A Test Suite for Quantum Network Applications

Quantifying an Application's Ability to Benchmark a Quantum Network

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Abstract

Quantum networks provide numerous potential benefits over classical networks, such as enhanced security and faster computation, making their further development a lucrative prospect. As is the case with any technology, the advancement of quantum networks relies on the development of frameworks to test their quality, and compare different implementations of the technology. One such framework is a benchmarking suite for quantum network systems, that can identify areas for improvement in their implementation, by determining the erroneous properties of the system.

This paper examines the viability of using a specific quantum network application as a benchmark for quantum network systems. In order to quantify the application's ability to benchmark, we assess its sensitivity to changes in the properties of the system. These properties include link parameters, quantum gate properties, qubit coherence times, and measurement properties.

We use the BB84 protocol as the benchmarking application for this project, which is a Quantum Key Distribution scheme used to establish secure keys between two parties. In particular, we use the qubit error rate and the key generation rate as the performance metrics for the application. For the setup of the experiments, we prepare two system configurations: generic quantum device nodes with a depolarising error channel, and NV device nodes with a heralded link. In order to assess how the application behaves with changes to different system properties, we observe how the performance metrics change while individually varying system parameters and keeping all other parameters constant.

We find that the application is sensitive to changes in multiple parameters across both network configurations, such as link parameters, single qubit gate properties, and measurement properties. Contrarily, the application is not affected by changes to parameters such as two qubit gate properties and coherence times. We conclude that the BB84 protocol can be used as an individual localised test for the parameters it is sensitive to, and also in combination with other applications, in a more comprehensive benchmarking suite, that provide coverage for a broader range of parameters.

1 Introduction

The advent of quantum technology has led to the emergence of quantum networks. There are several potential benefits of quantum networks compared to their classical counterparts, such as enhanced communication security and improved computational speed [1] [2]. These advantages make the further research and development of quantum networks extremely lucrative. Consequently, there have been numerous advancements in the field of quantum networks. For instance, QuTech's development of the world's first full stack quantum network system [3], as part of the Quantum Internet Alliance. Various such organisations are working to innovate and improve quantum network technology.

The rapid development of any technology naturally results in the need for systems that are able to assess the quality of implementations of the technology, and compare the quality of different instances of said technology. Quantum networks are no exception to this requirement. Therefore, the development of benchmarking frameworks for quantum network systems is essential to their advancement [4].

The possible errors in quantum networks arise from imperfections in quantum hardware, such as characteristics of quantum entanglement, quality of quantum operations, and memory lifetimes. Through benchmarking, it is possible to identify areas for improvement, thereby potentially optimising system performance.

With this project, we aim to contribute to a benchmarking suite for quantum network systems. The objective of the project is to provide an evaluation of a quantum network application's ability to benchmark a quantum network. In this paper, we explore the sensitivity of the application in detecting changes to certain properties of quantum networks, such as the fidelity of entanglement, entanglement times, quantum gate properties, and qubit coherence times.

By quantifying the sensitivity of a quantum network application in recognising errors in a quantum system, we can discern how informative the application is as a benchmark about the system. The results of this research can aid in the development of improved benchmarking frameworks for quantum networks, potentially enabling the widespread use of such networks in various fields [5].

A complete benchmarking suite is one that provides coverage of all parameters of a network system. Such a suite consists of several benchmarking applications that each provide coverage for a specific set of parameters. These applications should have minimal overlap between the parameters they are sensitive to, and the disparity between the number of parameters covered by each application should also be minimised. Therefore, a type of benchmarking application that could be useful in such a suite is one that is sensitive to a specific set of parameters, ensuring that the application is specialised to assess certain properties of the system, and that its coverage is not too broad.

Thus, the main research question for this research project is,

> For a particular quantum network application, namely the BB84 protocol, how informative is this application as a benchmark about the system? That is, how sensitive is the application in recognising errors in a number of properties of the total quantum system, such as quality of quantum entanglement, quality of quantum operations, and memory lifetimes?

The rest of this paper is structured in the following way: Section 2 describes the process of the experiments and provides a description of the chosen application. Then, Section 3 talks about the setup of the experiments and briefly describes the results obtained, and Section 4 explains how these results can be reproduced. Section 5 discusses the results and their implications in detail. Section 6 mentions any possible future improvements and Section 7 concludes the analysis. Appendix A provides background information on quantum computing, for any readers less familiar with the concept.

