Department of Electrical and Computer Engineering
North South University

Senior Design Project

“Energy-Entanglement Relation For Minimal QET Model Using Superconducting Quantum Computers”

Tasin Towsif Rahman	**ID # 1911774042**
Sibghat Ullah Rayyan Shaikh	**ID # 1831773042**
Monem Shahriar Sourav	**ID # 1831379042**

Faculty Advisor:

Dr. Mahdy Rahman Chowdhury

Associate Professor

ECE Department

Summer 2023

LETTER OF TRANSMITTAL

Summer, 2023

To

Dr. Rajesh Palit
Chairman,
Department of Electrical and Computer Engineering
North South University, Dhaka

Subject: **Submission of Capstone Project Report on "Energy-Entanglement Relation For Minimal QET Model"**

Dear Sir,

With due respect, we would like to submit our **Capstone Project Report** on the **"Energy-Entanglement Relation For Minimal QET Model using Superconducting Quantum Computers"** as a part of our BSc program. The report deals with the interrelation between the energy that is to be teleported using the minimal Quantum Energy Teleportation (QET) model and the changes in the entanglement of the quantum system of the model due to this. This project was valuable to us as it helped us gain experience from the theoretical field and apply it in real life, yielding practical results. We tried to the maximum competence to meet all the dimensions required by the report.

We will be highly obliged if you kindly receive this report and provide your valuable judgment. It would be our immense pleasure if you find this report useful and informative to have an apparent perspective on the issue.

Sincerely Yours,

....

Tasin Towsif Rahman

ECE Department

North South University, Bangladesh

....

Sibghat Ullah Rayyan Shaikh

ECE Department

North South University, Bangladesh

....

Monem Shahriar Sourav

ECE Department

North South University, Bangladesh

APPROVAL

Tasin Towsif Rahman (ID # 1911774042), Sibghat Ullah Rayyan Shaikh (ID # 1831773042), and Monem Shahriar Sourav (ID # 1831379042) from the Electrical and Computer Engineering Department of North South University have worked on the Senior Design Project titled "**Energy-Entanglement Relation For Minimal QET Model using Superconducting Quantum Computers**" under the supervision of Dr. Mahdy Rahman Chowdhury in partial fulfillment of the requirement for the degree of Bachelors of Science in Engineering and has been accepted as satisfactory.

Supervisor's Signature

………………………………………

Dr. Mahdy Rahman Chowdhury

Associate Professor

Department of Electrical and Computer Engineering

North South University

Dhaka, Bangladesh.

Chairman's Signature

………………………………………

Dr. Rajesh Palit

Professor

Department of Electrical and Computer Engineering

North South University

Dhaka, Bangladesh.

DECLARATION

This is to declare that this project is our original work. No part of this work has been submitted elsewhere, partially or fully for the award of any other degree or diploma. All project-related information will remain confidential and shall not be disclosed without the formal consent of the project supervisor. Relevant previous works presented in this report have been properly acknowledged and cited. The plagiarism policy, as stated by the supervisor, has been maintained.

Students' names and signatures

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1. Tasin Towsif Rahman

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2. Sibghat Ullah Rayyan Shaikh

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3. Monem Shahriar Sourav

ACKNOWLEDGEMENTS

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Furthermore, we thank the Department of Electrical and Computer Engineering, North South University, Bangladesh, for facilitating the research. We would also like to thank **Syed Emad Uddin Shubha,** our research assistant, for helping us with this project. We would also like to thank our loved ones for their countless sacrifices and continual support.

ABSTRACT

In the easiest terms possible, quantum entanglement means that two particles are together in such a way that the actions of one particle affect or cause changes to the other particle no matter the distance between the two particles. These particles could be photons, electrons, etc, and the state that they exist in could be, for example, one particle ‘spinning’ in one direction and the other spinning in the opposite direction. For our experiment, we consider two particles Alice and Bob. The goal of our study is to investigate the degree of breakdown of entanglement between the two for the minimal Quantum Energy Teleportation (QET) Model, during energy teleportation. Entropy is used as a quantitative measure of entanglement. The measurements in the circuit destroy the entanglement that exists between the two qubits when energy is transmitted from "Alice" to "Bob" in the Quantum Energy Teleportation (QET) Model. As a consequence, we use entropy to show the extent of degeneration in the entanglement; in other words, we present two disparities in the amount of transmitted energy and the entanglement expenditure. We investigate entanglement as a quantifiable physical resource in connection to energy in this experiment.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1 Introduction

1.1 Background and Motivation

Imagine being able to instantly transmit energy from one spot to another, as if by magic. You're stuck in an isolated place, closed off from the rest of the world, only possessing the essential needs for existence, that will run out in only a matter of days. Your only chance is that you have a satellite phone that you can use to make a call for rescue. However, the battery is getting close to the end of its life. So you risk calling a friend in town, first, to get you out of this predicament. When your friend attaches his charger, your phone begins to charge and you call for assistance. This is the potential of Quantum Energy Teleportation (QET), a protocol emerging from the thrilling realm of quantum physics. Masahiro Hotta pioneered the idea, which provides a mechanism for energy transmission via local operations and classical communication by taking advantage of the ground-state entanglement of a many-body quantum system. [1]

The QET procedure is fascinating. It entails taking measurements of each particle in an entangled pair. The initial particle's measurement introduces quantum energy into the system. The initial amount of energy can be extracted by meticulously choosing the measurement to be performed on the second particle. This is the essence of QET, a protocol that allows energy to be transported from a subsystem of a many-body quantum system to a remote subsystem while maintaining causality and local energy conservation. Using the QET protocol, this method of transmitting energy is substantially quicker than energy propagation during natural time evolution. [1][3]

The Energy Entanglement Relation, a basic feature of QET that offers a relationship between energy and entanglement, is at the heart of the theory. Understanding the interaction of these two important resources in quantum physics is critical for the development of quantum technology.

Hotta demonstrated this relation through the minimal QET model, which serves as the smallest instance of a quantum energy teleportation model. This model provides a theoretical framework for understanding the energy-entanglement relation and serves as the basis for further exploration of QET. [2]

The practical implementation of these theories, particularly on quantum computer servers such as those provided by IBM, is the focus of this paper. IBM's quantum computing service, Qiskit Runtime, allows for the execution of advanced quantum programs, making it an ideal platform for exploring the practical aspects of QET. IBM's quantum computer servers provide a unique opportunity to test these theories in a practical setting. [4][5]

The motivation behind this project is twofold. Firstly, the theoretical foundations of QET and the Energy Entanglement Relation provide a rich area for exploration and potential practical applications. The theoretical underpinnings of QET, as laid out by Hotta and others, offer a wealth of possibilities for practical implementation. Secondly, the advent of quantum computer servers like IBM's offers a unique opportunity to test these theories in a practical setting. The practical implementation of these theories could lead to significant advancements in quantum computing and communication.

This paper aims to bridge the gap between theory and practice, providing insights into the practical implementation of QET and experiments on the interrelation of energy and entanglement on IBM's quantum computer servers. It will delve into the details of quantum energy teleportation, the energy entanglement relation, and the minimal QET model, drawing on a wealth of academic research in these areas. The paper will also discuss the potential applications and implications of these theories in the context of quantum computing.

1.2 Purpose and Goal of the Project

The goal of this project is to analyze the degree of deterioration of entanglement in a quantum-entangled circuit in the minimal Quantum Energy Teleportation (QET) model. Understanding the energy entanglement relations of QET was one of the two key aspects of the quantum energy teleportation theory proposed by Hotta[1].

As the main goal of the investigation is to experimentally verify Hotta's theory, it led us to carry on our research with the only available experimental resource on QET which was made just recently[3]. For this purpose, we used entropy as the basis to show the level of degradation in the entanglement and recorded our findings.

In theory, we should be able to acquire entropy using values obtained before and after the projective measurement of Alice. Therefore we would modify Ikeda's circuit for the minimal QET model to conduct measurement operations in these two parts while making sure the measurements are done before the entanglement between Alice and Bob breaks.

Experimental investigations and studies on QET are in their infancy as the first experimental investigation of the theory was just published in 2023 [3]. While Ikeda was the first to experimentally demonstrate Hotta's QET theory, the investigation on the minimal QET model's energy entanglement relations has not been conducted yet. Our exploration in this field will lead to researchers gaining a deeper understanding of the minimal QET model and verification of existing theories while providing a basis for future research and practical implementation of QET.

Chapter 2 Related Works

2.1 Existing Research

Quantum Energy Teleportation or QET for short was proposed by Masahiro Hotta back in 2008. Hotta's QET protocol theorized that the energy of any quantum system is in a constant state of fluctuation and these natural energy fluctuations can be exploited on a quantum level. Quantum energy teleportation requires an entangled pair of particles. For QET to occur, a measurement must be made on each one of the particles in the entangled pair. The measurement done on the first particle injects energy into the system that allows effective energy transportation through local operations and classical communication while upholding basic laws of physics and laws of energy conservation[1].

