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Quantum Noise in the Flow of Time: A Temporal Study of the Noise in Quantum Computers

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***Abstract*—Over the last couple of years, Quantum Computing (QC) has captured the interest of computer scientists due to the fact of quantum speedup, the possibility of solving NP-hard problems, and achieving higher compute power. However, mitigating the impact of the noise inside each quantum device presents an immediate challenge. These changes open up new opportunities to investigate the effect of calibration parameters for individual characteristics of each qubit in a manner of time. In this paper, we investigate the temporal behavior of noisy intermediate-scale quantum (NISQ) computers based on calibration data and the characteristics of individual devices. In particular, we collect calibration data of IBM-Q machines over the last two years and compare the quantum error robustness against the processor types, quantum topology, and quantum volumes of the IBM-Q machines.**

***Index Terms*—Quantum Computing, Quantum Characteristics, Quantum Temporal Study, Quantum Error**

I. Introduction

Over the last couple of years, quantum computers has exceed new era of development. Scientist developed new quantum computers with capability of running quantum circuits up-to 127 qubits. However, these machines are not perfect and due to the high noise values over qubits, environment, and measurement they considered as NISQ quantum machines. Noisy Intermediate-Scale Quantum (NISQ) refers to the quantum computers with a number of qubits ranging from 50 to a few hundreds, where the computers experience imperfect control over qubits; thus, the noise places a severe limitation on what quantum computers can achieve in the near term [1]. Currently, NISQ computers are increasingly used to demonstrate the benefits of quantum computing verse traditional high-performance computing (HPC) domains, such as modelling and simulation, new material discovery, combinatorial optimization and scientific machine learning, etc. [1]–[5].

Prior studies [1], [3], [6] shows that NISQ computers suffer from high error rates; thereby, their utilization and adoption are inhibited. Due to the uncertainty and the various amplitudes of the noise, the probabilistic based method may not be able to distinguish between the correct and incorrect results. For example, the Bernstein-Vazirani (BV) algorithm that allows the program to infer the hidden key in a single shot on a perfect quantum machine would result in a probability of 100% on the correct state. Tannu et al. [7] showed that based on the quality of qubits and the topology of the machine, the result could be far from the desired outcome.

To characterize the severity of the noise, major quantum computing service providers such as IBM-Q systems make the noise metrics including T1, T2, frequency and readout error for each quantum computer publicly available. This information is further exploited by the research [7]–[18] that focus on intelligently mapping a quantum circuit onto different parts of a NISQ computer that exhibit different error rates.

The focus of this paper is to study the time serial quantum error data, and building a temporal error observation, prediction and comparison model to provide important system reliability information for end-users while submitting the jobs to the system. We conduct a detailed analysis to study the quantum error characteristics over a long period against the widely-used quantum computers - IBM-Q systems, and comprehensively explore the space of factors for the correctness of a quantum circuit execution.

In summary, this paper makes the following contributions:

- We study the quantum errors from the collected calibration data of 9 recent IBM quantum computers. The performance of the quantum machines is compared across topology, different temporal tests, and individual qubit evaluation.
- We define multiple observation based on different statistical methods to exploit new information about quantum computers.
- We applied stationary and non-stationary statistical tests on the collected quantum error data and find that most of the time, the quantum errors are stationary (i.e., the mean and the variance of the errors do not change over time). We leverage such stationary to predict the statistical properties of quantum errors.

II. BACKGROUND

Generally, quantum errors fit into two different categories, the retention (coherence) errors and operational errors. A qubit can retain data (position) for an only limited period of time, and this duration is called the Coherence Time. Retention errors are categorized into two types, T1 and T2 errors.

A qubit in high energy state $|1\rangle$ naturally decays to lower energy state $|0\rangle$, the time associated with this decay is called the T1 (spin-lattice) Coherence Time (time that qubit would relax to state $|0\rangle$). Similarly, T2, also known as spin-spin relaxation process, is the effect of the environment or other qubits on the target qubit.

