Generalized measurements on quantum devices

Filip Maciejewski, Michał Oszmaniec

KCIK on-line session "Current Trends in Quantum Information", 15.05.2020

Outline

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- Part I

  "Simulating all quantum measurements using only projective measurements and postselection"

  Michał Oszmaniec, FBM, and Zbigniew Puchała, Phys. Rev. A 100, 012351 (2019)

- Part II

  "Mitigation of readout noise in near-term quantum devices by classical post-processing based on detector tomography"

  FBM, Zoltán Zimborás, and Michał Oszmaniec, Quantum 4, 257 (2020)

- Summary + some current research topics

INTRODUCTION

Generalized quantum measurements - POVMs

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$$\vec{M} = (M_1, \ldots, M_n)$$

s.t.

$$\forall_i M_i \geq 0, \quad \sum_{i=1}^{n} M_i = \mathbb{1}$$

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$$\vec{P} = (P_1, \ldots, P_n)$$

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$$\forall_i \; P_i \geq 0 \;, \quad \sum_{i=1}^{n} P_i = \mathbb{1} \;, \quad \forall_{i,j} \; P_i P_j = \delta_{ij} P_i$$

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$$q(i \mid \vec{M}, \rho) = \mathrm{Tr}(\rho M_i)$$

PART I

PHYSICAL REVIEW A **100**, 012351 (2019)

Simulating all quantum measurements using only projective measurements and postselection

Michał Oszmaniec,[1,*] Filip B. Maciejewski,[2,†] and Zbigniew Puchała[3,4,‡]

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(Received 15 August 2018; published 31 July 2019)

We report an alternative scheme for implementing generalized quantum measurements that does not require the usage of an auxiliary system. Our method utilizes solely (a) classical randomness and postprocessing, (b) projective measurements on a relevant quantum system, and (c) postselection on nonobserving certain outcomes. The scheme implements arbitrary quantum measurement in dimension d with the optimal success probability $1/d$. We apply our results to bound the relative power of projective and generalized measurements for unambiguous state discrimination. Finally, we test our scheme experimentally on an IBM quantum processor. Interestingly, due to noise involved in the implementation of entangling gates, the quality with which our scheme implements generalized qubit measurements outperforms the standard construction using an auxiliary system.

DOI: 10.1103/PhysRevA.100.012351

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- Standard method of performing POVMs – Naimark's dilation:

$$\forall_i \; \mathrm{Tr}\big(\rho \otimes \underbrace{|0\rangle\langle 0|}_{\text{ancilla}} \underbrace{P_i}_{\text{PM on extended space}}\big) = \mathrm{Tr}(\rho M_i)$$

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- Answer – yes, but the protocol is probabilistic.

Simulation of POVMs by PMs

We want to sample from this

$$\vec{M} = (M_1, M_2, M_3)$$

$$\mathrm{Tr}(\rho M_i)$$

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$$\downarrow$$

$$\vec{P}^{(1)} = (P_1^{(1)}, 0, P_3^{(1)}, P_4^{(1)})$$

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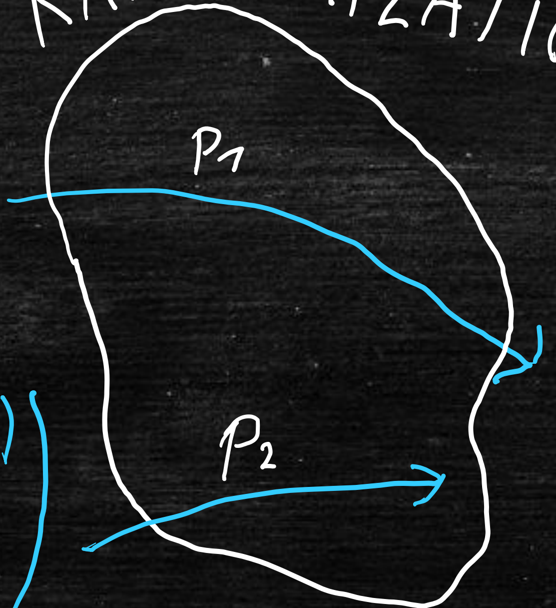
RANDOMIZATION



