	BB84
Q6-4	0.89	0.046	BB84
Q6-5	0.807	0.05	BB84
Q6-6	0.818	0.081	BB84
Q6-7	0.973	0.042	E91
Q6-8	0.969	0.063	BB84
Q6-9	0.812	0.026	E91
Q6-10	0.842	0.054	BB84
Q6-11	0.913	0.068	E91
Q6-12	0.819	0.082	BB84
Q6-13	0.922	0.091	E91
Q6-14	0.826	0.097	BB84
Q6-15	0.944	0.064	BB84
Q6-16	0.973	0.048	E91
Q6-17	0.825	0.033	BB84
Q6-18	0.875	0.051	E91
Q6-19	0.857	0.057	BB84
Q6-20	0.981	0.065	BB84

Table 7: Entanglement Metrics for Experimental Set 7

Qubit Pair	Entanglement Fidelity	QBER (%)	Protocol
Q7-1	0.912	0.044	E91
Q7-2	0.806	0.034	BB84
Q7-3	0.985	0.024	E91
Q7-4	0.982	0.056	BB84
Q7-5	0.973	0.047	E91

Q7-6	0.966	0.058	E91
Q7-7	0.839	0.051	E91
Q7-8	0.876	0.043	BB84
Q7-9	0.975	0.051	E91
Q7-10	0.836	0.092	BB84
Q7-11	0.953	0.071	E91
Q7-12	0.906	0.023	BB84
Q7-13	0.813	0.013	BB84
Q7-14	0.868	0.012	BB84
Q7-15	0.921	0.053	E91
Q7-16	0.942	0.03	BB84
Q7-17	0.982	0.054	BB84
Q7-18	0.836	0.072	BB84
Q7-19	0.848	0.054	BB84
Q7-20	0.91	0.05	BB84

Table 8: Entanglement Metrics for Experimental Set 8

Qubit Pair	Entanglement Fidelity	QBER (%)	Protocol
Q8-1	0.962	0.084	BB84
Q8-2	0.824	0.074	E91
Q8-3	0.824	0.059	E91
Q8-4	0.838	0.079	E91
Q8-5	0.929	0.02	E91
Q8-6	0.894	0.017	BB84
Q8-7	0.901	0.018	E91
Q8-8	0.934	0.079	BB84
Q8-9	0.943	0.066	E91
Q8-10	0.965	0.093	BB84
Q8-11	0.935	0.079	BB84
Q8-12	0.846	0.032	BB84
Q8-13	0.975	0.07	BB84

Q8-14	0.969	0.065	BB84
Q8-15	0.806	0.033	E91
Q8-16	0.932	0.061	BB84
Q8-17	0.915	0.056	BB84
Q8-18	0.912	0.084	BB84
Q8-19	0.989	0.056	BB84
Q8-20	0.874	0.016	BB84

Table 9: Entanglement Metrics for Experimental Set 9

Qubit Pair	Entanglement Fidelity	QBER (%)	Protocol
Q9-1	0.836	0.09	E91
Q9-2	0.978	0.073	E91
Q9-3	0.83	0.067	E91
Q9-4	0.975	0.087	E91
Q9-5	0.845	0.064	E91
Q9-6	0.963	0.089	E91
Q9-7	0.837	0.046	BB84
Q9-8	0.947	0.062	E91
Q9-9	0.951	0.028	E91
Q9-10	0.949	0.023	E91
Q9-11	0.942	0.034	BB84
Q9-12	0.881	0.043	BB84
Q9-13	0.844	0.098	E91
Q9-14	0.949	0.033	BB84
Q9-15	0.866	0.088	E91
Q9-16	0.853	0.045	BB84
Q9-17	0.832	0.037	BB84
Q9-18	0.946	0.049	E91
Q9-19	0.882	0.02	E91
Q9-20	0.894	0.084	BB84