Quantum operation errors can be categorized into three different sub-groups, including single-qubit gate errors, single qubit readout errors, and two qubit gate errors (referred to as CX gate errors). Single and two qubit gate errors occur when there is noise in the system when applying a gate to a qubit state. Readout errors are the errors related to the faulty reading of final qubit state.

A. Quantum Computer Topology

Quantum algorithms are normally designed as a set of quantum gates to be applied to the qubits of a quantum computer. The mapping between the logical qubits and physical qubits on NISQ machines depends on the qubit connectivity and supported gates. Each NISQ machine can have its own topology: some qubits can be directly accessible by one subset of qubits while other qubits cannot.

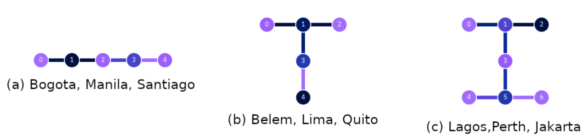

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Fig. 1: IBM-Q Machine Topology: (a) IBM-Q Bogota, Manila, and Santiago with linear connection between qubits, (b) IBM-Q Belem, Lima, and Quito With tree shape connectivity (c) IBM-Q Lagos, Perth, and Jakarta with 'H' shape connectivity. **Circles** represent qubits and **Lines** represent direct connection between qubits [19].

For example, Figure 1 shows the different connectivity patterns of qubits in the IBM-Q systems. On Linear topology 1 (a), qubits 1, 2, 3, 4, and 5 are connected in a linear fashion way, in order to apply CX gate between qubit 2 and qubit 4 compiler applies swap operation. In practice when a quantum algorithm is compiled for a particular NISQ computer, the two qubits that are not directly connected would be compiled with swap gates so that the original circuit would be redesigned in favor of that NISQ computer's topology. Thus, the same quantum algorithm can be mapped in different ways to generate different quantum circuits on different machines, or even with different swap strategies for the same machine.

III. METHODOLOGY

Based on the collected data, for each interested quantum computer property, we conduct detailed analysis on their potential relations to the overall error resilience of the system. IBM-Q quantum computers are accessible to the public users. In totally we collected calibration data from 9 real IBM-Q quantum systems from July 2020 to the end of April 2022. The general configurations of target IBM-Q machines are shown in Table I. The data trace is open-sourced for public access.

TABLE I: Configurations of available IBM-Q machines.

Machine	# of Qubits	Processor	Topology
Santiago	5	Falcon r4L	L
Quito	5	Falcon r4T	T
Lima	5	Falcon r4T	T
Bogota	5	Falcon r4L	L
Belem	5	Falcon r4T	T
Manila	5	Falcon r5.11L	L
Jakarta	7	Falcon r5.11H	H
Perth	7	Falcon r5.11H	H
Lagos	7	Falcon r5.11H	H

We collected T1, T2, the number of qubits, Readout error, and CNOT errors from 9 recent active IBM-Q machines through Qiskit API [20].

The total time interval of data collection spans for up to 2 years for calibration data on 9 different IBM-Q machines. We show the time trend analysis on 5 Qubits and some 7 Qubits as a example to plot the difference between individual features.

A. Observations

T1 and T2 errors rely on different factors such as quality of qubits [15], different processor types and many other related design factors. As shown in Figure 2a, T1 time can diverge based on the machine and the time of calibration. For example, in Figure 2a IBM-Q Santiago the values of T1 drops significantly for half of 2021 and most of 2022. But on IBM-Q Belem and Lima, the T1 values for all the qubits are more clustered. On top of last argument, we observe that one single machine can experience different phases for T1, T2 and Readout errors. Based on our observation and historical data for one particular machine we can detect unmoral behavioural for qubits properties.