Building on Hotta's theory, Kazuki Ikeda conducted the experimental implementation using several of IBM's superconducting quantum computers[3]. Ikeda was able to realize Hotta's minimal QET model into a quantum circuit that was then implemented in quantum computers. Ikeda's circuit for quantum energy teleportation now serves as the basis for further experiments. His findings were found to be consistent with theory and further improved through mitigation.

Quantum teleportation has enabled the transfer of quantum information [6], but teleportation of quantum physical quantities had not yet been realized until this experiment[3]. The successful demonstration of QET on real hardware marks a significant milestone in quantum information science and technology[3].

QET is a realistic benchmark achievable with current technology due to the process using local operations and classical communication; thus opening new possibilities for the future as technology advances further.

The following provides a thorough description of the state of current research regarding Quantum Energy Teleportation:

1. Masahiro Hotta proposed that quantum energy teleportation can be effectively achieved via local operations and classical communication thus eliminating the chances of breaking any known laws of physics. [Source: Hotta, M. (2011). Quantum energy teleportation: an introductory review. arXiv preprint arXiv:1101.3954.]
2. Masahiro Hotta proposes two energy entanglement inequalities on the minimal QET model. Their relations allow researchers to gain an understanding of entanglement by relating both entanglement itself and entanglement to energy as physical resources. [Source: Hotta, M. (2010). Energy entanglement relation for quantum energy teleportation. Physics Letters A, 374(34), 3416-3421]
3. Kazuki Ikeda (2023) is able to experimentally implement Hotta's minimal QET model on real IBM superconducting quantum computers by making the relevant quantum circuits. His results were found to be consistent with the theory. [Source: Ikeda, K. (2023). First Realization of Quantum Energy Teleportation on Quantum Hardware. arXiv preprint arXiv:2301.02666.]

Chapter 3 Methodology

3.1 System Design

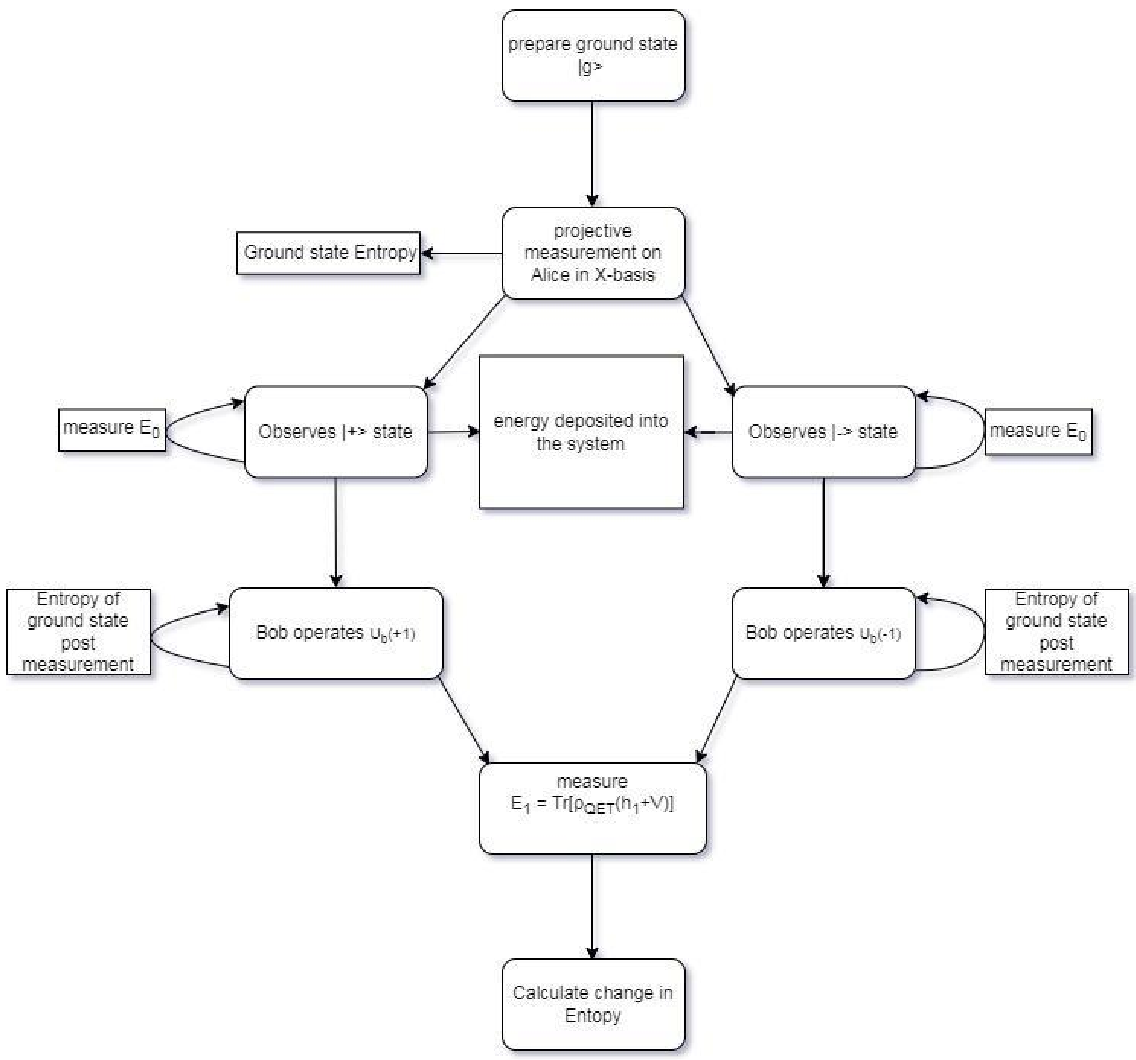

Figure. 1 System Flow Chart

The proposed methodology involves the following steps:

1. A circuit is prepared to calculate the entropy of ground-state entanglement, $S_{AB}(g)$, before the projective measurement of Alice. The entropy of the ground-state entanglement before the projective measurement of Alice is given by the equation:

$$S_{AB}(g) = -\operatorname*{Tr}_{B}\left[\rho_B \ln \rho_B\right]$$

2. The entropy of 'ρB', which is the reduced post-measurement state of Bob is then measured as $S_{AB}(\mu)$. The new entropy can be calculated by that of the post-measurement state with output 'μ' by the equation:

$$S_{AB}(\mu) = -\operatorname*{Tr}_{B}\left[\rho_B(\mu) \ln \rho_B(\mu)\right]$$

3. The difference between the ground state entanglement and the entropy of the state of Bob post-measurement is calculated using the two values of $S_{AB}(g)$ and $S_{AB}(\mu)$ to form ΔS_{AB}. This consumption of ground-state entanglement by measurement can be shown as the difference between the initial ground-state entanglement and the average post-measurement state entanglement, with entropy as the quantitative measure. The equation for ΔS_{AB} can be calculated by the following equation:

$$\Delta S_{AB} = S_{AB}(g) - \sum_{\mu} p_A(\mu) S_{AB}(\mu)$$

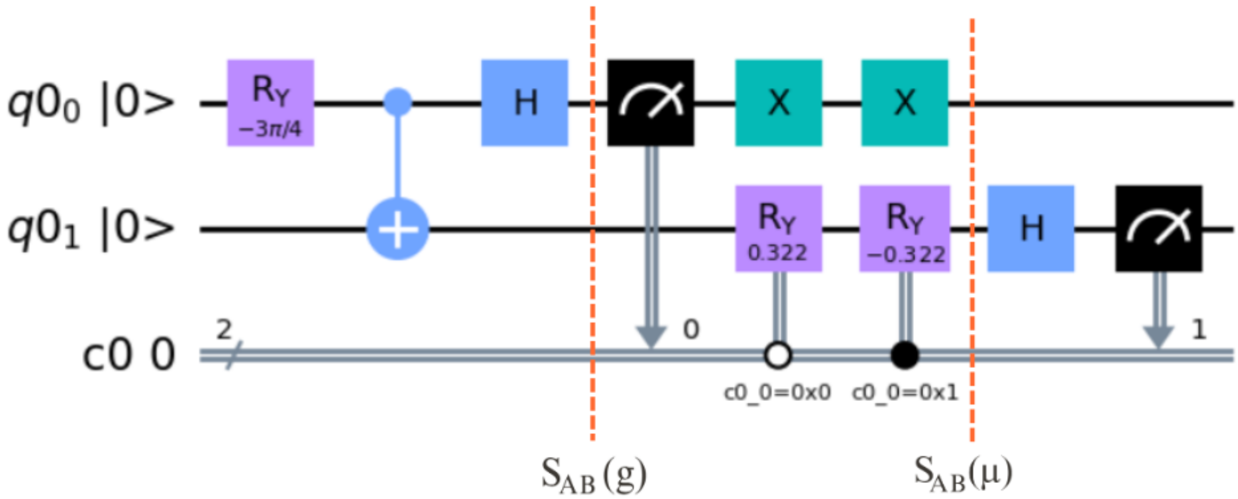

Figure. 2 The complete Quantum Energy Teleportation model with approximate labels for when the measurements of $S_{AB}(g)$ and $S_{AB}(\mu)$ are done.