2 Methodology

In order to test an application's ability to benchmark a quantum network, we must observe how the application's performance changes, if at all, with respect to changes in the network system.

In particular, we will test the BB84 Protocol and its ability to benchmark a quantum network system. The protocol is named after its founders, Charles Bennett and Gilles Brassard, and the year of its development, 1984. The implementation of the BB84 protocol is provided in the NetQASM GitHub repository [6].

The BB84 Protocol

The BB84 Protocol is a Quantum Key Distribution protocol that allows two parties to exchange a secure cryptographic key over a potentially insecure communication channel [7]. This communication is done by transmitting each bit in a key in one of two bases, the X and Z quantum bases, which is then received and subsequently randomly measured in either of the two possible bases. After this exchange, the two parties communicate the bases they used to measure each bit, and discard any bits where they used different bases. The bits with matching bases form the raw key. A visualisation of this protocol can be found in Figure 1.

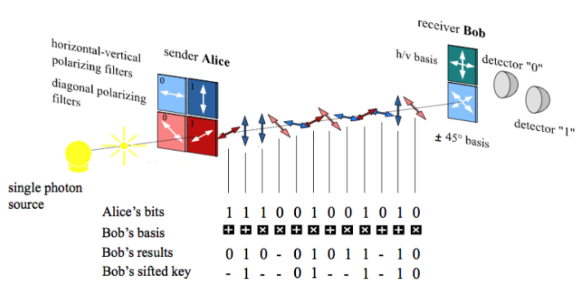

Figure 1: Visualisation of the BB84 Protocol

Process

In order to test the BB84 protocol's ability to benchmark, we will examine its effectiveness in assessing certain properties of a quantum network. Properties such as quality of entanglement, quality of quantum operations, and memory lifetimes will be assessed in this project. There are multiple performance metrics in the application that can be used to potentially benchmark a quantum network system. However, the fundamental characteristic of a quantum communication protocol is its Qubit Error Rate (QBER).

The QBER is the proportion of bits received that were different from the bits transmitted, despite being measured in the same basis on either side. Moreover, in order to gain further insight into the working of the application, we look at the QBER for bits measured in either basis separately, thus splitting the metric into X basis QBER and Z basis QBER. This distinction between both bases helps us understand how different parameters of the stack affect the quantum state of the qubits in the application.

Another metric we will use to determine the application's sensitivity is its key generation rate, which is the number of bits generated by the application in one second. Using this metric we can determine how time based parameters, such as measurement times, affect the amount of bits generated in the raw key per unit time. It should be noted that the key generation rate only takes into account the length of the raw key, thus disregarding any bit flips caused by the transmission. Thus, parameters such as gate depolarisation probabilities will not affect the key generation rate. This was done in order to keep the key generation rate independent from the qubit error rate.

The project uses SquidASM [8], an SDK developed at QuTech that helps users create quantum network applications. SquidASM allows users to write quantum network protocols in high-level language, which is then converted to NetQASM [9] (which has an assembly-like structure). All code in this project will be run on a simulator called NetSquid [10], rather than on real hardware. This choice was made after taking into account the ability to precisely tune parameters in a simulator, as well as the ease of switching between different implementations of a quantum system.

The experiments are conducted by individually varying each network parameter, in order to assess the change in performance with respect to changes in the parameter. In most cases, while varying a parameter, all other parameters will be set to their ideal state (perfect fidelity and no errors). This decision was made in order to ensure that the errors in other parameters do not contribute to the assessment of the individual parameter. In certain cases, one or more parameters was set to an imperfect but constant value, this was done due to the the dependence of some parameters on other parameters.

The experiments are executed on two types of quantum network configurations. The first system is a setup consisting of two nodes, which are generic quantum devices, connected with a magic state distribution link with depolarising error (hereon referred to as a "depolarise link"). The second setup also consists of two nodes, which are Nitrogen Vacancy (NV) centre quantum devices [11], that are connected using a heralded link [12].

Hypothesis

For an application such as the BB84 protocol, we expect that certain parameters do not affect the performance metrics of the application. Firstly, we expect that two qubit gate properties do not affect the system's performance, due to the clear absence of any two qubit gate operations in the application. Furthermore, we expect that coherence times also do not affect the performance metrics. This is attributed to the lack of any real processing of the qubits on either node i.e. the qubit does not undergo a series of operations on either the sender or receiver node.