Simulation of POVMs by PMs

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RANDOMIZATION

$$p_1 Tr(\rho P_i^{(1)}) + p_2 Tr(\rho P_i^{(2)})$$

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RANDOMIZATION

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CLASSICAL PROCESSING

POVMs vs PMs – main results

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(and we noticed that readout noise in those devices is terrible…)

PART II

- Quantum 4 257 (2020)

Mitigation of readout noise in near-term quantum devices by classical post-processing based on detector tomography

Filip B. Maciejewski[1,2,3], Zoltán Zimborás[4,5,6], and Michał Oszmaniec[2,3]

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[2] International Centre for Theory of Quantum Technologies, University of Gdansk, Wita Stwosza 63, 80-308 Gdansk, Poland
[3] Center for Theoretical Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warszawa, Poland
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[5] BME-MTA Lendület Quantum Information Theory Research Group, Budapest, Hungary
[6] Mathematical Institute, Budapest University of Technology and Economics, P.O.Box 91, H-1111, Budapest, Hungary

arXiv:1907.08518v2 [quant-ph] 25 Mar 2020

We propose a simple scheme to reduce readout errors in experiments on quantum systems with finite number of measurement outcomes. Our method relies on performing classical post-processing which is preceded by Quantum Detector Tomography, i.e., the reconstruction of a Positive-Operator Valued Measure (POVM) describing the given quantum measurement device. If the measurement device is affected only by an invertible classical noise, it is possible to correct the outcome statistics of future experiments performed on the same device. To support the practical applicability of this scheme for near-term quantum devices, we characterize measurements implemented in IBM's and Rigetti's quantum processors. We find that for these devices, based on superconducting transmon qubits, classical noise is indeed the dominant source of readout errors. Moreover, we analyze the influence of the presence of coherent errors and finite statistics on the performance of our error-mitigation procedure. Applying our scheme on the IBM's 5-qubit device, we observe a significant improvement of the results of a number of single- and two-qubit tasks including Quantum State Tomography (QST), Quantum Process Tomography (QPT), the implementation of non-projective measurements, and certain quantum algorithms (Grover's search and the Bernstein-Vazirani algorithm). Finally, we present results showing improvement for the implementation of certain probability distributions in the case of five qubits.

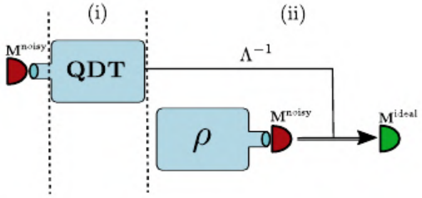

Figure 1: Pictorial representation of our error-mitigation procedure. (i) In the first stage, one performs the tomography of a noisy detector $\mathbf{M}^{noisy}$ (red semicircle). (ii) In the next stage, when measuring an arbitrary quantum state ρ, one employs a post-processing procedure on the measured statistics through the application of Λ^{-1}, the inverse of a stochastic noise map obtained in the QDT. This gives access to the statistics that would have been obtained in an ideal detector $\mathbf{M}^{ideal}$ (green semicircle).

of delicate quantum states with unprecedented precision [1]. Due to the advent of quantum cloud services (IBM [2, 3], Rigetti [4], DWave [5]), any researcher has a possibility to perform experiments on actual quantum devices. However, if one really hopes for utilizing such near-term devices for real-life applications such as quantum computation [6], quantum simulations [7] or generating random numbers [8], experimental imperfections must be taken into account. Hence, to properly characterize noise occurring in the devices and to develop error correction and mitigation schemes that may help to fight it have become tasks of fundamental importance [9, 10, 11, 12, 13, 14, 15]. In the present work, we address this problem for the

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We want to estimate this

Instead, we estimate this

$$\underbrace{\mathrm{Tr}(\rho P_i)} \xrightarrow{\text{NOISE}} \underbrace{\mathrm{Tr}(\rho M_i)}$$