4. The above steps are repeated using different values of h and k, and the change in entropy as well as for the maximum amount of teleportable energy through QET, λ_{AB} is then observed.

$$\frac{1+\sin^2\varsigma}{2\cos^3\varsigma}\ln\frac{1+\cos\varsigma}{1-\cos\varsigma}\frac{\max_{U_B(\mu)}E_B}{\sqrt{h^2+k^2}}$$

5. Graphs are generated to show the relation between ΔS_{AB} and λ_{AB}, in order to validate the inequality theorized by Hotta, which is,

$$\Delta S_{AB}\geq\frac{1+\sin^2\varsigma}{2\cos^3\varsigma}\ln\frac{1+\cos\varsigma}{1-\cos\varsigma}\frac{\max_{U_B(\mu)}E_B}{\sqrt{h^2+k^2}}$$

An overview of what occurred during this experiment can be simplified below:

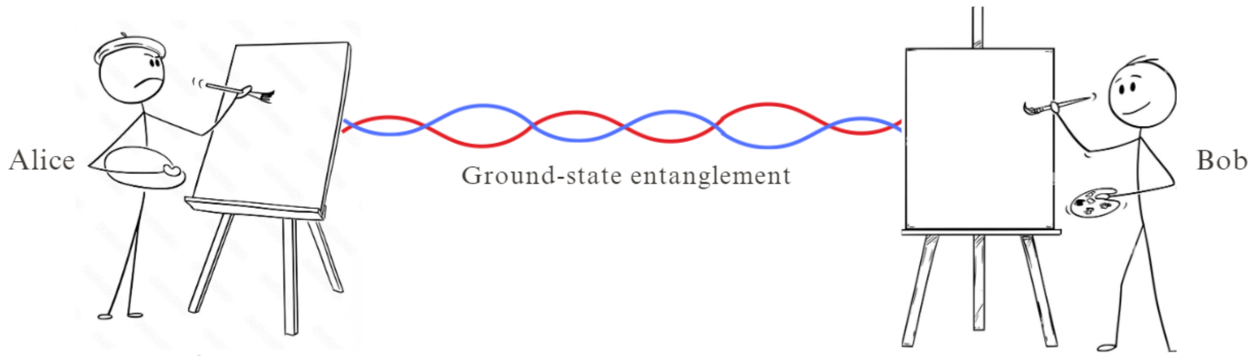

Figure. 3 Visualization of Alice and Bob's Entanglement

The above visual is a straightforward stick figure drawing of two painters planning to paint the same painting. At the start of the process, Alice and Bob are in an entangled state. It is to be noted that complete entanglement existed between Alice and Bob when entropy was first measured.

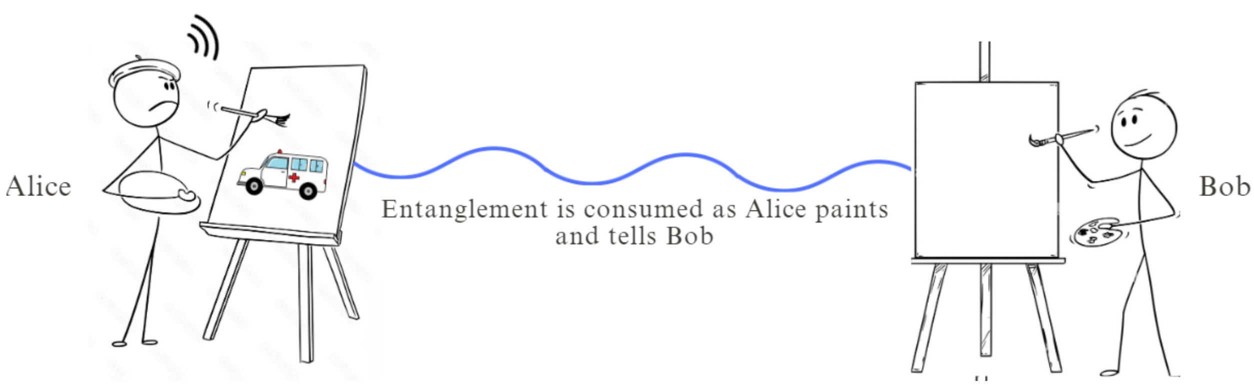

Figure. 4 Visualization of the consumption of Alice's Entanglement

Alice paints an ambulance and shares this information through classical channels (speaking or phone calls) of what she drew with Bob, as best as she can describe, so that he can draw it. This is a metaphor for Alice depositing energy into her system by performing measurements to her qubit resulting in the entanglement being consumed.

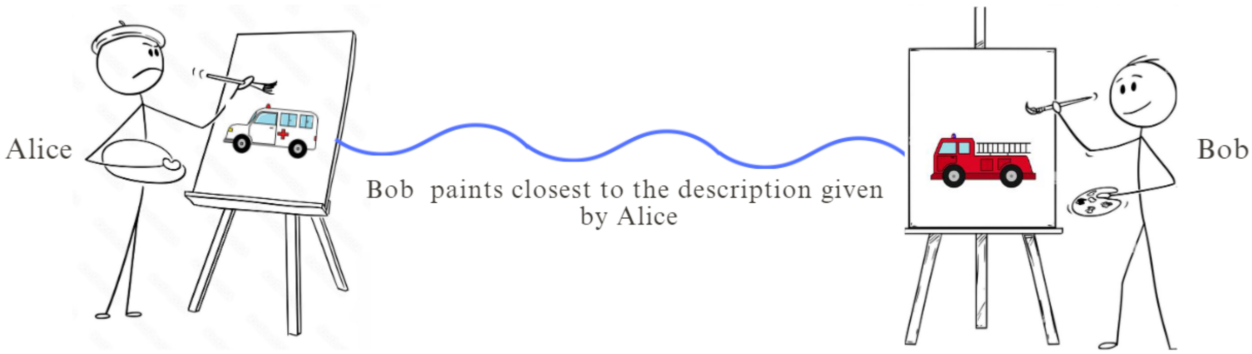

Figure. 5 Visualization of Bob replicating Alice's deposited energy to the closest degree based on the information provided

Bob sketches a firetruck using the description he received from Alice, suggesting that it's not possible for him to draw everything exactly based on the description by Alice, but he can get quite close. This symbolizes the difference between the ground state entanglement and the entropy of the ground state of Bob after measurements are performed in Alice's qubit, suggesting that there is always a system loss of energy when trying to conduct quantum energy teleportation. But the point to be considered is that for communication to occur between the two entanglement is to be consumed. Our goal is now to observe how much entanglement is being used in the process of Alice communicating with Bob.

3.2 Hardware and/or Software Components

Tool	Function	Similar Tools
Python	Programming Language, Multitude of libraries for general and quantum computing	Languages specializing in math and numerical analysis: MATLAB, Julia
Qiskit	Designs Quantum Circuits, Conducts Quantum Simulation, Has access to IBM Quantum Hardware	Forest, Cirq
Google Colab	Interactive Environment for Code Implementation, Allows multiple users to work on the same code, Documentation, Integrates Libraries and Tools	Visual Studio Code, Jupyter

IBM Quantum Experience	IBM Quantum Experience is a cloud platform allowing users to remotely access real quantum computers and simulators. It supports quantum experimentation, and program execution on live quantum processors via Qiskit, and offers educational resources, including a visual Quantum Composer, in a collaborative environment.	Quantum Inspire, QX Simulator, D-Wave

TABLE I: List of Tools used.

Python in Quantum Computing:

Quantum computing is a rapidly advancing field in computer science that investigates the capabilities of quantum mechanics for carrying out intricate calculations. Python, with its adaptability and extensive libraries, plays a pivotal role in quantum computing development and exploration. Python's scripting capabilities make it easy to simulate quantum circuits, study the effects of noise, and optimize quantum algorithms before running them on actual quantum hardware.

Use Case:

1. Qiskit - IBM's Quantum Computing Framework:

- Overview: Qiskit is an open-source quantum computing framework developed by IBM, designed to work seamlessly with Python.
- Integration with Python: Qiskit's Python API enables researchers and developers to create and manipulate quantum circuits using familiar Python syntax.
- Quantum Algorithm Implementation: Python facilitates the implementation of quantum algorithms, such as Grover's algorithm or Shor's algorithm, using Qiskit's intuitive interface.

2. Quantum Circuit Simulation:

Python Libraries (Qiskit Aer, Cirq):

- Qiskit Aer: It is a high-performance simulator for quantum circuits, allowing researchers to simulate quantum computations in Python.
- Cirq: Google's quantum computing library also provides Python tools for simulating and running quantum circuits.

3. Quantum Machine Learning:

Quantum Machine Learning (QML) Library:

- Overview: Python-based QML libraries bridge classical and quantum machine learning, offering tools for exploring quantum-enhanced machine learning models.
- Integration: Python enables the seamless integration of classical and quantum components, allowing researchers to experiment with novel quantum machine learning algorithms.

Qiskit: Open-Source Quantum Computing Framework

Qiskit is a comprehensive open-source quantum computing framework developed by IBM that provides tools and libraries for programming and working with quantum computers. Designed to be accessible to both quantum researchers and software developers, Qiskit empowers users to experiment with quantum algorithms, design quantum circuits, and run experiments on both simulators and real quantum hardware.