Depolarise Link	Sensitive
Link fidelity	Yes
Entanglement generation time	Yes
Entanglement generation probability	Yes

Generic Quantum Device	Sensitive
Single qubit depolarisation probability	Yes
Two qubit depolarisation probability	No
Single qubit gate time	Yes
Two qubit gate time	No
Measurement time	Yes
Coherence times	No

Table 1: A table depicting whether the BB84 protocol can detect changes in a network system parameter for a generic device with a depolarise link

Heralded Link	Sensitive
Length	Yes
Attenuation coefficient	Yes
Probability of photons being lost when entering the connection	Yes
Dark count probability	Yes
Detector efficiency	No
Hong-Ou-Mandel visibility	Yes

NV Quantum Device parameters	Sensitive
Single qubit depolarisation probability	Yes
Two qubit depolarisation probability	No
Qubit initialisation depolarisation probability	No
Probability of measuring a 1 instead of 0	Yes
Probability of measuring a 0 instead of 1	Yes
Coherence times	No

Table 2: A table depicting whether the BB84 protocol can detect changes in a network system parameter for an NV device with a heralded link

3 Experimental Setup and Results

In this section, the results of the experiments, as well as the setup of the simulation environment are discussed. To comprehensively assess the application's sensitivity to a specific parameter within the network stack, we must observe any changes in the application's performance metrics while varying said parameter exclusively. Thus, we must keep all other network parameters constant and, if possible, perfect, i.e. the rest of the parameters do not cause any errors in the system. The experiments are grouped by the type of quantum network system they are executed on, as described in Section 2.

Any parameters which were found to not affect the performance metrics are not included in the plots displayed in this section, due to these plots showing only trivial data. Finally, it was found that there was an innate similarity in varying time based parameters in NV and generic quantum devices, i.e. an obvious inverse relationship between the key generation rate and all time-based parameters. Due to this similarity, only plots from the generic quantum device are included for the time-based parameters.

Generic Quantum Device with a Depolarise Link

The first experiments are conducted on a simulated generic quantum device, with a channel between the sender and receiver node that contains depolarising noise. For this setup, there are many possible parameters to be varied, across the node and link stacks. However, some parameters clearly do not contribute to the execution of the application, such as two qubit gate parameters, as the application does not contain any two qubit gates. The variation of two of these parameters, namely the single qubit gate fidelity of the generic device and the fidelity of the depolarise link, affects the QBER in the network stack for the BB84 protocol. These results can be seen in Figure 2.

Furthermore, there are several time-based parameters for a quantum network setup such as entanglement times, memory times, and gate execution times. Out of all the parameters, we find that the variation of four parameters directly affects the key generation rate of the application. These parameters are: the entanglement generation time, entanglement generation probability, single qubit gate execution time, and the measurement time. Figure 3 displays how the time-based parameters relate to the key generation rate. In order to test the entanglement generation time, the entanglement generation probability had to be set to an imperfect value of 0.8. Similarly, in order to test the entanglement generation probability, the entanglement generation time was set to 1000ns. Table 1 indicates whether the parameters of this setup affect either performance metric.

NV Device with a Heralded Link

The next step was to conduct similar experiments on an NV quantum device, with a heralded link between the two nodes. Similar to the previous setup, there are several parameters that do not affect the application's performance, such as rotation fidelities and two qubit gate operations.

In most cases, other parameters are set to their ideal state when testing individual parameters. There are three exceptions to this rule: the length of the heralded link, the error probability of a photon entering the connection, and the attenuation coefficient of the fibre. For these three parameters, the dark count probability is set to a small but non-zero constant value of 0.01. Furthermore, for the attenuation coefficient, the length of the link is set to 100km. Similarly, for the length of the link, the attenuation coefficient is set to 0.1, as these two parameters are codependent. In Figure 4, it is shown how the parameters of this setup affect the QBER of the application.

As mentioned earlier, the time-based parameters for both setups are similar and affect the key generation rate in a similar manner. Thus, the results for the key generation rate for this setup are not included. Figure 3 depicts the relationship between the time-based parameters from the previous setup and the key generation rate. Table 2 shows whether the parameters of this network setup affect the required performance metrics.