POVMs as a model of noise

- However, if the noise is classical:

$$\vec{P} \xrightarrow{\text{NOISE}} \vec{M}$$

$$\overbrace{\mathrm{Tr}(\rho P_i)}^{\text{We want to estimate this}} \xrightarrow{\text{NOISE}} \overbrace{\mathrm{Tr}(\rho M_i)}^{\text{Instead, we estimate this}}$$

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POVMs as a model of noise

- However, if the noise is classical:

$$\vec{p} \xrightarrow{\text{NOISE}} \Lambda \vec{p}$$

STOCHASTIC MAP

We want to estimate this

Instead, we estimate this

$$\underbrace{\mathrm{Tr}(\rho P_i)} \xrightarrow{\text{NOISE}} \sum_j \underbrace{\mathrm{Tr}(\rho \Lambda_{ij} P_j)}$$

Mitigation of classical noise

- Hence, on the level of probability vectors:

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$\Lambda^{-1} \longleftarrow$ MITIGATION

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COHERENT PART

MITIGATION

DENOISED STATISTICS

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DISTURBANCE

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ESTIMATION

PROBABILITIES

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- I have the results in additional slides!

Summary + some current research topics

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- We experimentally benchmarked our mitigation procedure in various quantum information protocols on up to 5 qubits.

+ some current research topics

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Thank you!

Additional slides

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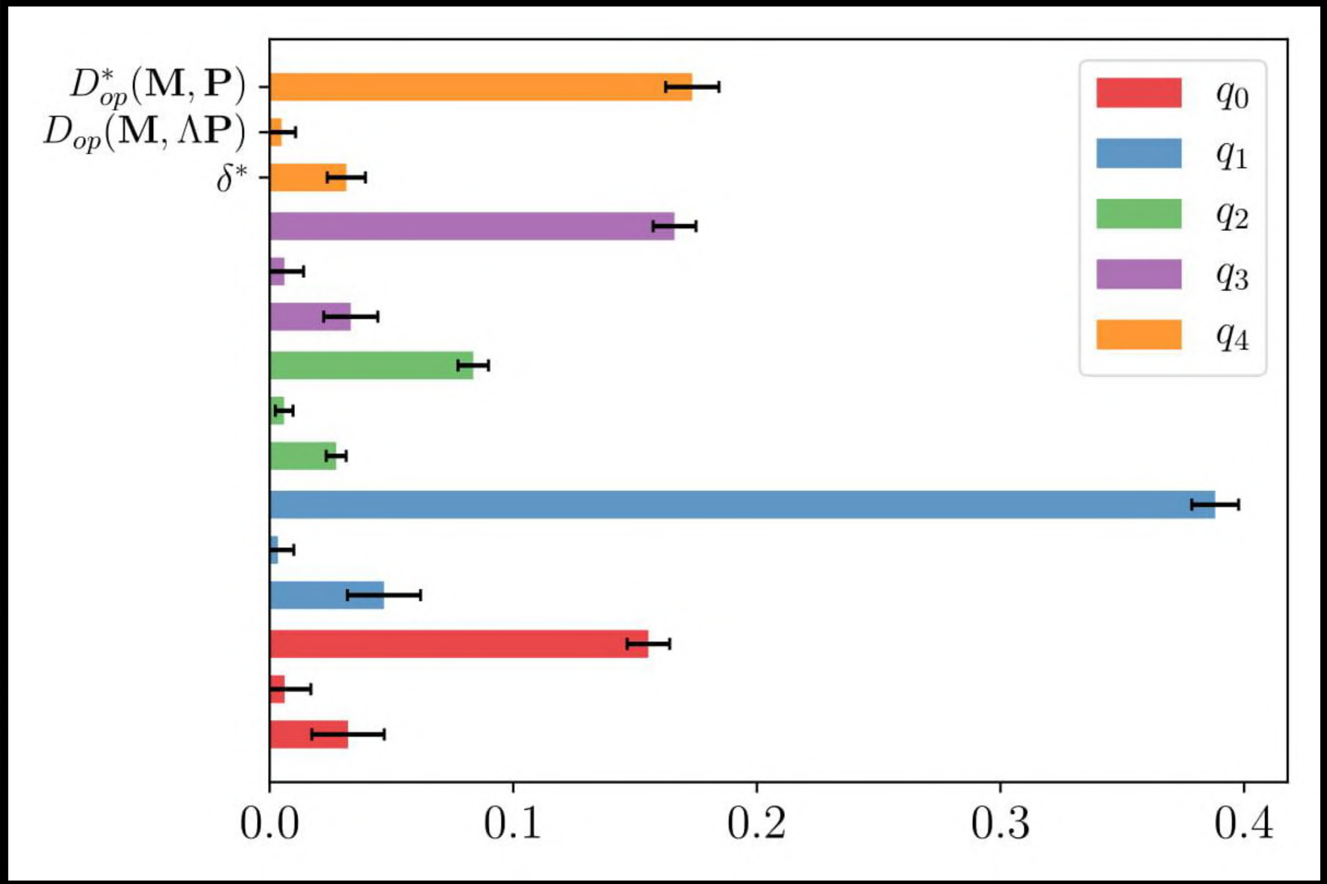
SINGLE QUBIT