Key Components:

Quantum Circuits:

- Qiskit represents quantum circuits as objects in Python, making it easy to create and manipulate them programmatically.
- Users can design quantum circuits using a set of quantum gates, including Hadamard, CNOT, and others.

Quantum Registers and Classical Registers:

- Qiskit supports the creation of quantum registers and classical registers, allowing users to define the qubits and classical bits needed for their quantum programs.

Quantum Simulators:

- Qiskit provides simulators that allow users to emulate quantum circuits on classical hardware, aiding in algorithm development, testing, and debugging.

Real Quantum Devices:

- Qiskit enables users to execute their quantum programs on IBM's cloud-based quantum processors, providing access to real quantum hardware.

Quantum Algorithms:

- Qiskit includes implementations of various quantum algorithms, such as Shor's algorithm, Grover's algorithm, and quantum teleportation, showcasing the potential of quantum computing.

Quantum Networking:

- Qiskit supports quantum networking protocols, allowing for the exploration of quantum communication and distributed quantum computing.

Quantum Machine Learning:

- Qiskit extends its capabilities to quantum machine learning, allowing users to explore the intersection of quantum computing and classical machine learning.

Use Cases:

Algorithm Development:

- Qiskit allows researchers to implement and experiment with quantum algorithms, fostering innovation in the field of quantum computing.

Education:

- Qiskit serves as an educational tool, enabling students and educators to explore quantum computing concepts and applications.

Quantum Cloud Services:

- With IBM Quantum Experience, Qiskit users can access IBM's quantum processors via the cloud, democratizing access to quantum computing resources.

Qiskit's user-friendly Python interface, extensive documentation, and the community's high level of engagement render it a great resource for all individuals. interested in exploring and contributing to the rapidly evolving field of quantum computing.

Google Colab:

Google Colab, also referred to as Colaboratory, is a cloud-based platform offered by Google. that offers a free and interactive environment for running Python code. It is designed to facilitate collaborative work, especially in the domains of machine learning, data analysis, and research. Google Colab is widely used by individuals, researchers, and data scientists due to its ease of use, access to powerful computing resources, and seamless integration with popular machine learning frameworks.

Key Features of Google Colab:

Cloud-Based Environment:

- Google Colab runs entirely in the cloud, eliminating the need for users to set up and maintain their local computing environments. It provides a consistent and accessible platform from any device with an internet connection.

Jupyter Notebooks Integration:

- Google Colab supports Jupyter Notebooks, enabling users to generate and distribute papers that integrate real-time code, mathematics, visual representations, and explanatory text. This makes it an excellent tool for interactive coding and data exploration.

Free Access to GPU and TPU Resources:

- A notable characteristic of Google Colab is its offering of complimentary access to Graphics Processing Units (GPUs) and Tensor Processing Units (TPUs). This is particularly valuable for users working on computationally intensive tasks, such as deep learning.

Pre-Installed Libraries:

- Google Colab is equipped with numerous pre-installed Python libraries that are frequently used in the fields of machine learning and data science, including NumPy, Pandas, Matplotlib, and popular machine learning frameworks such as TensorFlow and PyTorch.

Collaboration Features:

- Google Colab is specifically designed to facilitate collaboration, enabling concurrent work by numerous users on a shared document.. Users can leave comments, provide feedback, and share their notebooks easily.

Google Drive Integration:

- Colab is seamlessly integrated with Google Drive. Users can save their notebooks directly to Google Drive, making it convenient to organize and share their work.

Version History and Recovery:

- Colab automatically records the version history of notebooks, offering a convenient method to monitor modifications and revert to previous states. This feature is valuable for collaborative projects and individual version control.

Easy Sharing:

- Notebooks created in Google Colab can be easily shared with others. Users can generate a shareable link or even publish their notebooks to the web, allowing broader access to their work.

Support for Various Data Formats:

- Colab supports various data formats, including images, audio, and video. This versatility enables users to work with diverse types of data in their projects.

Overall, Google Colab provides a powerful and accessible platform for coding, experimentation, and collaboration in a cloud-based environment, making it particularly popular in the machine learning and data science communities.

IBM Quantum Experience:

IBM Quantum Experience is an initiative by IBM that offers cloud access to real quantum computers for researchers, developers, and enthusiasts. It offers a platform for users to execute quantum experiments, explore quantum algorithms, and gain practical experience with quantum computing.

Key Features of IBM Quantum Experience:

Cloud-Based Quantum Computing:

- IBM Quantum Experience operates in the cloud, allowing users to access quantum computers remotely through the internet. This eliminates the need for users to have their own quantum hardware.

Real Quantum Processors:

- Users can execute their quantum programs on real quantum processors, gaining insights into the challenges and opportunities presented by quantum hardware.

Quantum Simulator:

- In addition to real quantum processors, IBM Quantum Experience provides a quantum simulator. This simulator allows users to test and debug their quantum programs in a controlled environment before running them on actual quantum hardware.

Qiskit Integration:

- Qiskit, IBM's open-source quantum computing framework, is integrated into IBM Quantum Experience. Users can leverage Qiskit to design and run quantum circuits, access quantum algorithms, and perform quantum simulations.

Educational Resources:

- IBM Quantum Experience offers educational resources, tutorials, and documentation to help users understand the principles of quantum computing and how to use the platform effectively.

Community and Collaboration:

- The platform fosters a community of quantum computing enthusiasts, researchers, and developers. Users can collaborate, share their experiences, and contribute to the broader understanding of quantum computing.

Quantum Composer:

- The Quantum Composer is a visual tool provided within IBM Quantum Experience that allows users to design quantum circuits using a graphical interface. It simplifies the process of creating and visualizing quantum algorithms.

Quantum Lab:

- The Quantum Lab provides an environment for users to run experiments, access quantum devices, and explore the quantum programming landscape. It serves as a practical learning ground for those new to quantum computing.

Quantum Job Management:

- Users can submit quantum jobs to the platform and monitor the progress of their experiments. The platform provides information on job status, execution time, and other relevant metrics.

Quantum Volume:

- IBM Quantum Experience introduces the concept of Quantum Volume, a metric that quantifies the capabilities of a quantum computer. It takes into account factors such as error rates, gate fidelities, and connectivity.

Chapter 4 Investigation/Experiment, Result, Analysis and Discussion

The results and findings obtained from our experiments are reported here in a chronological way following the order of the experiments conducted. For the analysis of entanglement breaking, we do POVM measurement of Alice(A). The figure below is a partial snippet of the circuit for the minimal QET model. This part of the circuit represents the preparation of the ground state before any measurements are made.

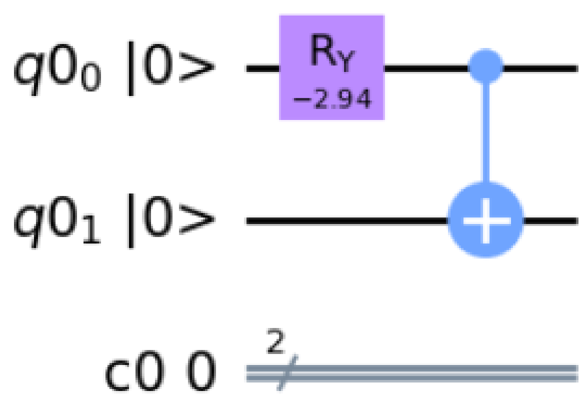

Fig. 6 Preparation of the ground-state of QET protocol

The state vector of the current entangled state for Alice and Bob, before any measurements, is as follows.

$$|\psi_{AB}\rangle = 0.098537618|00\rangle - 0.9951333267|11\rangle$$

Next, we calculate the density matrix of the ground state, which is shown below. A density matrix describes the quantum state of a physical system. It allows for the calculation of the probabilities of the outcomes of any measurement performed on the system.

$$\rho_{AB} = \begin{bmatrix} 0.0097096622 & 0 & 0 & -0.0980580676 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -0.0980580676 & 0 & 0 & 0.9902903378 \end{bmatrix}$$

The figure below is a state-city plot of the density matrix for the ground state of the quantum entangled system of the QET model.