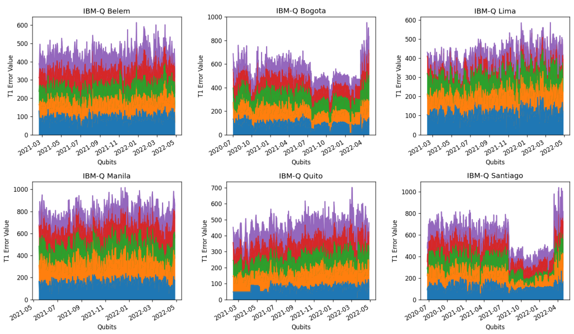
Similarly in Figure 2b IBM-Q Bogota and Santiago's T2 value is fluctuating for most of year 2021 whereas IBM-Q Manila, Belem, Lima show consistency for their Qubits' T2 Value.

We can use the same method to observe the faults for Readout errors along with CNOT gate error. An example of these observation has been shown in Figure 3.

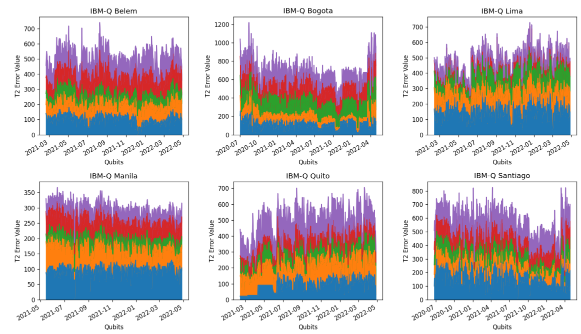
IV. QUBITS' STATISTICAL ANALYSIS

To further investigate the temporal data, we explore one of the classical statistical methods [21], the unit root test, on quantum calibration data to test if the collected temporal error data is stationary or not.

We observe that the properties such as variance and co-variance of time series for T1, T2, and readout errors do not



(a) IBM-Q 5-Qubits T1 Errors Over Time



(b) IBM-Q 5-Qubits T2 Errors Over Time

Fig. 2: IBM-Q 5-Qubits Machines T1 (Left) and T2 (Right) Errors, each color represents individual qubits on that machine. X axis represent the timestamp and Y axis represents the μ seconds time

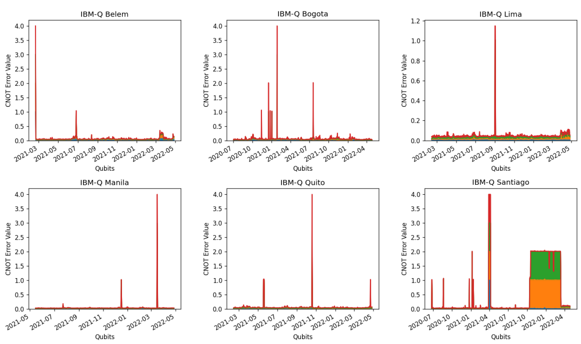


Fig. 3: IBM-Q 5-Qubits Machines CNOT gate Errors, each color represents individual qubits on that machine. X axis represent the timestamp and Y axis represents the CNOT Error rate

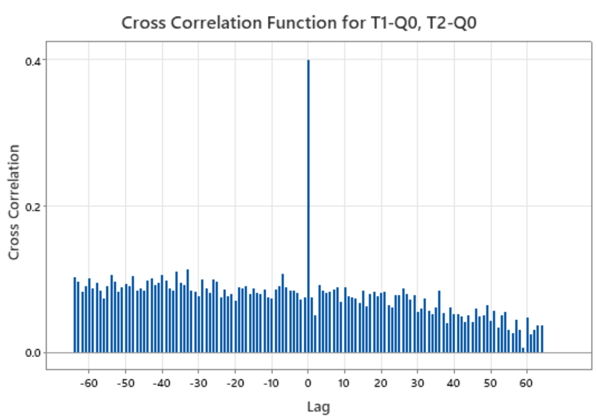


Fig. 4: IBM-Q 5-Qubits Machines Qubits 0 T1 and T2 Cross co-relations Errors. X axis represents the timestamp intervals and Y axis represents the crfoss correlations between T1 and T2 on qubits 0 for entire data-set.

change over time. In Figure 4, the blue line represents the significant limits (out of bound) for entire 2020 to 2022 data-set. As shown in Figure 4 the cross co-relation between T1 and T2 shows no changes except for one significant event, therefore for most of the time the prediction between T1 and T2 value would be successful. We can observe this better in Figure 5.