DETECTOR TOMOGRAPHY



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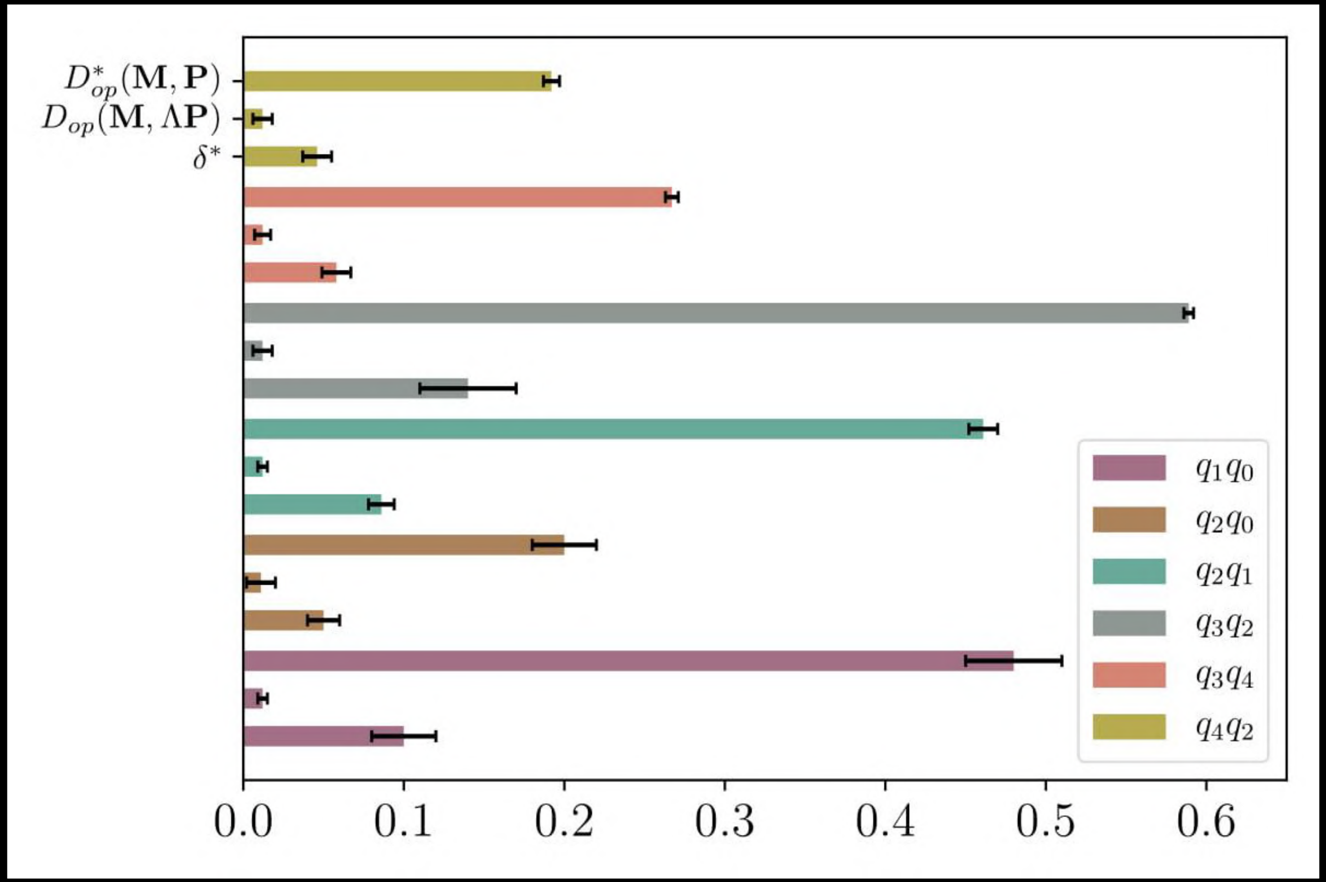
TWO
QUBIT