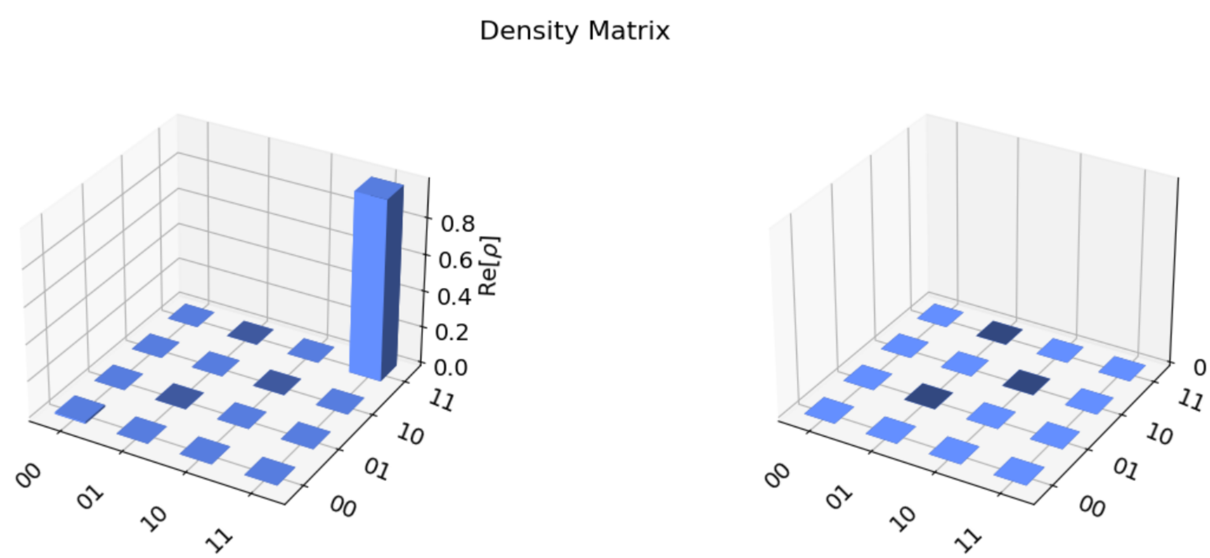

Fig. 7 State-city plot for density matrix of ground-state

Since Alice and Bob are entangled, any changes in the system are reflected by the state of Bob. Thus, after tracing Alice, the reduced state of Bob is as follows:

$$\rho_B = \begin{bmatrix} 0.0097096622 & 0 \\ 0 & 0.9902903378 \end{bmatrix}$$

Using this reduced state of Bob we calculate the entropy of the ground state, **SAB(g)**.

The circuit below shows the conditional operations of Bob. After measurements were made to Alice's qubit, Bob performs conditional operations to his qubit based on the outputs (μ) observed by Alice. Measurements made to Alice's qubit is what causes energy to be deposited into the system.

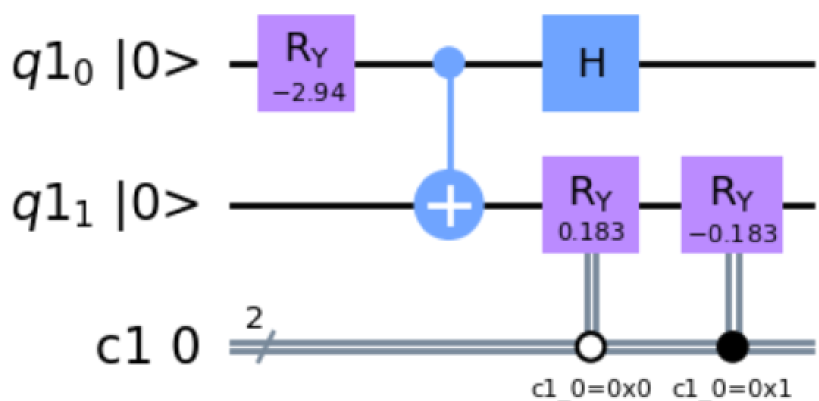

Fig.8 Bob performing conditional unitary operations based on the output of Alice

Then we again find out the statevector for the new state that the system exists in after Bob's operations.

$$|\psi_{AB}\rangle = 0.0696766179|00\rangle + 0.0696766179|01\rangle - 0.7036655235|10\rangle + 0.7036655235|11\rangle$$

Next, we calculate the density matrix for the mixed state in which the quantum system exists. The result is as shown below.

$$
\rho_{AB} = \begin{bmatrix} 0.0048548311 & 0.0048548311 & -0.0490290338 & 0.0490290338 \\ 0.0048548311 & 0.0048548311 & -0.0490290338 & 0.0490290338 \\ -0.0490290338 & -0.0490290338 & 0.4951451689 & -0.4951451689 \\ 0.0490290338 & 0.0490290338 & -0.4951451689 & 0.4951451689 \end{bmatrix}
$$

The figure below is a state-city plot of the new density matrix, to help better visualize the condition that the system is in.

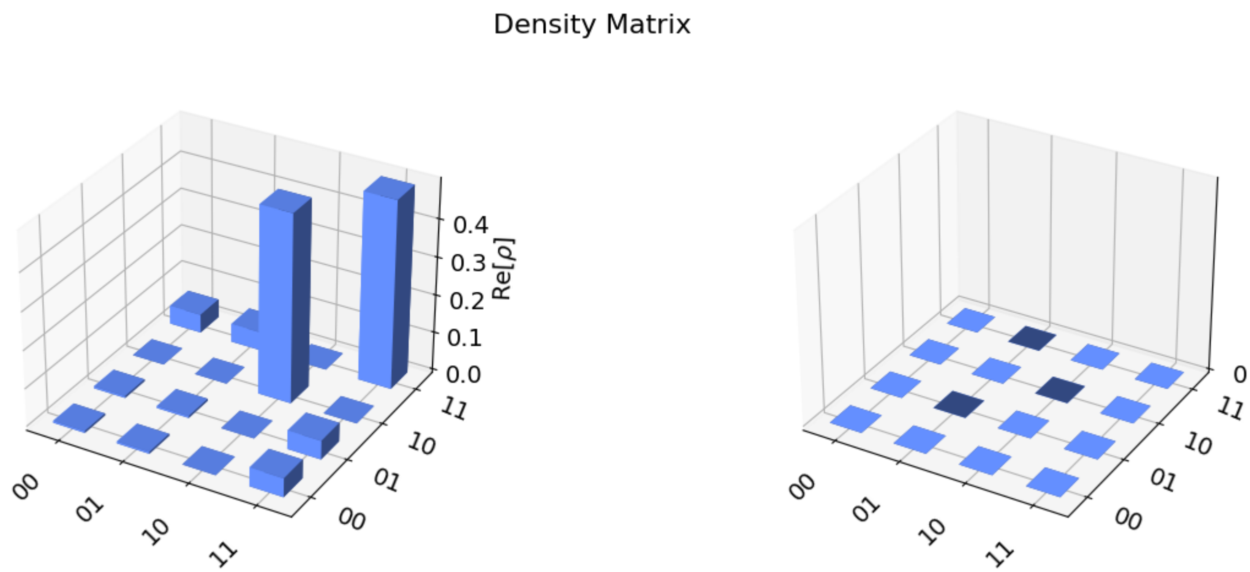

Fig. 9 State-city plot for density matrix of state of Bob post-measurement

After the measurements conducted on Alice outputting ‘µ’, the reduced state of Bob is as shown below.

$$
\rho_B = \begin{bmatrix} 0.0097096622 & 0 \\ 0 & 0.9902903378 \end{bmatrix}
$$

Using this we calculate the entropy of the quantum system, post-measurement, **SAB(μ).** The difference between the two entropies **SAB(g)** and **SAB(μ),** gives us insight into how much breaking of the entanglement occurs for different values of 'h' & 'k', which are added so that the ground state |g >, returns the zero mean energy for all local and global Hamiltonians. We then compare these data of changes in entropy, $\mathbf{\Delta S_{AB}}$**,** to $\boldsymbol{\lambda_{AB}}$ which is the maximum amount of energy that can be teleported using the minimal QET model.

The graphs below show the results of our experiments conducted to observe changes in the entropy of the system with the maximum amount of energy that can be teleported using the minimal QET model. The graphs below show the variations for $\mathbf{\Delta S_{AB}}$ and $\boldsymbol{\lambda_{AB}}$ both individually as well as a combination of both to help better analyze the data. For all the experiments we kept the value for 'h' fixed at 1 and varied the values for 'k' for obtaining good observation values. The first 3 graphs represent the outcomes of the theoretical study of our project and the last 2 graphs represent the actual outcomes obtained using IBM quantum resources.

