Interaction Free Measurement on IBMQ

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***Abstract*—Interaction free measurement—*ascertain the presence or absence of an object without interacting with it*—is a surprising phenomena in quantum mechanics. In this article, we demonstrate the implementation of quantum Zeno based interaction free measurement on IBM quatum devices and address the implementation challenges and gate errors of the circuit.**

I. Introduction

Since 20th century, quantum physics has never stopped surprising the world, specially some quantum properties such as quantum entanglement [1], non-locality of quantum mechanicsetc and counterfactual quantum communication [2], [3], [4], [5]. Interaction free measurement (IFM)—*building block of counterfactual quantum communicaiton*—is another surprising phenomena in quantum mechanics to ascertain the presence or absence of an object (absorptive object). The concept of the IFM was first considered by Dicke [6], and extended by Elitzur and Vaidman [7]. The basic idea was to infer the existence of an object without interacting with it but the efficiency of the protocol limits to the margin of 1/2 in the presence of the absorptive object [7]. Later, the efficiency of the IFM protocols was further improved to 100% by using quantum Zeno effect [8]. In this article, we demonstrate the implementation of quantum Zeno based IFM [8] on the IBM quantum devices and address the implement challenges of IFM on real quantum computer and validate our results with IBM quantum simulator.

II. Interaction Free Measurement

Fig. 1 shows the schematic of the Kwiat *et. al.* version of IFM where BS stands for unbalanced beamsplitters. We consider an interferometer of N BS with the initial state of the photon is $|\psi_0\rangle_{\mathrm{p}} = |0\rangle_{\mathrm{p}}$ where $|0\,(1)\rangle_{\mathrm{p}}$ denotes the photon is in lower (upper) path and each BS transforms the input state as follows

$$\mathcal{U} = \begin{pmatrix} \cos\theta_N & -\sin\theta_N \\ \sin\theta_N & \cos\theta_N \end{pmatrix}, \qquad (1)$$

where $\theta_N = \pi/(2N)$. In order to ascertain the presence or absence of the photon, the protocol starts by throwing the photon towards BS_1. In the absence of the absorptive object in the interferometer, Kwiat *et. al.* interferometer transforms the state $|\psi\rangle$ as

$$|\psi_0\rangle_{\mathrm{p}} \to \mathcal{U}^N |0\rangle_{\mathrm{p}}, \qquad (2)$$
$$= |1\rangle_{\mathrm{p}}. \qquad (3)$$

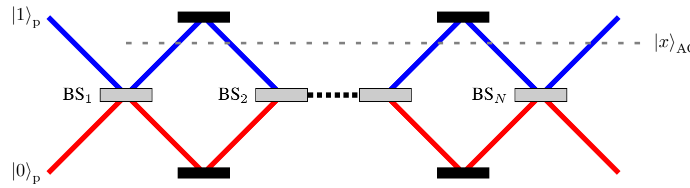


Fig. 1. Kwiat *et. al.* interferometer to perform the interaction free measurement.

In the presence of the absorptive object in the upper path of the photon, BS_1 transform the initial state of the photon as

$$|\psi_0\rangle_{\mathrm{p}} \to |\psi_1\rangle_{\mathrm{p}} = \cos\theta_N |0\rangle_{\mathrm{p}} + \sin\theta_N |1\rangle_{\mathrm{p}}. \qquad (4)$$

The presence of the absorptive object in the interferometer is similar to performing measurement in the upper path of the photon. If the measurement is 0, the photon reaches to BS_2 and protocol continues. In case the measurement outcome is 1, the photon is absorbed by the absorptive object and the protocol is discarded. After BS_n $(n \le N)$, the state of the photon is given as

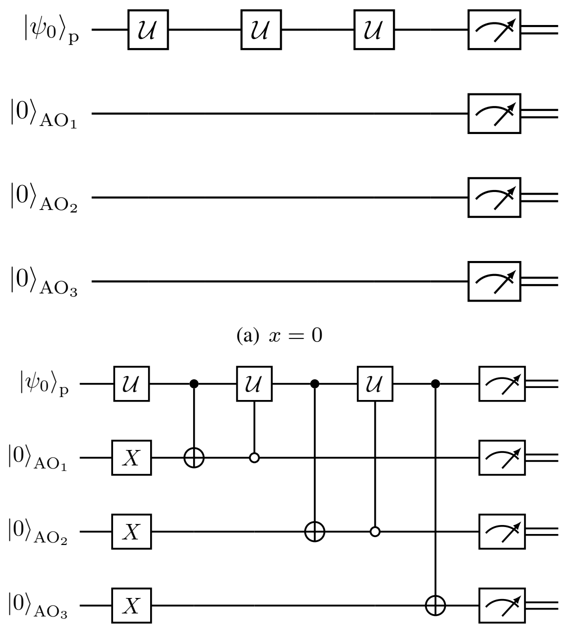
$$\rho_n = \cos^{2n-2}\theta_N \mathcal{U} |\psi_0\rangle \langle\psi_0| + \sin^2\theta_N \sum_{i=0}^{n-2} \cos^{2i}\theta_N \epsilon, \qquad (5)$$

where ϵ shows the erasure state of the photon. At the end of the protocol, the photon end up in state $|\psi_0\rangle$ with probability $\cos^{2N}\theta_N$. From the above discussion we can conclude that the presence or absence of the absorptive object in the interferometer changes the trajectory of the photon. In the absence of the absorptive object, the photon ends up in the state $|1\rangle_{\mathrm{p}}$ with probability one. In case the absorptive object is present, the photon collapses back to the initial state under the repeated measurements with probability $\cos^{2N}\theta_N$. Under the asymptotic limits of N, the probability that the photon is not discarded approaches to 1.