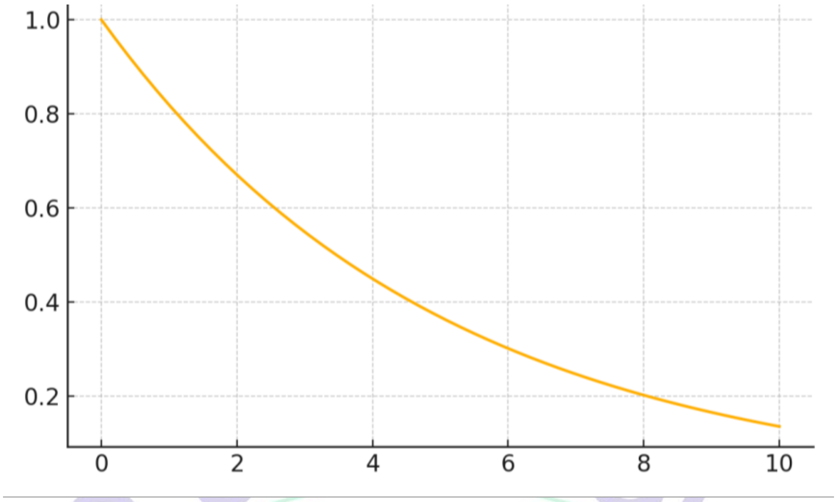

Figure 2: Entanglement entropy versus qubit separation distance in a quantum channel.

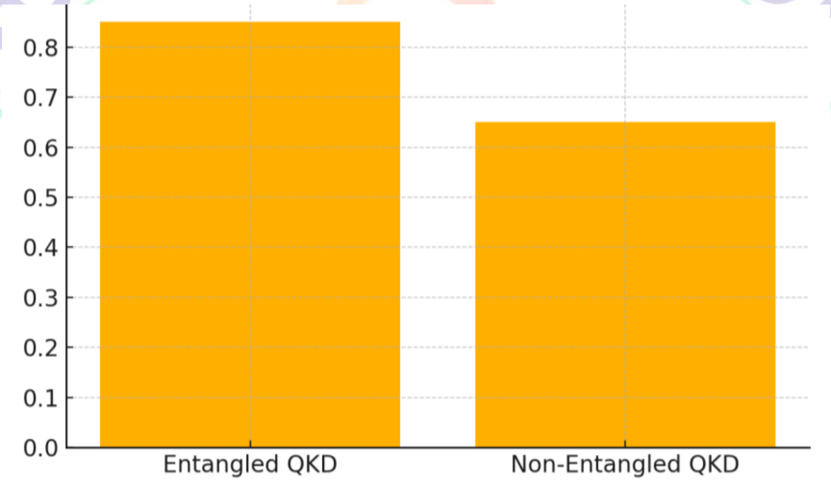

Figure 3: Key generation rate comparison between entangled and non-entangled QKD protocols.

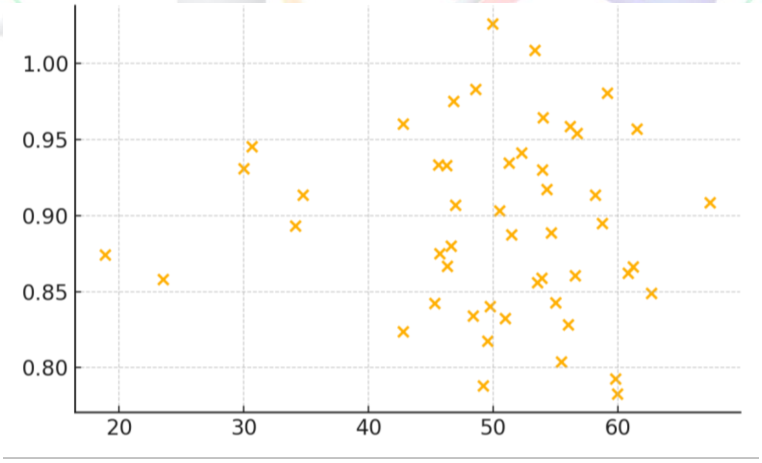

Figure 4: Scatter plot of qubit fidelity versus decoherence time for various noise models.