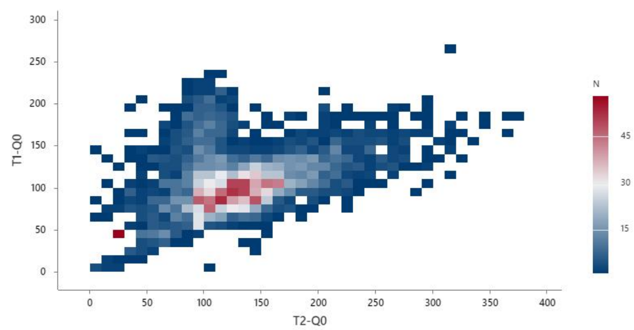


Fig. 5: IBM-Q 5-Qubits Machines Qubits 0 T1 and T2 Cross co-relations heatmap

In Figure 6, the p-values for stationary data-set should be above 0.05 [22]. As shown in this Figure, for T1, T2 most of the time the KPSS p-value is above the threshold, and for readout and CNOT the KPSS test satisfy the stationary trend. In terms of CNOT depending on other factors such as T1, T2, the p-value fluctuates between stationary and non-stationary trends. We observed that using stationary trends we can successfully predict the behavior of each machine for the fixed time interval. For more accurate prediction for CNOT trends we might need to combine non-stationary and stationary methods.

V. Statistical Models

In this section, investigation about different temporal statistical methods on individual features of IBM-Q machines is being presented. Using temporal analysis we investigate the possibility of mapping and predicting the T1, T2, Readout, and CNOT errors through time.

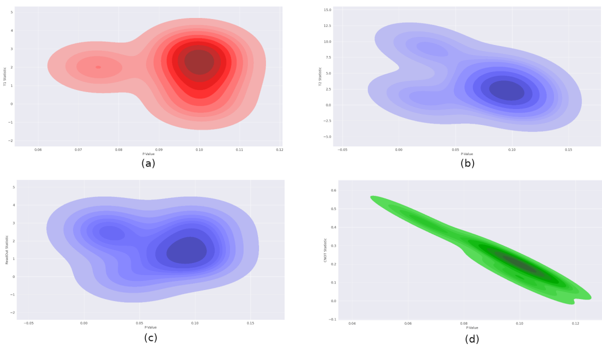


Fig. 6: IBM-Q 5-Qubits Machines KPSS Test (a) KPSS test on T1 Error (b) KPSS Test on T2 Error (c) KPSS Test on Readout Error (d) KPSS on CNOT Errors

Depending on the frequency, a time series can be monthly, daily, or even hourly. Using time series models such as the Autoregressive Integrated Moving Average (ARIMA) [23], we predict the temporal error behavior of IBM-Q machines. An ARIMA model is characterized by 3 terms ($p, d,$and q) where p is the order of AR (Auto-Regression) term, and q is the order of MA (Moving Average). Similarly, d is the number of differences required to make the time series stationary.

Exponential Smoothing (ES) is another method for forecasting time series data, proposed in the late 1950s [24]. There are three main types of exponential smoothing: Single Exponential Smoothing (SES), Double Exponential Smoothing (DES), and Triple Exponential Smoothing (TES) aka Winters' method. Using our collected data and data from other researches [7], [9], [13], [14], we apply three methods on the data and find out that the SES method offers the 23% accuracy, the DEs offers 47% to 80% accuracy and the Winters' method has the highest prediction accuracy for the behavior of each qubit's error characteristic in respect to the overall system. An Example of these results has been shown in Figure 7.