DETECTOR
TOMOGRAPHY



Experimental results – mitigation benchmark

- And we benchmarked our mitigation procedure on IBM's device:

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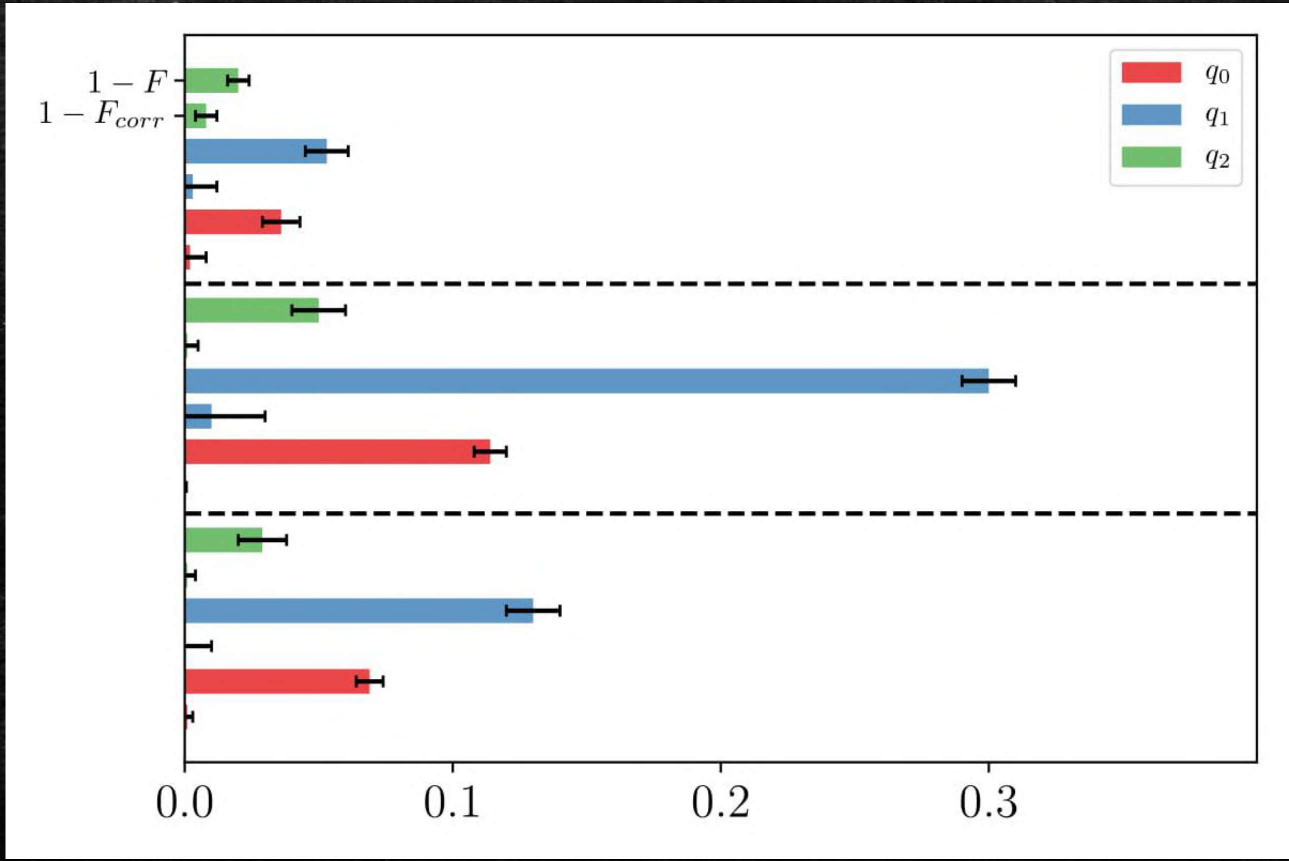
SINGLE QUBIT