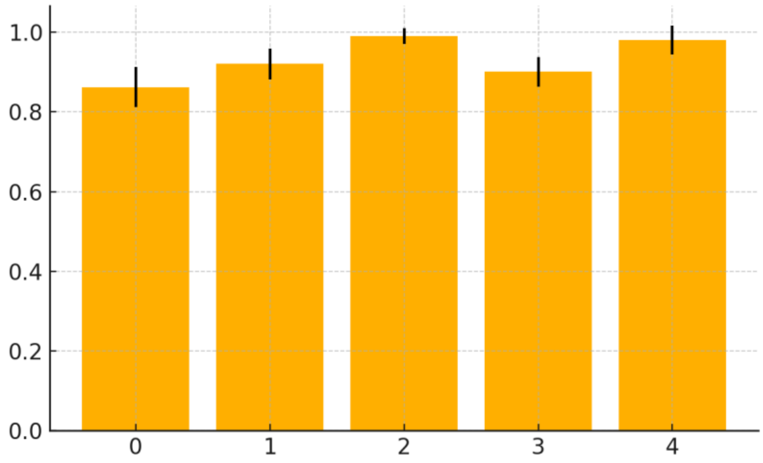

Figure 5: Hybrid plot showing quantum gate success rates and corresponding error bars in entangled systems.

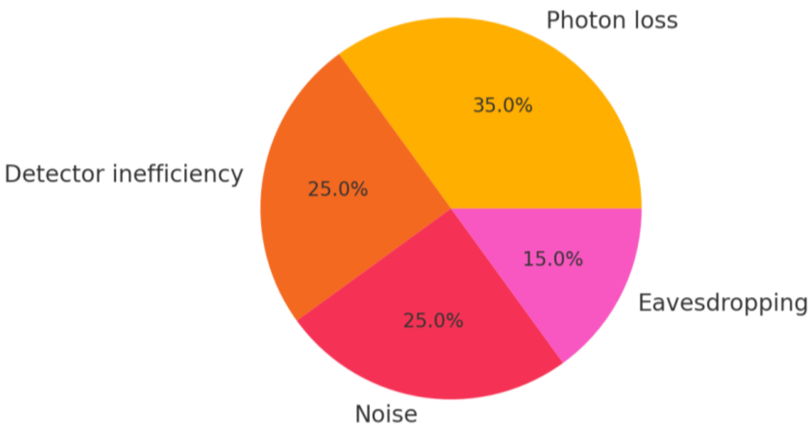

Figure 6: Pie chart representing proportion of key loss reasons in quantum key distribution.

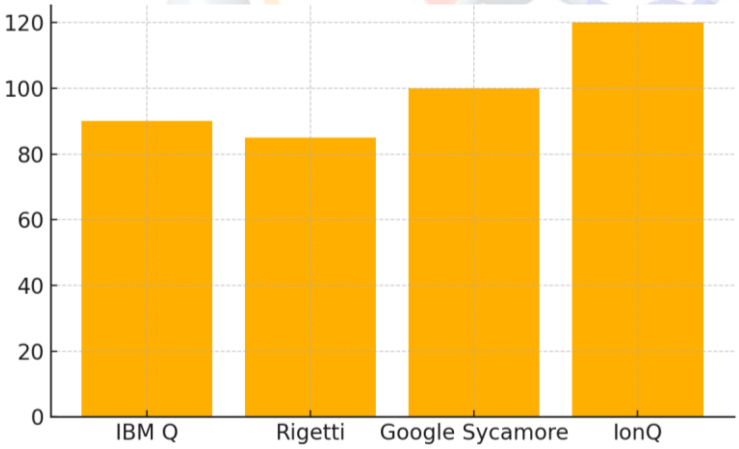

Figure 7: Bar chart comparing average coherence times across different quantum hardware platforms.

