情報演習３今井研
最終回

子安出穂

Noisy Intermediate-Scale Quantum (NISQ)

- Operational error.

- Decoherence error. A qubit can only maintain its state for a limited amount of time due to its fragile nature.

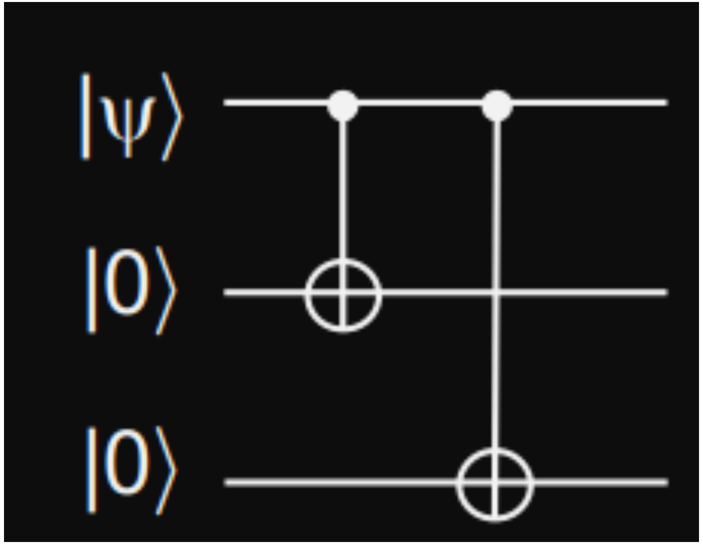
- Crosstalk. The state of a qubit might be corrupted by the simultaneous operations occurring on its neighbor qubits

- Readout error.

Bit flip code (readout error)

Encode

$$|0\rangle \Rightarrow |000\rangle$$
$$|1\rangle \Rightarrow |111\rangle$$



Decode

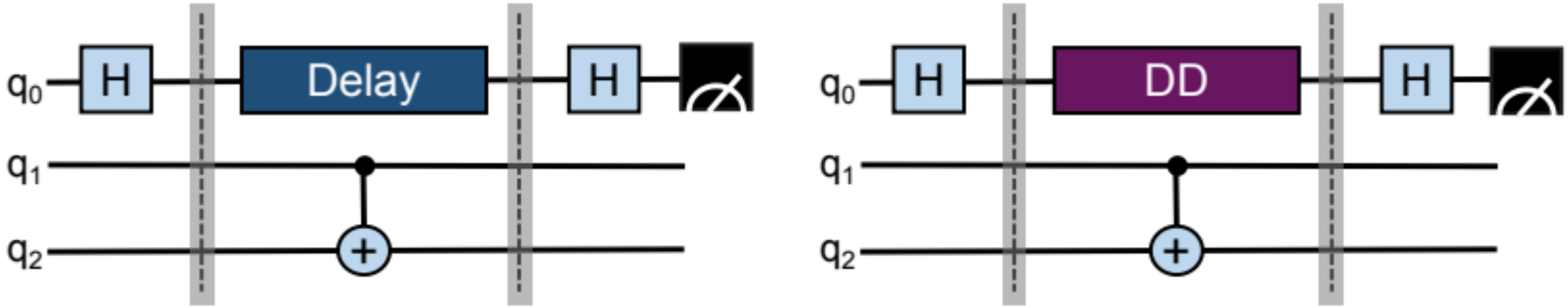
$$|000\rangle \Rightarrow |0\rangle$$
$$|001\rangle \Rightarrow |0\rangle$$
$$|010\rangle \Rightarrow |0\rangle$$
$$|100\rangle \Rightarrow |0\rangle$$
$$|011\rangle \Rightarrow |1\rangle$$
$$|101\rangle \Rightarrow |1\rangle$$
$$|110\rangle \Rightarrow |1\rangle$$
$$|111\rangle \Rightarrow |1\rangle$$

Dynamic Decoupling (DD) technique

- Idle-idle qubit, where no operation is applied to its neighbor qubits in parallel.
- Crosstalk-idle qubit, where simultaneous operations are occurring on its neighbor qubits such that the target qubit has a probability of being influenced by crosstalk. CNOT-gate is the dominant crosstalk source.

$\Rightarrow$ Apply “X-X” or “RZ(π)” gate!