Using single machine calibration data helps to increase the accuracy to predicting the behaviour of individual qubits. However, the co-relations between different characteristic would not be held. Figure 8 show the same algorithm previously ran on qubit 0 for a single machine instead of entire data-set.

VI. Related Work

Understanding the quantum error behaviors on different quantum computers is essential for future quantum compiler design, quantum result uncertainty analysis, and resource management for multi-processor quantum computing architecture design. Tannu et. al. [7], [14] characterized quantum errors over qubits and discuss the variety of quantum error characteristics on NISQ quantum computers. Followed by Patel et al. [25], collecting months of quantum error-related data, a study has been conducted exploring the noise characteristics on different quantum operations and gates on five IBM quantum computers.

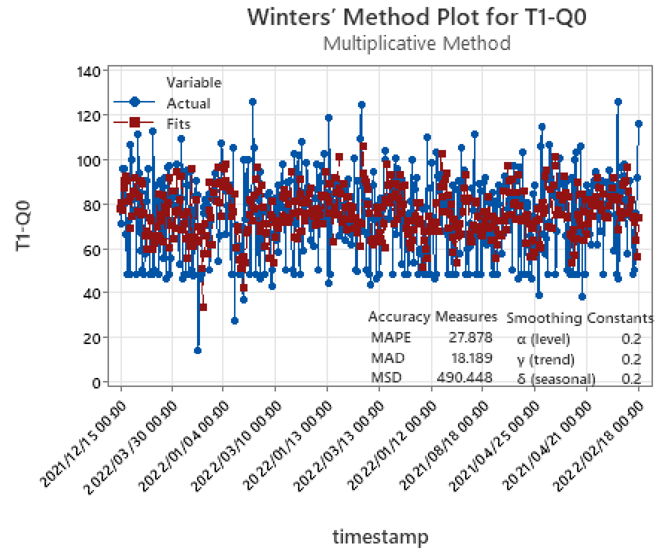


Fig. 7: IBM-Q 5-Qubits Machines Qubits 0 T1 Errors Prediction

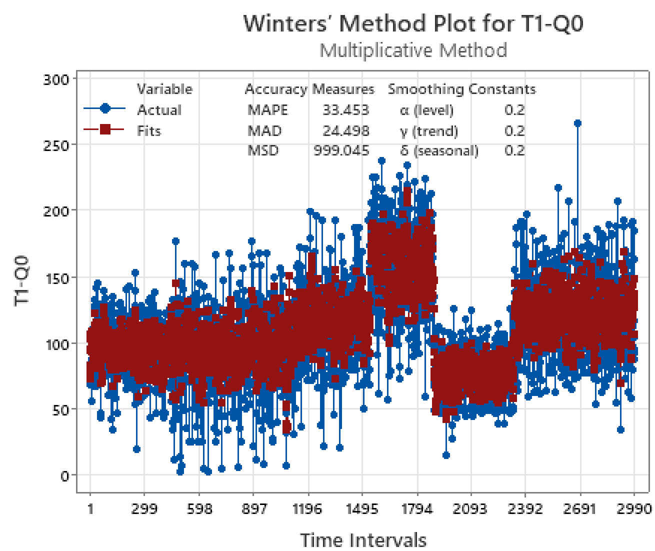


Fig. 8: Single IBM-Q Machine Qubits 0 T1 Errors Prediction

VII. Conclusion

We investigate the temporal behavior of NISQ computer errors based on the calibration data and used the characteristics of individual devices to characterize the errors temporally. We also showcase that most of the time the quantum errors are stationary, and we leverage this characteristic to predict the statistical properties of quantum errors. We show that a better more depth investigation of machine behaviour can help to understand the errors and determine the health of machine.

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