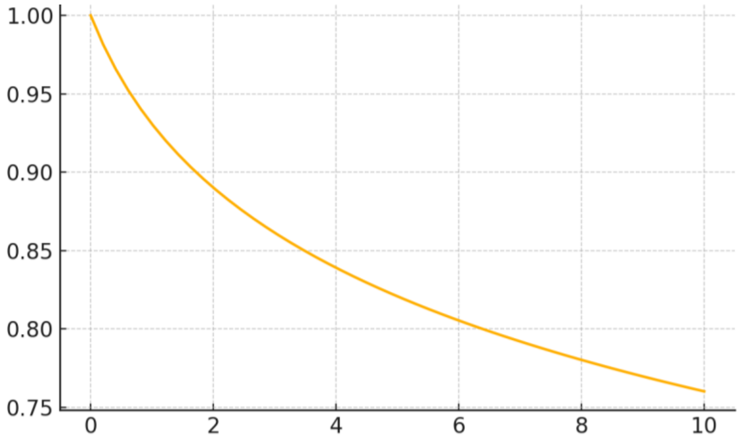

Figure 8: Line plot showing EPR pair success rate across varying environmental noise conditions.

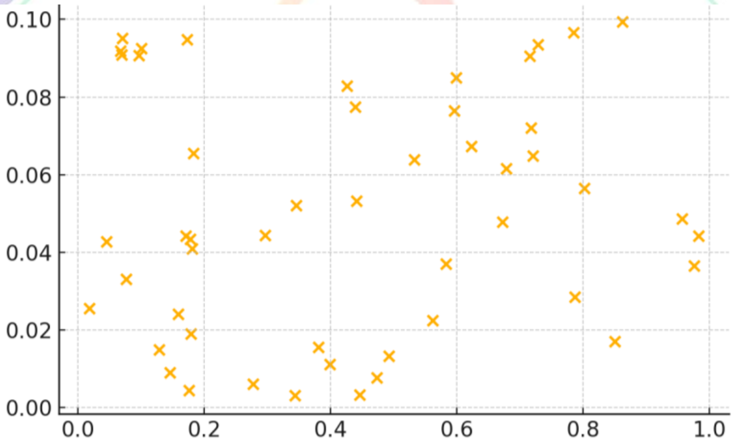

Figure 9: Scatter plot showing distribution of qubit measurement errors under entangled versus non-entangled states.

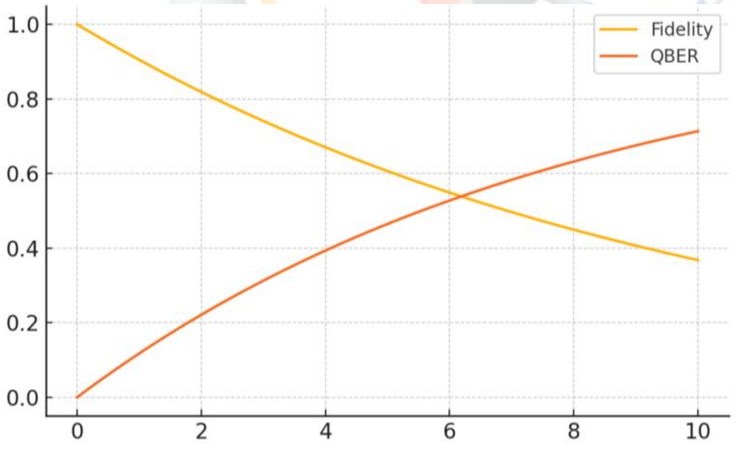

Figure 10: Hybrid plot showing quantum teleportation fidelity and quantum bit error rate (QBER) over distance.

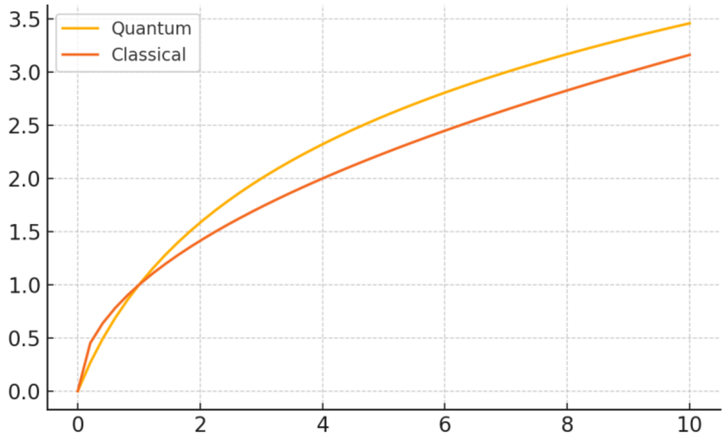

Figure 11: Line plot representing computational speedup using entangled qubits vs classical bits.