Dynamic Decoupling



(a) (b)

	Yang’s experiments	My Experiments
Quantum Computer	● ibmq_toronto ● ibmq_sydney ● ibm_manhattan	● ibmq_montreal
graph	● 1~57 path graph ● 1~39 star graph ● hardware topology graph	● 5~7 star graph
error correction	● QREM (Quantum Readout Error Mitigation)	● bit flip code ● Dynamic Decoupling

準備

期待値

$$\langle\psi| A |\psi\rangle = \sum_{i=0}^{2^n-1} a_i |\gamma_i|^2$$

$$\langle A_0^1 A_1^2 A_0^3\rangle = \langle\psi| A_0^1 \otimes A_1^2 \otimes A_0^3 |\psi\rangle$$

グラフ状態

$$G_1 |\psi_G\rangle = |\psi_G\rangle$$
$$G_2 |\psi_G\rangle = |\psi_G\rangle$$
$$\vdots$$
$$G_n |\psi_G\rangle = |\psi_G\rangle$$

スタビライザー

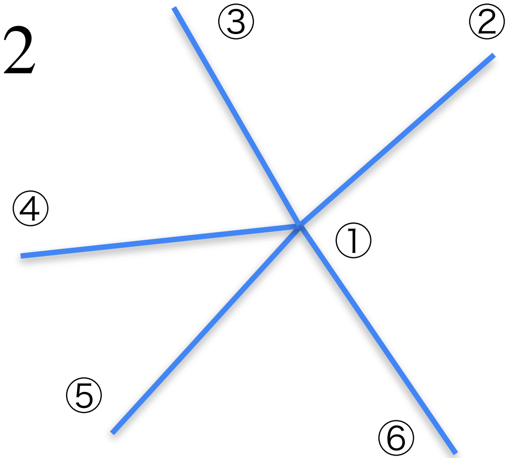
$$G_i = X_i \otimes \bigotimes_{j \in negibor(i)} Z_j$$

準備

S : 注目しているstar graph

N : star graphの頂点数

$$I_S^N := \sqrt{2}(N-1)\langle G_1 \rangle + \sqrt{2}\sum_{i=2}^{N}\langle G_i \rangle$$