III. Interaction Free Measurement on IBMQ

In the previous section, we briefly explained the theory of IFM. Here it is important to not that, in the absence of the absorptive object, the Kwiat *et. al.* interferometer rotates the input state by an angle $\theta = N\theta_N$ and the measurement is performed at the end of the protocol to determine the path of the photon.

In the presence of the absorptive object, measurement is performed in each cycle of the interferometer and the measurement outcome based operations are performed. The repeated measurements and measurement outcome based operations



(a) $x = 0$

(b) $x = 1$

Fig. 2. Interaction free measurement on IBM quantum devices for $N = 3$.

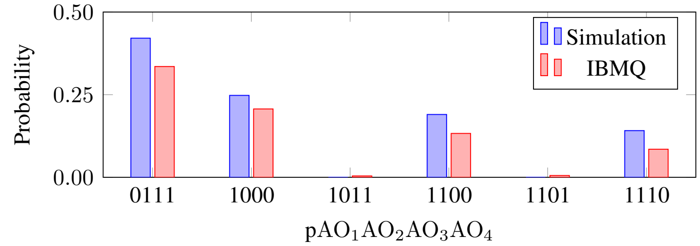


Fig. 3. Measurement results for $N = 3$ in the presence of the absorptive object. We implemented our circuit (see Fir. III on IBMQ-Essex quantum computer (pink bars) and validate our results with IBM quantum simulator (blue bars). Here it is important to note that the post-measurement states 1011 and 1101 correspond to the imperfect absorptive objects.

leads to two challenges in the implementation of IFM on IBMQ. These two challenges are

- Measurement outcome based operations involve the ifelse conditions but IBM quantum devices do not support ifelse conditions on the real quantum computer.
- In IBM quantum devices, currently it is not possible to perform further operations once you perform the measurements. In IBM quantum devices, you can perform measurements only at the end of the protocol.

In order to overcome these challenges, we consider the N qubits to represent the absence or presence of the absorptive object in the interferometer. We associate one qubit with each cycle. We assume that once the photon interacts with absorptive object, the photon is discarded and the absorptive object jumps to high energy level which shows the absence of the absorptive object in the rest of the cycles of the interferometer. We consider the initial state of composite system is

$$|\phi_0\rangle = |\psi_0\rangle_p |x_1 x_2 ... x_N\rangle_{AO_1 AO_2 ... AO_N}, \quad (6)$$

where $x_1 = x_2 = ... = x_N = x \in \{0, 1\}$ and $|0\,(1)\rangle_{AO}$ shows the absence (presence) of the absorptive object. The protocol starts by applying $\mathcal{U}$ corresponding to BS_1 as follows

$$|\phi_1\rangle = \left(\mathcal{U} \otimes I^{\otimes N}\right) |\psi_0\rangle_p |x_1 x_2 ... x_N\rangle_{AO_1 AO_2 ... AO_N}, \quad (7)$$

where I denotes the single qubit identity operator. For $x = 1$, we apply the CNOT gate instead of the performing measurement in the Hadamard basis where p act as control qubit and AO_1 is the target qubit; and the composite state of the system transforms as

$$|\phi_1\rangle \rightarrow \left(\cos\theta_N |01\rangle_{pAO_1} + \sin\theta_N |10\rangle_{pAO_1}\right) \otimes |11...1\rangle_{AO_2 AO_3 ... AO_N}. \quad (8)$$

In (8), the first term shows that the photon is not absorbed by the absorptive object and the second term denotes the photon is discarded in first cycle. We perform the controlled-$\mathcal{U}$ operation corresponding to BS_n to overcome the problem of ifelse conditions where p is the target qubit and AO_{n-1} act as control qubit in n^{th} cycle where $1 < n \leq N$. The composite state of the system after N cycles is given as

$$|\phi_n\rangle = \cos^n\theta_N |0111...1\rangle_{pAO_1AO_2...AO_N} + \sin\theta_N \sum_{i=1}^{N} \cos^{i-1}\theta_N |111...10...0\rangle_{pAO_1AO_2...AO_{i-1}AO_i...AO_N}, \quad (9)$$

where $|111...10...0\rangle_{pAO_1AO_2...AO_{i-1}AO_i...AO_N}$ shows that the photon is discarded in the i^{th} cycle. Fig. 2 shows the schematic of IFM implementation on the IBMQ for $N = 3$. We implement our circuits on 5-qubit IBMQ-Essex quantum computer and plot the measurement results in Fig. 3 (pink bars) and compare our results with IBM-quantum simulator (blue bars) for $x = 1$.

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