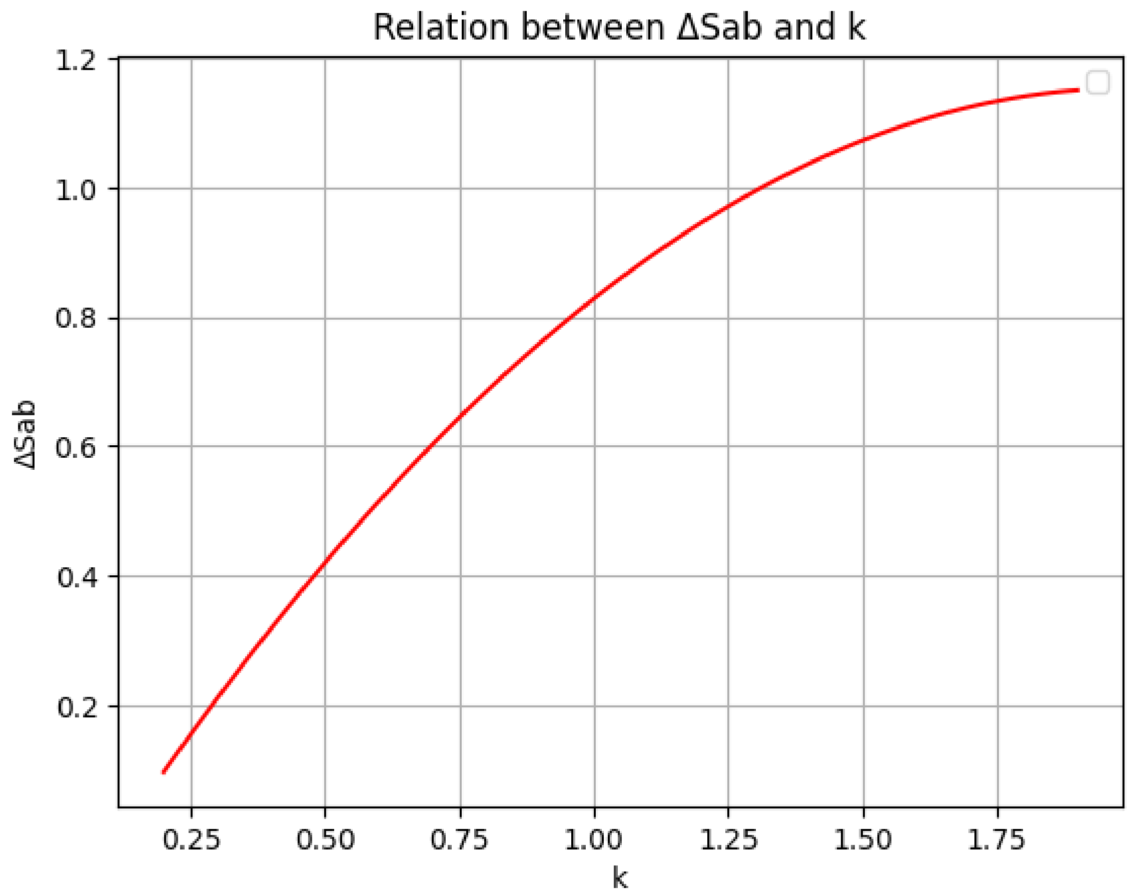

Fig. 10 Graph for changes in $\boldsymbol{\Delta S_{AB}}$ for a range of values of ‘k’ based on theoretical data

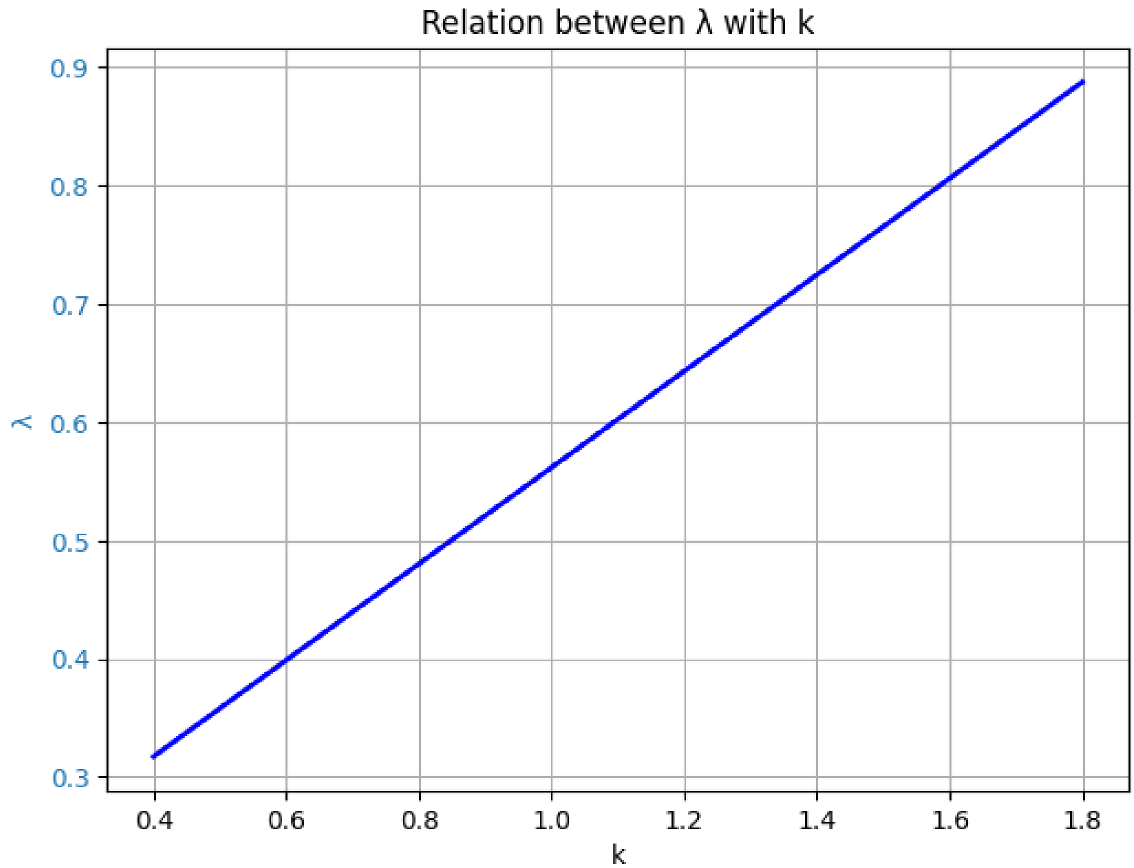

Fig. 11 Graph for changes in λ_{AB} for a range of values of ‘k’ based on theoretical data

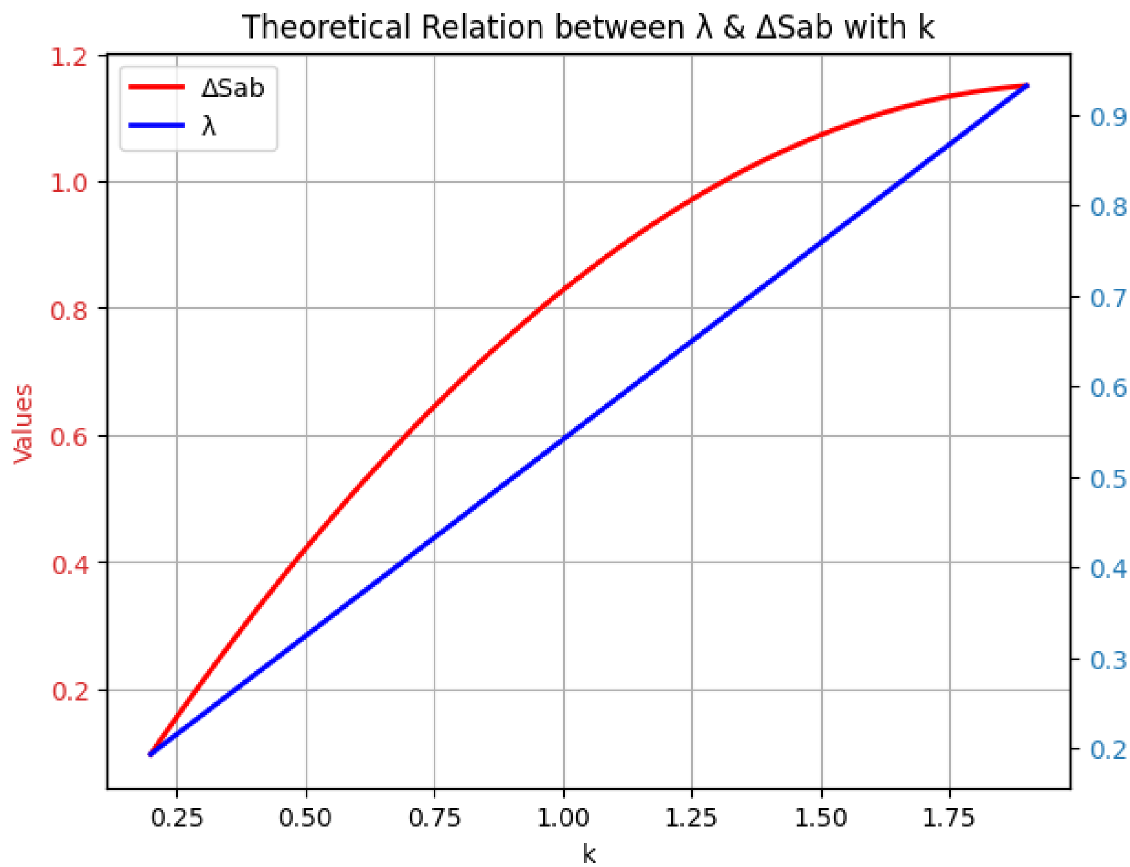

Fig. 12 Graph for comparison of $\mathbf{\Delta S_{AB}}$ and $\boldsymbol{\lambda}_{\mathbf{AB}}$ based on theoretical data