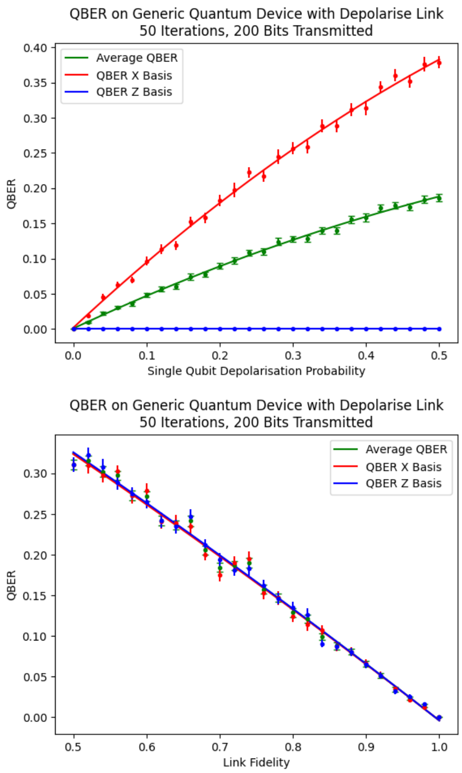

Figure 2: Qubit error rate on a generic quantum device with a depolarise link

4 Responsible Research

For any research, it is essential that all results are reproducible. It is also important that any claims made in the research are backed up by thoroughly conducted experiments. In this project, we aim to uphold the same high standards of research.

Section 2 clearly underlines the method used for the execution of the experiments, as well as a justification of the chosen performance metrics. Furthermore, the exact application being used is provided, and an explanation of the simulation platform is also present. Lastly, Section 3 describes the parameters that are set to an imperfect value due to a dependence between parameters, as well as their exact value.

It is inevitable that most experiments include some randomness in the results, and this is especially true in the case of quantum computing. In order to account for this randomness, the experiments are executed 50 times for each parameter value, while also transmitting 200 bits in each iteration. The high number of total shots provides us with an accurate estimation of the required performance metrics. Thus, replicating these experiments with a similarly high number of iterations should result in similar results.

5 Discussion

In this section, the results of Section 3 are discussed in depth. The discussion is divided based on the type of link or quantum device for which the parameters are being tested.

Depolarise Link

The second plot in Figure 2 shows how the QBER changes with the fidelity of the depolarise link. It can be seen that the link fidelity is inversely proportional to the QBER. Furthermore, both the X and Z basis QBERs are similarly proportional to the link error probability. This result proves that the link fidelity does not discriminate between qubit states.

The top two plots of Figure 3 depict the relationship of the key generation rate, with the entanglement generation time and entanglement generation probability respectively. The entanglement generation probability is the probability that an attempt of entanglement between the two nodes is successful. Furthermore, one attempt of entanglement takes the same amount of time as specified in the entanglement generation time. Therefore, reducing the entanglement probability or increasing the entanglement time will result in the protocol taking longer to execute. Thus, the entanglement generation time is inversely proportional to the key generation rate. Similarly, the probability of the entanglement failing is also inversely proportional to the key rate.

This implies that the BB84 application can benchmark the three parameters of the depolarise link, as it is sensitive to changes in all properties of the link.

Generic Quantum Device

The first plot in Figure 2 shows how the QBER changes with the depolarisation probability of a single qubit gate. It can be seen that the depolarisation probability increases with the overall QBER. For this parameter, the X and Z basis QBERs behave differently. As seen in the plot, the Z basis QBER is not affected by the single qubit gate error. This is due to the working of the BB84 protocol; a gate (the hadamard quantum gate) is only applied to the qubit if it is supposed to be in the X basis. Therefore, no gates are applied to the Z basis qubits, hence the gate errors do not affect qubits in this basis.

The bottom two plots of Figure 3 shows how the key generation rate is affected by the gate execution time and the measurement time. These parameters have a relatively straightforward relationship with the key rate, increasing either parameter simply increases the overall execution time of the application, which in turn reduces the key generation rate. Thus, the key generation rate is inversely proportional to the gate execution time and the measurement time.