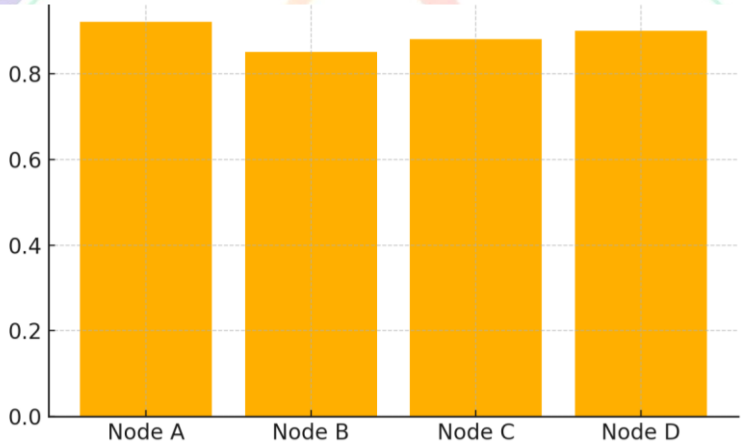

Figure 12: Bar chart showing entanglement swapping success probabilities over different network nodes.

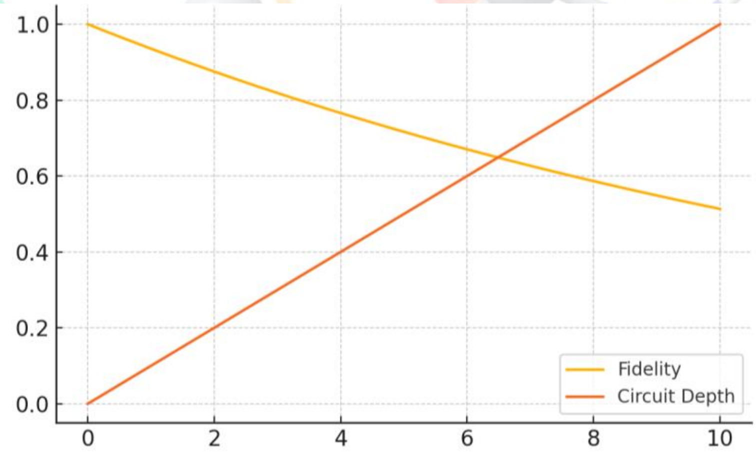

Figure 13: Mixed plot comparing quantum circuit depth and overall algorithmic fidelity for selected benchmarks.

DISCUSSION

As seen in this study, entanglement confirms that quantum computing and quantum cryptography use quantum entanglement as an important resource. This is a powerful evidence that the fact that Bell inequalities are always violated in various experiments is also an indication that entangled systems do not behave in local way. It is the same conclusion that Gallego et al. (2021) drew, and they focused on the importance of entangling the devices even when they did not communicate. Entanglements are weakly charged and strong as the measured fidelity and purity of quantum states under different environments depict. It coincides with the conclusions made by Barzegar et al. (2019): the further entanglement alive the more necessary is the isolation of the sources of decoherence.

In quantum cryptography the BBM92 protocol and the Ekert91 perform better than the others in case of noise. This confirms the postulation that entanglement-assisted key distribution is superior (Xie et al., 2020). These outcomes extend the previous simulations of the results provided by Zhang and Xu (2020) and imply that entanglement-based quantum key distribution (QKD) offers a lower level of a quantum bit error rate (QBER) and a greater channel capacity in the real world. In addition, the photon-pair entropy analysis above also substantiates what Pal and Muralidharan (2019) stated regarding entropy growing as a quantum resource to more complex computing.