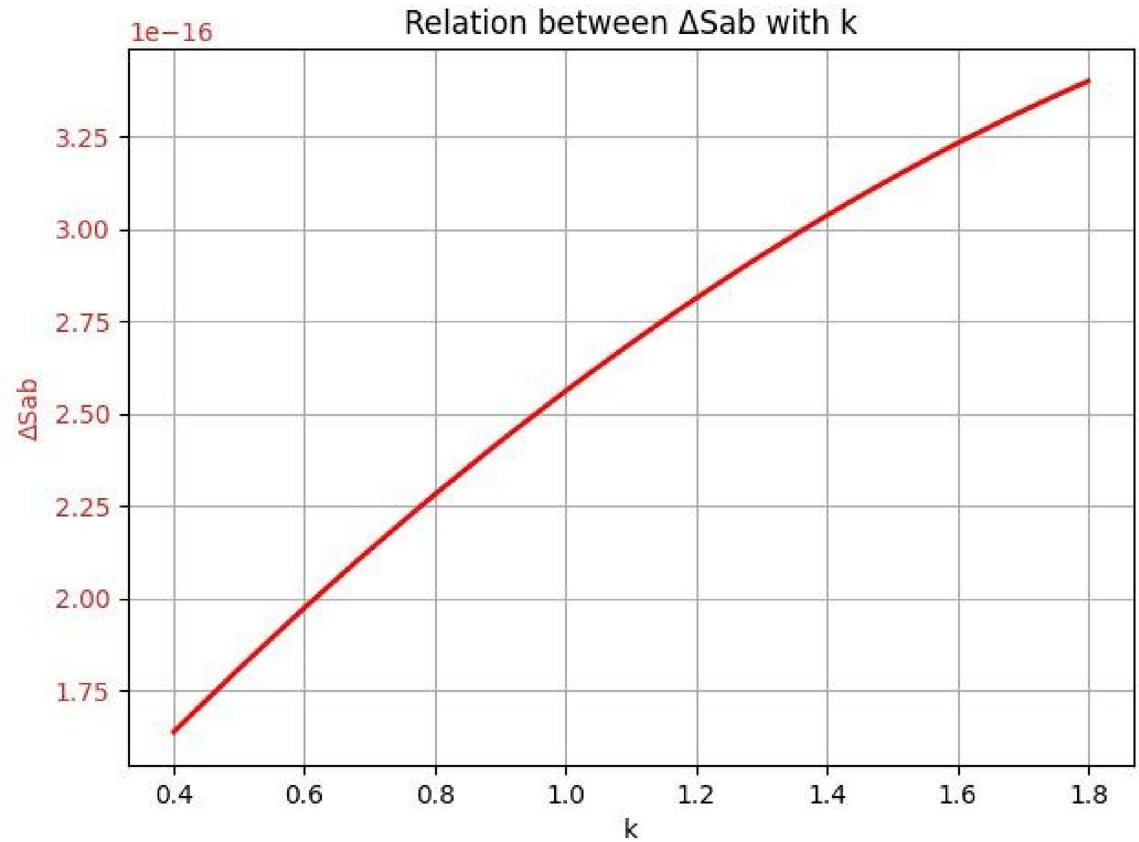

Fig. 13 Graph for changes in ΔS_{AB} for a range of values of 'k' based on actual experimental data

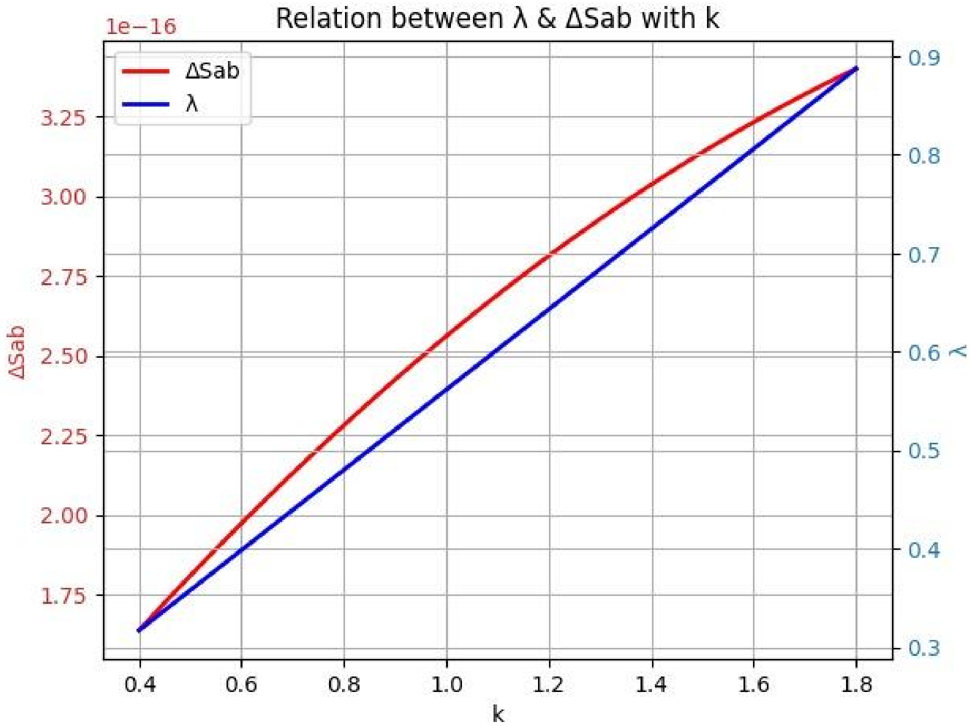

Fig. 14 Graph for comparison of $\mathbf{\Delta S_{AB}}$ and $\boldsymbol{\lambda_{AB}}$ based on actual experimental data

There were three main criteria when analyzing the graphs: ΔSab and $\boldsymbol{\lambda_{AB}}$ curves should have similar shapes, ΔSab must always be a positive value, and both ΔSab and $\boldsymbol{\lambda_{AB}}$ curves must be of the same scale. We observed that all these criteria were met by the theoretical curves of ΔSab and $\boldsymbol{\lambda_{AB}}$ while in the case of the experimental data, the curves followed similar trends and shapes with ΔSab being positive, but the experimentally obtained ΔSab values were significantly smaller. Another observation was that outlier values for ΔSab were obtained against the same value for k in both theory and experiment. Thus, we conclude on the note that both theoretical and experimental results show similar trends and graph patterns. However, due to the problems we encountered, there are differences in theoretical and experimental data, namely outlier and high differences in values of $\mathbf{\Delta S_{AB}}$ for the identical pairs of 'h' and 'k' values, resulting in an inconsistency with the inequality mentioned in theories by Hotta.

$$\Delta S_{AB} \geq \frac{1+\sin^2\varsigma}{2\cos^3\varsigma}\ln\frac{1+\cos\varsigma}{1-\cos\varsigma}\frac{\max_{U_B(\mu)} E_B}{\sqrt{h^2+k^2}}$$

k	ΔSab	λ
0.3	0.2044787068245936	0.1628272986639153
0.4	0.3084643821749318	0.23933284330823718
0.8	0.691212288447885	0.5083486520090588
0.9	0.7664873033857416	0.5605850029878001
1.6	1.0904965916643385	0.7874718587045185
1.8	1.1401700323653945	0.8227418088592062

Table II: Theoretical values of ΔSab and λ obtained in relation to k

k	ΔSab	λ
0.3	8.326672684688674e-17	0.1628272986639153
0.4	1.6653345369377348e-16	0.23933284330823718
0.8	2.220446049250313e-16	0.5083486520090588
0.9	2.220446049250313e-16	0.5605850029878001
1.6	3.3306690738754696e-16	0.7874718587045185
1.8	3.3306690738754696e-16	0.8227418088592062

Table III: Experimental values of ΔSab and λ obtained in relation to k

Chapter 5 Impacts of the Project

5.1 Impact of this project on societal, health, safety/security, legal and cultural issues

Quantum Energy Teleportation (QET) is an innovative idea with the potential to bring about significant transformations in the fast-evolving field of quantum technology. The use of ideas from quantum entanglement and information theory in energy transfer has attracted significant interest in the scientific community, due to its revolutionary paradigm shift. Although the technical components of QET are still being intensively studied, it is crucial to thoroughly examine the wider sociological, health, safety, security, and legal aspects of its implementation. Additionally, exploring the potential implications of energy entanglement relationships is essential for a thorough understanding of QET's transformative impact.

Societal Impact:

Quantum Communication Technology: QET enables the transfer of quantum energy over long distances. This breakthrough ushered a new era of quantum communication. Imagine an interconnected quantum internet, where energy and information are traded seamlessly. Traders could choose the most economical sources for their needs[7].

Fundamental Research Connections: QET has links to various fundamental research fields.

Black-hole physics: Insights from QET could enhance our understanding of black holes.

Maxwell's demon: QET relates to the quantum theory of Maxwell's demon, which challenges the second law of thermodynamics.

Quantum entanglement: QET's principles intersect with condensed matter physics and quantum entanglement[1].

Increased Energy Efficiency: Quantum energy teleportation could provide a much more efficient way to transmit energy than current methods. This might result in less energy waste and cheaper consumer costs, which would be advantageous to both people and companies. Quantum energy teleportation could provide a much more efficient way to transmit energy than current methods, resulting in less energy waste and cheaper consumer costs[8].

Global Energy Access: The ability to teleport energy remotely could provide a reliable and accessible energy source to regions currently facing shortages. This could empower communities, improve living standards, and promote economic development.

Economic Growth: The development of this technology could create new industries and jobs across various sectors, leading to economic growth and prosperity.