Overall, this means that the application can detect changes to a few parameters of a generic quantum device. However, other important parameters such as the relaxation time, phase coherence time, and the two qubit gate properties do not affect the performance metrics of the application. Therefore the BB84 protocol can function as a benchmarking application for single qubit gate properties and measurement times,

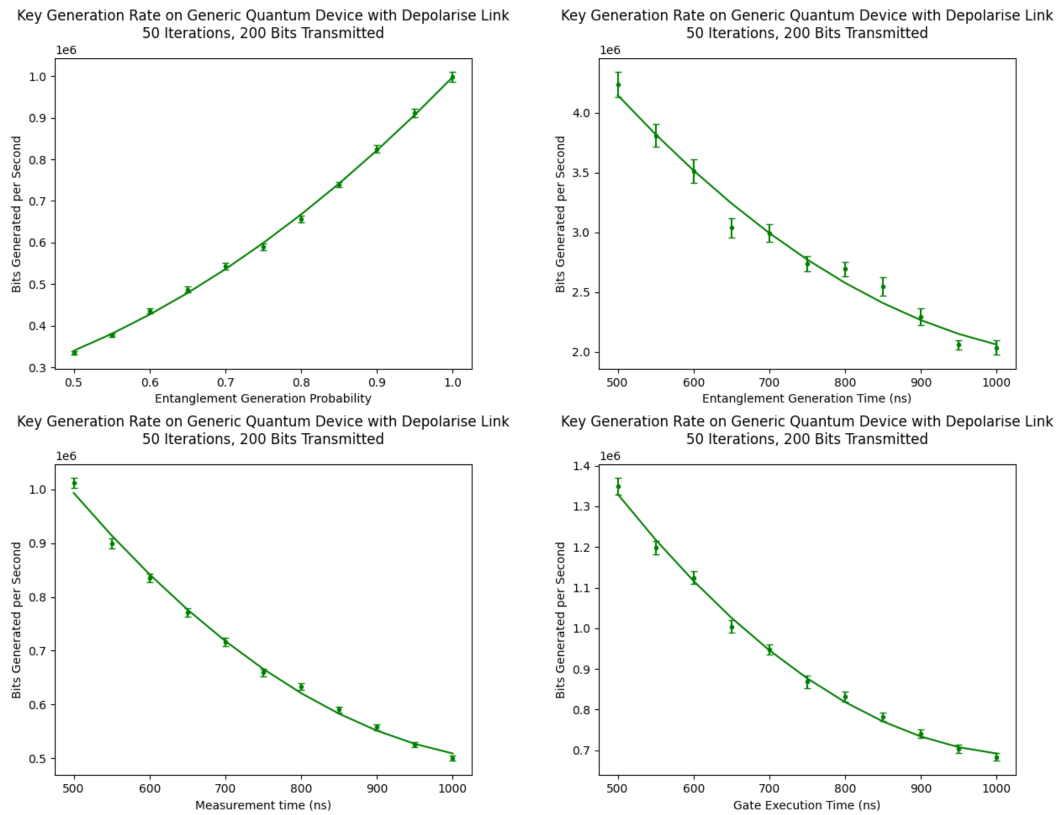

Figure 3: Key generation rate on a generic quantum device with a depolarise link

but not parameters such as two qubit gate properties or coherence times. This is in line with the hypothesis discussed in Section 2.

Heralded Link

The first five plots of Figure 4 portray the relationships between five parameters of the heralded link and the QBER of the application. The Hong-Ou-Mandel visibility directly affects the entangled state fidelity of the system [12], potentially causing dephasing of the qubit. Thus, a lower visibility directly translates to an increased X QBER, as seen in plot 1. Furthermore, it is important to note that the separation between the QBERs of different bases which can be seen in the parameters in plots 2-4 is present due to the non-zero value of the dark count probability, as explained in Section 3.

Overall, the application can benchmark the majority of the link parameters, however the detector efficiency of the link does not affect the required performance metrics.

NV Quantum Device

Lastly, the final three plots of Figure 4 present the changes in QBER with respect to some NV device parameters. The first of these parameters is the single qubit gate error. As opposed to the generic quantum device, this parameter does affect the Z basis QBER. This difference in working is due to the fundamental functionality of an NV device, which relies on gate operations while measuring qubits. Thus, both bases are affected by this parameter, however the X basis has a quadratic relation with the gate error, while the Z basis relation is linear.

The last two parameters are the measurement errors of the device i.e. the probability of measuring a 0 instead of a 1, and vice-versa. For these parameters, the QBER increases with an increase in the error probabilities.

Similar to the generic device, parameters such as the relaxation time, phase coherence time, and two qubit properties do not affect the performance metrics. However, the application can function as a benchmark for single qubit gate properties, and measurement times and errors. These results are again in line with the hypothesis in Section 2.

Overall Implications

The results discussed in this section provide several interesting implications. Firstly, we find that the application is sensitive to most link parameters, in both setups. This implies that the application can act as a benchmark for the the entire link, covering most parameters. However, due to the coverage being achieved by combining the QBER and the key generation rate in the case of a depolarise link, we can use the performance metrics individually to act as localised tests for the link parameters.