Classical bound $\quad I_S^N \le 2N - 2$

Quantum Bound $\quad I_S^N \le 2\sqrt{2}(N-1)$

5 star graph

$\langle G_1 \rangle$: 0.635498046875

$\langle G_2 \rangle$: 0.80395508

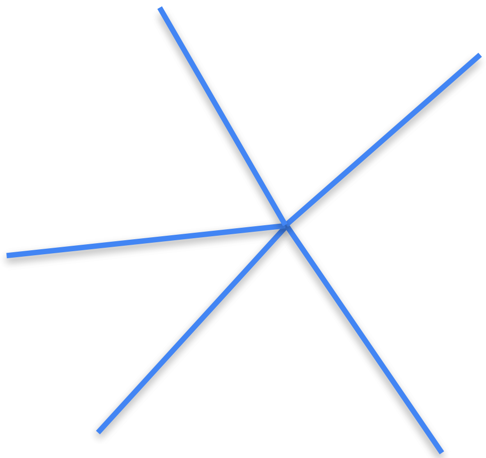
$\langle G_3 \rangle$: 0.76049805

$\langle G_4 \rangle$: 0.88183594

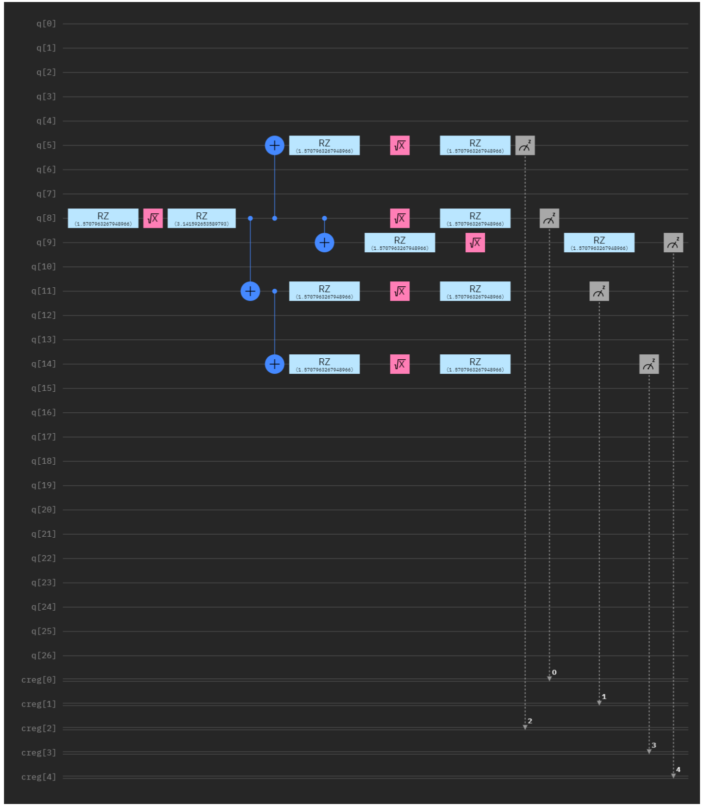
$\langle G_5 \rangle$: 0.83447266

I_S^5 : 8.234617544579667

Classical Bound : 8



$$\langle G_1 \rangle$$

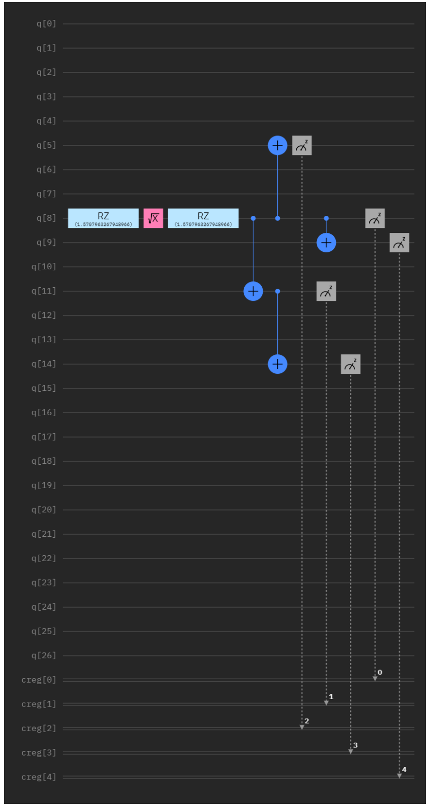


#CX-gate : 4
circuit depth : 10

測定値：

0.635498046875

$$\langle G_n \rangle (n \geq 2)$$



#CX-gate : 4

circuit depth : 7

測定値の平均 :