STATE TOMOGRAPHY



Experimental results – mitigation benchmark

TWO
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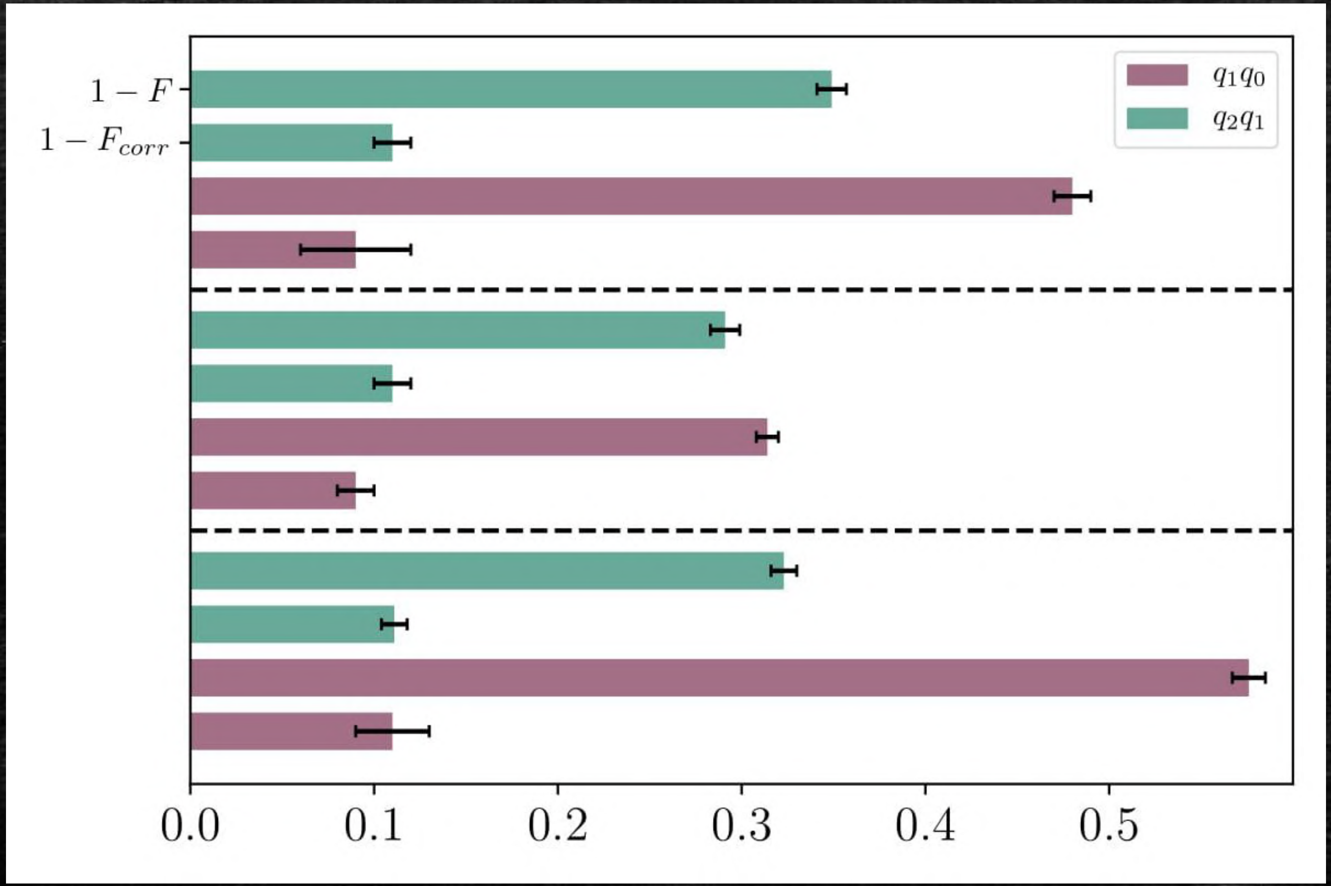