In the case of node devices, the application is sensitive to single qubit gate properties and measurement properties. Contrarily, the application cannot detect changes in two qubit gate properties or coherence times. Thus, the application can be used individually as a localised test for the parameters it

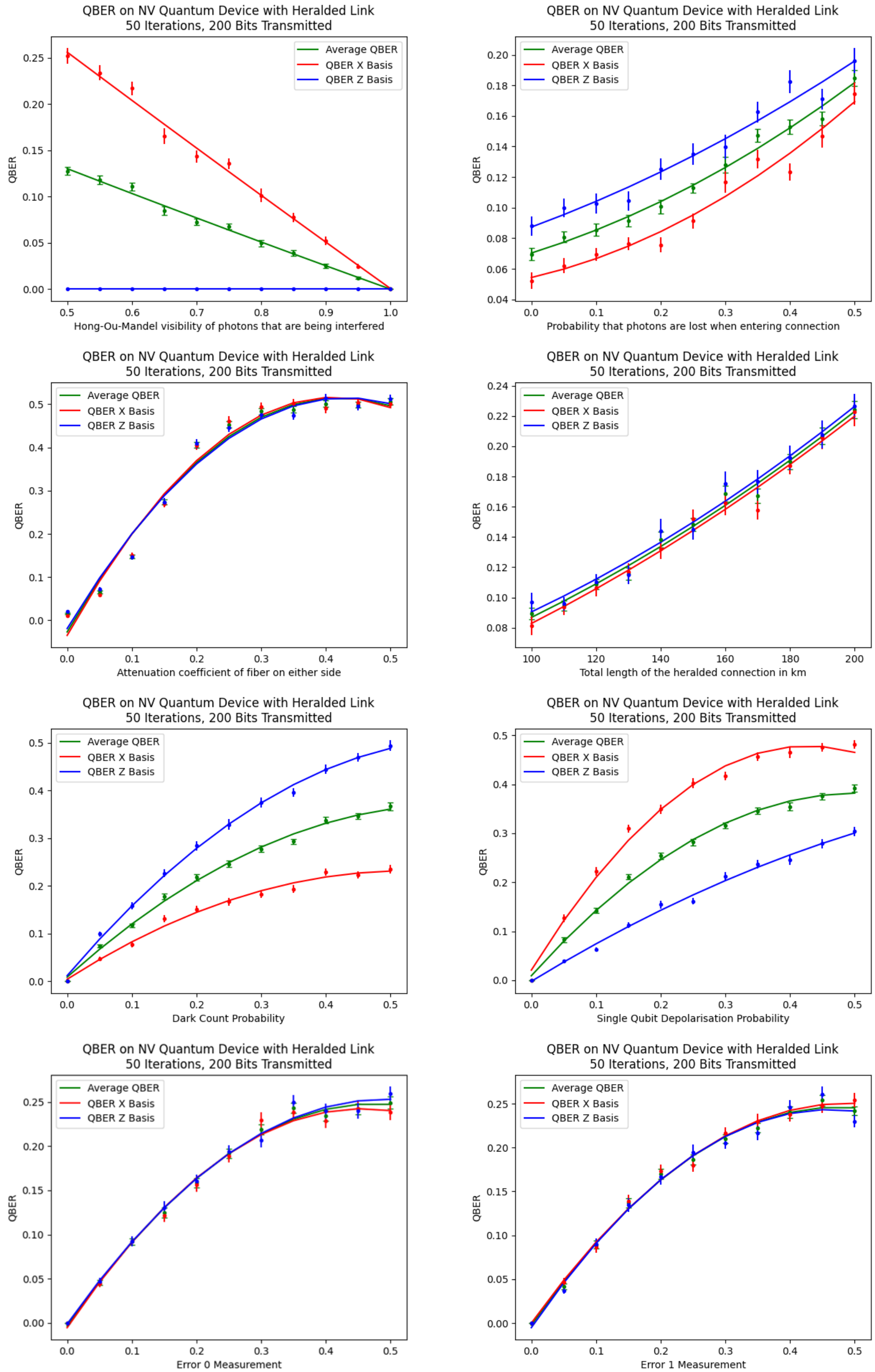

Figure 4: Performance metrics on an NV quantum device with a Heralded link

can benchmark. Additionally, it can be used as part of a more comprehensive benchmarking suite, with other applications that provide additional coverage for certain parameters, and coverage for a broader range of parameters.