Improved Education and Communication: The teleportation of information along with energy could revolutionize communication and education, especially in remote areas. This could provide access to quality education and learning opportunities for all, regardless of their location.

Enhanced Public Services: The improved efficiency and reliability of energy that is easily transferable to any part of the world could translate to better public services, such as improved healthcare, transportation, and communication infrastructure.

Increased Innovation: The understanding and application of quantum energy teleportation could inspire new inventions and innovations across various fields, leading to advancements in science, medicine, engineering, and other sectors.

Impact on Health:

1. Enhanced Medical Diagnosis:

Quantum Imaging Techniques: The principles of quantum entanglement and teleportation could be applied to develop new imaging techniques with superior resolution and sensitivity compared to existing methods. Quantum imaging techniques have the potential to bring about substantial improvements in imaging resolution and sensitivity. This, in turn, might provide earlier and more precise detection of illnesses such as cancer, Alzheimer's, and heart disease[9].

Personalized Medicine: Medical practitioners could create customized treatment regimens based on each patient's particular requirements and response to medication by using quantum technologies to analyze individual genetic and biological data**.** Quantum computing could increase the efficiency, accuracy, or speed of some machine learning methods, leading to more specialized and effective medical care[10]. More specialized and effective medical care could arise from this.

2. Advanced Treatment Options:

Targeted medication delivery: Quantum energy teleportation holds the potential to enhance therapeutic efficacy and minimize side effects by precisely delivering medications to diseased cells. This might completely alter how illnesses like cancer are treated.

Gene Therapy: Quantum technologies could be used to safely and efficiently deliver gene-editing tools to specific cells, potentially leading to cures for genetic diseases. With the ability of quantum computers, we will be able to form thousands of combinations of a drug in the blink of an eye and analyze millions of gene sequences within seconds to find which sequences to target for therapy.

Quantum Surgery: The ability to control and manipulate energy at a quantum level could enable minimally invasive and highly precise surgical procedures, reducing risks and improving patient recovery times.[11]

3. Improved Healthcare Access and Delivery:

Telemedicine and telepresence: Quantum teleportation's increased efficiency and reliability of communication could improve telemedicine and telepresence, enabling remote consultations and patient monitoring.

Decentralized Healthcare Infrastructure: Quantum technologies could contribute to the development of a more decentralized healthcare system, empowering individuals to take control of their health and manage their own data.

Impact on Security:

Quantum Energy Teleportation (QET), while still in the realm of theoretical exploration, holds significant implications for security and defense. Let's delve into its potential impact:

Quantum Technologies in Defense and Security: NATO acknowledges quantum as a crucial emergent and disruptive technology owing to its capacity for transformation.[12]. Quantum technologies exploit phenomena at the atomic and sub-atomic scale, where the world becomes probabilistic rather than deterministic.

Quantum-resistant Cryptography: With the advancement of quantum computers, traditional encryption methods will become vulnerable. The research on energy-entanglement relationships might be crucial for developing novel, quantum-resistant cryptographic protocols that can withstand even the most powerful quantum attacks. [13]

Secure Communication Channels: Quantum energy teleportation could be used to set up very safe communication channels where data is stored in the energy levels of particles that are entangled with each other. This could revolutionize secure communication for government, military, and financial institutions.

Space-to-Ground Quantum Communication: Researchers aim to achieve quantum communication between space and the ground. Such communication would be crucial for future quantum networks in space[14].

Enhanced Network Security: Quantum energy teleportation could be utilized to develop new techniques for intrusion detection and prevention systems. A quantum network can teleport information between unconnected nodes using quantum entanglement, which is an important step towards building a super-secure quantum internet[15]. By monitoring the entanglement patterns in network traffic, researchers can identify and neutralize cyberattacks more effectively.

Securing Sensitive Data: Quantum technologies can encrypt and store sensitive data in a way that is virtually impossible to crack, even with advanced computing capabilities. This could significantly enhance the security of critical infrastructure, financial records, and personal data.

National Security and Defense: Quantum-enabled Surveillance and Intelligence Gathering, Researchers might develop more sophisticated surveillance and intelligence-gathering technologies by manipulating energy states and entanglement patterns. This could have implications for national security and defense capabilities.

Quantum-resistant Defense Systems: The correlation between energy and entanglement can facilitate the development of quantum-resistant defense systems capable of safeguarding against adversaries leveraging quantum technologies.

Legal Implications:

While the legal impact of QET is not explicitly addressed in the available research, its potential applications could be far-reaching. As quantum technologies advance, legal frameworks may need to adapt to address issues related to energy teleportation, security, and ownership. For instance, once a quantum internet becomes available (likely in the 2030s), energy teleportation could revolutionize power distribution and raise legal questions about rights, responsibilities, and regulations[7].

Patenting Quantum Technologies: The development of quantum energy teleportation technologies will likely lead to a surge in patent applications. Establishing clear guidelines and standards for patenting these technologies will incentivize innovation while preventing patent thickets and ensuring fair competition.

Protecting Entangled Data: With the potential for sensitive information to be encoded in the energy states of entangled particles, robust legal frameworks are needed to protect the privacy and security of this data. This may involve adapting existing data protection laws or developing entirely new legal frameworks to address the unique challenges posed by quantum technologies.

Transnational Data Flows of Entangled Information: The international nature of quantum research and development necessitates the harmonization of legal frameworks governing the transfer of entangled data across borders. This will require international cooperation and dialogue to ensure the smooth flow of information while protecting individual privacy and national security interests.

Contract Law and Liability: As the technology evolves, legal frameworks will need to address potential liability issues arising from failures in quantum energy teleportation processes. This may involve establishing clear rules regarding responsibility for damages caused by errors or malfunctions in the technology.

Cybersecurity Threats and Quantum Technologies: Quantum technologies could be used to develop more sophisticated cybercrime methods. Quantum computing could be used to break most modern cryptography, rendering communications as insecure as if they weren't encoded at all [16]. In order to effectively enforce cybercrime laws and address these evolving threats, legal frameworks will need to be modified.

International Cooperation and Legal Harmonization: As the development and deployment of quantum energy teleportation technologies are likely to transcend national borders, international cooperation and harmonization of legal frameworks will be critical to ensuring responsible governance and preventing conflicts.

Public Education and Legal Awareness: In order to ensure fair and equal application of the law in this quickly developing field, it will be imperative to educate legal experts and the general public about the legal and ethical implications of quantum technology.

5.2 Impact of this project on Environment and Sustainability

Impact on Environment and Sustainability:

Quantum Energy Teleportation (QET) is a cutting-edge topic in the discussion of energy technology. It holds the potential to provide creative solutions to the urgent problems we face today. The use of quantum entanglement and information theory concepts in energy transfer not only places QET at the forefront of scientific advancement but also prompts a rigorous evaluation of its potential influence on the environment and sustainability. Our study investigates the fundamental mechanisms of a technology that has the potential to revolutionize the provision of energy and communication. As we explore this frontier, environmental scientists and policymakers will need to consider the ecological effects and sustainability of energy teleportation in the quantum era.

Renewable Energy Transmission: Quantum energy teleportation could revolutionize renewable energy integration by enabling long-distance transmission of energy generated from solar, wind, and geothermal sources with minimal losses. This could significantly reduce reliance on fossil fuels and combat climate change.

Smart Energy Grids: Quantum energy teleportation could enhance the creation of more resilient and efficient smart grids that maximize energy consumption and minimize environmental effects by permitting real-time monitoring and control of energy flows across the grid.

Long-distance Transmission: Quantum energy teleportation holds the potential to revolutionize renewable energy integration by enabling efficient and loss-minimized transmission of solar, wind, and geothermal energy over vast distances. By doing so, reliance on fossil fuels and the greenhouse gas emissions they produce can be greatly reduced, encouraging a move toward clean energy sources.

Reduced Energy Consumption: Quantum communication, utilizing entangled particles for information transfer, offers significantly lower energy consumption compared to traditional methods. This translates to a reduced environmental footprint and contributes to overall energy sustainability.

Chapter 6 Conclusions

6.1 Summary

On the end note, we can conclude by saying that both the theoretical and experimental data and graphs follow similar trends and patterns. They agree with the motion of Hotta as described in his studies, that change in entropy has to be larger than the amount of energy that can be teleported using the minimal QET model. Despite the similarities, there exist variations in theoretical and experimental data, including outlier values for the same pairs of 'h' and 'k' values, due to the difficulties we faced. The quantum servers that we used from the IBM Quantum Platform kept changing the servers every week, and sometimes within days. Different servers mean different numbers of qubits it is capable of handling and thus different error maps, thus resulting in different results each time. The servers we initially used were ibmq_lagos, ibmq_quito, ibmq_belem, ibmq_nairobi, ibmq_lima, ibmq_jakarta. The first 3 servers are 5 qubit systems and the rest are capable of handling 7 qubits max. Unfortunately, these servers are no longer available for use in the IBM Quantum Platform, resulting in us not being able to verify and experiment further. The job queues were sometimes as high as 100000, sometimes causing the runtime to get canceled since it was taking too long. Despite all the difficulties we faced, we tried our very level best to produce and report meaningful results from the experiments conducted for our study.

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