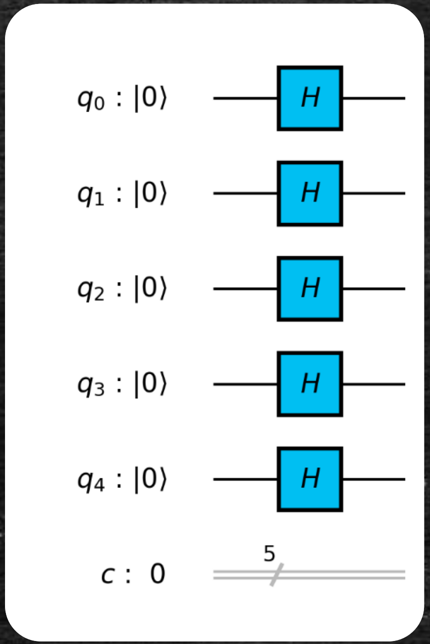
Experimental results – mitigation benchmark

FIVE QUBIT

PROBABILITY DISTRIBUTIONS

Experimental results – mitigation benchmark

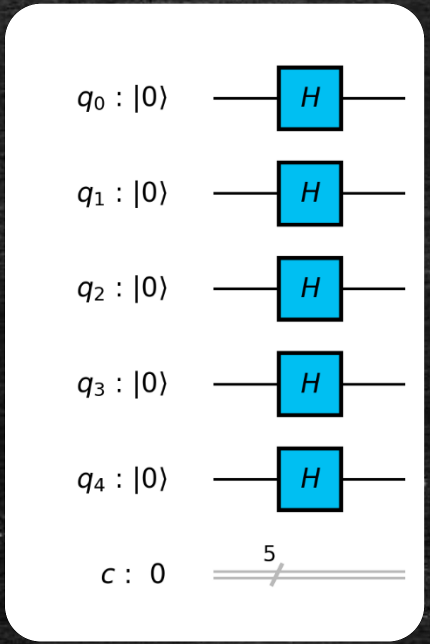
FIVE QUBIT PROBABILITY DISTRIBUTIONS



„UNIFORM"

Experimental results – mitigation benchmark

FIVE QUBIT PROBABILITY DISTRIBUTIONS



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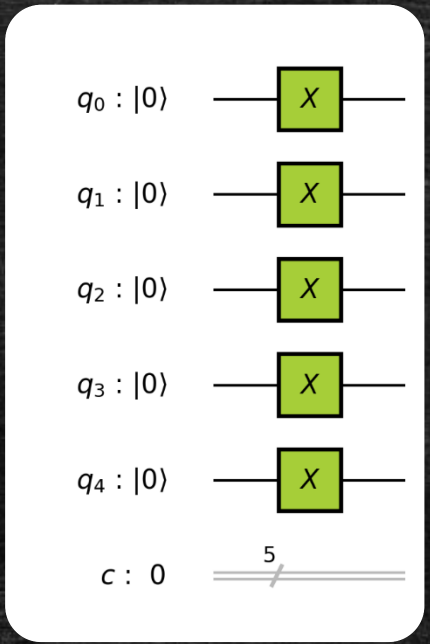

„NOT"