6 Future Recommendations

In this section, shortcomings of the current research method will be discussed, as well as any possible future improvements to rectify these shortcomings.

In this project, the sensitivity of an application to a particular parameter is assessed by setting all other parameters to constant values. In the future, it might be interesting to vary multiple parameters at once, and see how these parameters interact with each other. This could help in seeing how the application would function in a more real world-like scenario.

Furthermore, the application currently being used is quite simplistic. In the future, it might be beneficial to modify the application to use more advanced computational techniques. For example, adding an eavesdropper as an intermediate node between the sender and receiver. This could help the application extend its detection capabilities to more parameters.

7 Conclusion

In this paper, we have proposed the idea of using the BB84 protocol as a benchmark for a quantum network system. We test its viability on two types of setups: a generic device with a depolarise link, and an NV device with a heralded link. We use two main performance metrics in order to assess the application's feasibility as a benchmarking application, the Qubit Error Rate and the key generation rate. The experiments are performed by varying a system parameter while keeping all other parameters constant, and thus measuring how the performance metrics change with these variations. We find that the application covers most properties of a depolarise and heralded link, but does not cover parameters such as two qubit gate properties and coherence times for the NV and generic device. Thus, we conclude that in its current state, the BB84 protocol can be used either as an individual benchmark for the parameters it is sensitive to, or in combination with other applications, in a more comprehensive benchmarking suite, that provide coverage for a broader range of parameters. There are some future improvements that might improve this application's benchmarking capabilities, such as adding an eavesdropper in order to increase the application's complexity and thus potentially make it sensitive towards more parameters.

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A Quantum Computing Background Knowledge

This section serves to provide basic knowledge on quantum computing in order to help readers better understand the content of this paper.

Unlike their classical counterparts, quantum bits, or qubits, can not only be 0 or 1, but also in between either of those states. This in-between state is known as a superposition. While qubit states can be in a superposition, when trying to find out a qubit's value, it must be measured. The measurement of a qubit collapses it onto the $|0\rangle$ or $|1\rangle$ state, also known as the pole states. For example, if the qubit state is an equal superposition of the $|0\rangle$ and $|1\rangle$ state, measuring the qubit will result in either pole state, each with a 50% probability. The Bloch sphere is a method of visualising quantum states, as seen in Figure 5. As mentioned earlier, the poles of the Bloch sphere represent the $|0\rangle$ and $|1\rangle$ state, and the equator of the sphere represents all equal superposition states. Similarly, any quantum state can be represented on the Bloch sphere.

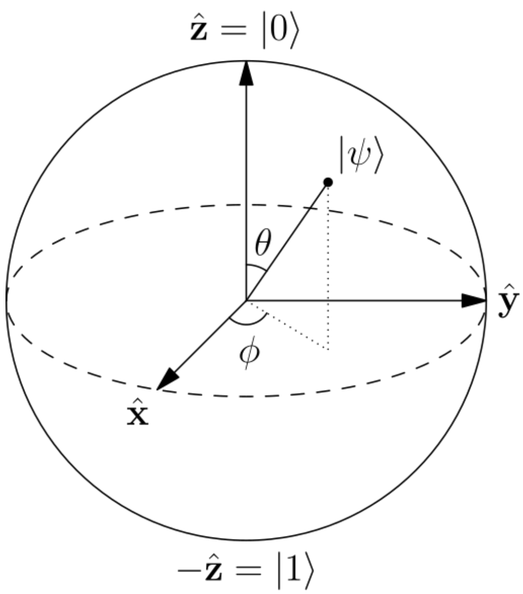

Figure 5: The Bloch sphere

Quantum gates are a series of rotations that manipulate a qubit state. For example, an X gate is simply a rotation of π around the X axis. Thus, applying the X gate to the $|0\rangle$ state results in the $|1\rangle$ state. There are several such gates that are fundamental to quantum computing. Once again, the Bloch sphere can help visualise these rotations. Thus, errors in quantum gates can cause the computed state to be slightly different from the expected state, hence causing inaccuracies in measurements.

Relaxation and dephasing of qubits are how qubits lose their information over time. Relaxation is the decay of a qubit state to the $|0\rangle$ state. Dephasing is the loss of phase information in the qubit, this can be understood as the state rotating around the Z axis on the Bloch sphere.