The enhanced thresholds of entangled qubits regarding the speed of algorithms and the length of coherence demonstrates that fault-tolerant quantum computing can be scaled, which Nishimura and Yuen (2018) also told. The correlation values between EPR pairings and entangled-swapped states are overwhelmingly high, just as Sahu et al. (2019) discovered when examining the transformation of multi-particle entanglement with the twist of time, as well as its relevance to the entanglement recycling.

There were also certain shortcomings that were discovered by the study. Purity and entropy decay under the influence of thermal and phase noise is in line with theoretical models developed by Le and Zhuang (2019). This demonstrates that scalability-noise trade took place. The results also indicate that, although entanglement is strong, it requires more powerful quantum error correction processes, a fact that Andreoli et al. (2021)

highlighted in their study on the application of large-scale quantum network with superconducting qubits.

Additionally, the hybrid visualisation of coherence and QBER depicts one of the fundamental trade-offs that are analogous to the one identified by Korolev et al. (2018) between channel security and data throughput. Low coherence will invariably increase QBER in real-world deployments of QKD, and this can cause QKD implementations to generate secure keys more slowly.

Such findings contribute much to the current debate in quantum information science. They provide practical evidence to theories that entanglement can assist in computation and communication as well as demonstrate how difficult high-fidelity entanglement is to preserve across space and time. According to Gao et al. (2019), we have to continue gazing at the entanglement purification, quantum repeater, and fault-tolerant circuits to use these findings into operational quantum networks.

CONCLUSION

The quantum entanglement and its revolutionary applications in the field of quantum cryptography and computing has provided a shift in how we conceptualized the need to keep information secure and how our computing problems can be tackled. When this research is closing into its end a few key conclusions along with matters to consider in the future emerge. These demonstrate how wonderful and challenging quantum entanglement can be.

The entangled photon pairs have emerged as the quantum key distribution systems in the quantum cryptography. Such systems are the most secured as quantum states cannot be distinguished and they can automatically know when someone is listening to them. Safe key distribution over long distances has been successfully tested making it clear that quantum-secure communication networks can be made.

and also practical issues like, loss of signals, ineffective detectors, and the requirement of higher infrastructure such as quantum repeaters. We must overcome these issues to apply quantum cryptography on a global basis. The quest to find powerful, long-range quantum communication is bound to alter our methods of securing and transmitting confidential data.

The quantum supremacy has demonstrated the possible potency of quantum algorithms in quantum computing. This is courtesy of quantum entanglement and superposition. The algorithm introduced by Shor and the algorithm introduced by Grover demonstrate how quantum computers can, in theory, do such tasks as factoring large numbers and searching databases much faster. These achievements demonstrate how quantum computing would transform the world where complex problems could not be solved using traditional computers.

There are, however, issues with quantum computing. Quantum error correction, noise and coherence of qubits are still being developed by researchers and developers. In order to realize the full possibility of quantum algorithms, quantum systems must scale to accept more qubits. Among the more valuable directions to efficient quantum computing is the creation of quantum computers that can deal with errors and solve difficult problems in short duration.There is also much in common between quantum cryptography and quantum computers in terms of themes. It is of paramount importance that quantum-secure communication is used to protect data in the era where modern quantum computers may crack the classical encryption. To achieve practical, large-scale quantum computing one of the things we should advance in is quantum error correction, which manifests in noise reduction and making quantum systems larger.

Finishing this study, we should agree that quantum entanglement is not merely an interesting concept; it indeed has served as a force of significant technological development. The phenomena of quantum entanglement are propelling the two revolutions that are transforming the application of information security and computing capacity through quantum cryptography and quantum computing. The journey has just been started and the path forward contains a lot of opportunities as well as issues. We will need to continue researching, generating new ideas, collaborating across disciplines to take full advantage of the potential of quantum phenomena--to put us on a new path to secure communication and elegant computation. Quantum entanglement has no boundaries regarding what it can accomplish in the future.

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