Experimental results – mitigation benchmark

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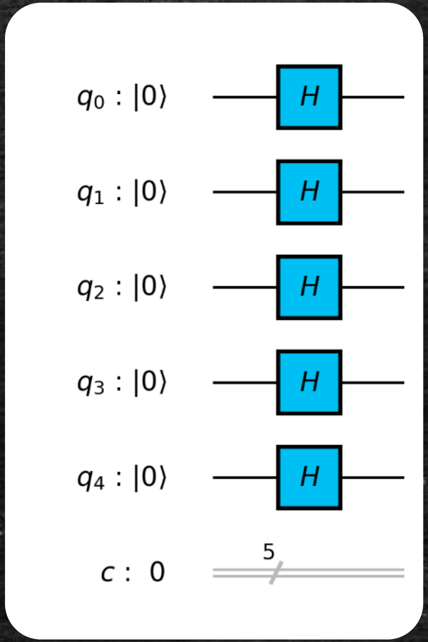

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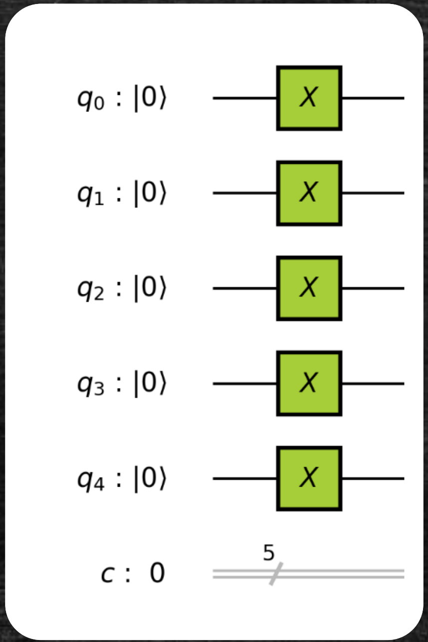

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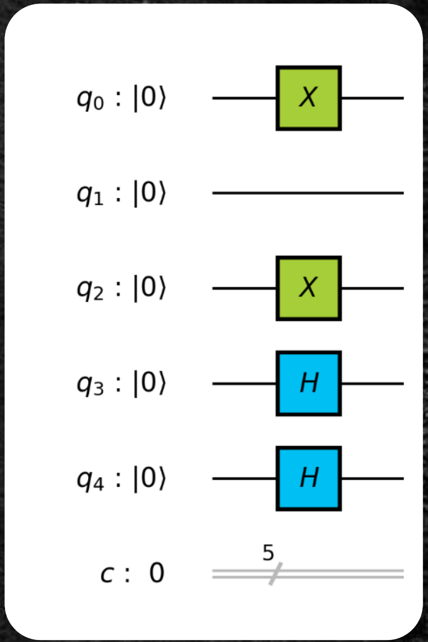

„MIXED"

Experimental results – mitigation benchmark

FIVE QUBIT

PROBABILITY DISTRIBUTIONS

Name	Standard	Corrected	α
Uniform	0.110 ± 0.006	0.100 ± 0.007	0
NOT	0.66 ± 0.02	0 ± 0	0.36 ± 0.09
Mixed	0.196 ± 0.006	0.031 ± 0.008	0.019 ± 0.005

(a) Without accounting for correlations.

Name	Corrected	α
Uniform	$\pm$	$\pm$
NOT	$\pm$	$\pm$
Mixed	$\pm$	$\pm$

(b) Accounting for correlations for **one pair**.

Experimental results – mitigation benchmark

FIVE QUBIT PROBABILITY DISTRIBUTIONS

Name	Standard	Corrected	α
Uniform	0.110 ± 0.006	0.100 ± 0.007	0
NOT	0.66 ± 0.02	0 ± 0	0.36 ± 0.09
Mixed	0.196 ± 0.006	0.031 ± 0.008	0.019 ± 0.005

(a) Without accounting for correlations.

Name	Corrected	α
Uniform	0.03 ± 0.02	0
NOT	0.004 ± 0.023	0.04 ± 0.04
Mixed	0.022 ± 0.007	0.023 ± 0.007

(b) Accounting for correlations for **one pair**.