0.8226318359

6 star graph

$\langle G_1 \rangle$: 0.603515625

$\langle G_2 \rangle$: 0.74902344

$\langle G_3 \rangle$: 0.69018555

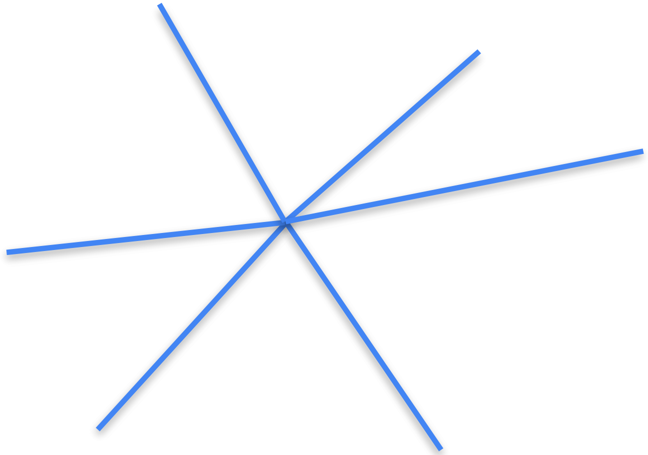
$\langle G_4 \rangle$: 0.84838867

$\langle G_5 \rangle$: 0.73681641

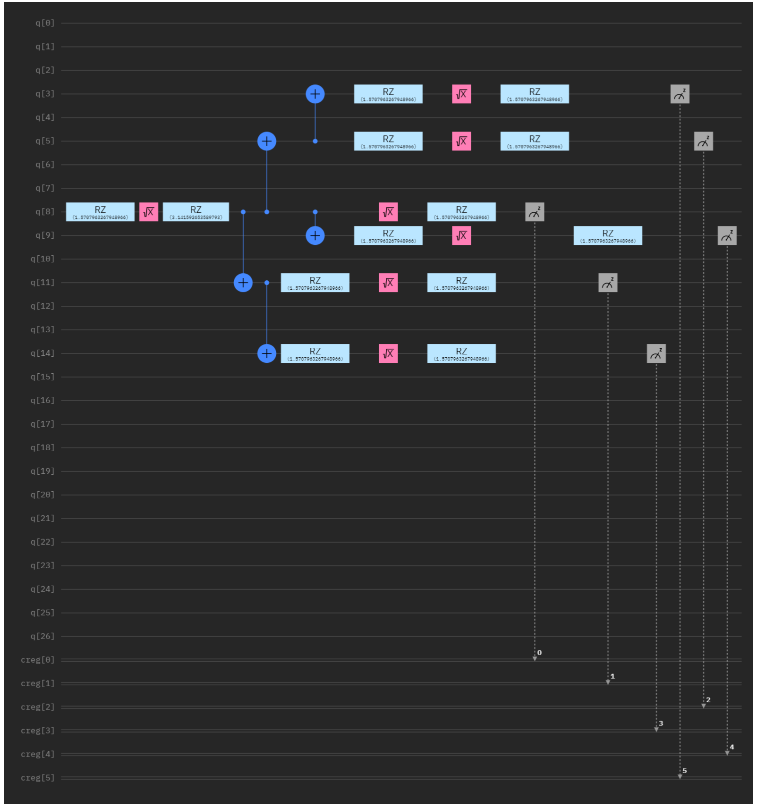
$\langle G_6 \rangle$: 0.75537109

I_S^6 : 9.612923340720634

Classical bound : 10



$\langle G_1 \rangle$

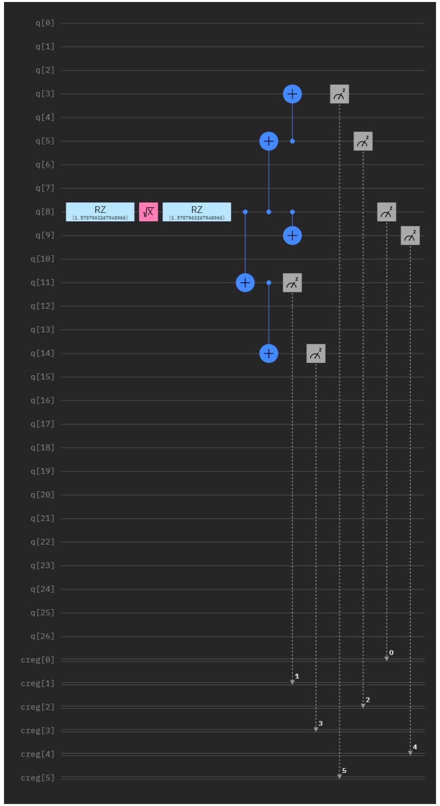


#CX-gate : 5
circuit depth : 10

測定値：

0.603515625

$\langle G_n \rangle (n \geq 2)$



#CX-gate : 5
circuit depth : 7

測定値の平均：

0.7559570313

7 star graph

$\langle G_1 \rangle$: 0.404541015625

$\langle G_2 \rangle$: 0.5534668

$\langle G_3 \rangle$: 0.60058594

$\langle G_4 \rangle$: 0.63085938

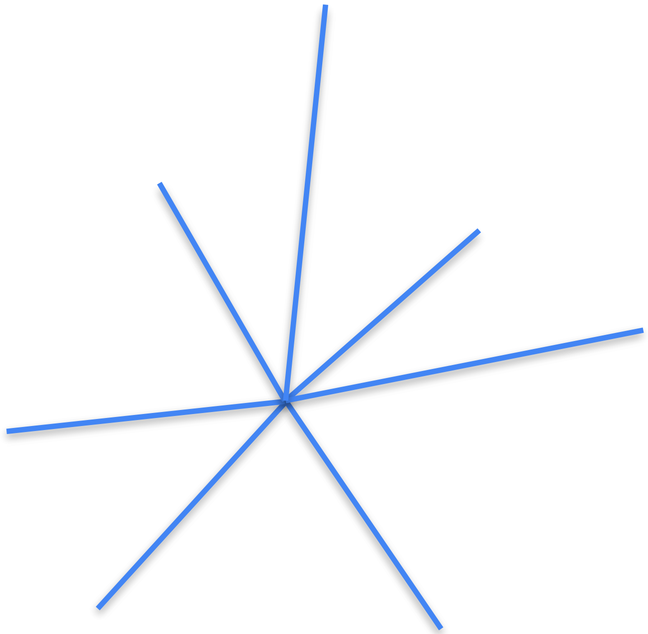
$\langle G_5 \rangle$: 0.55493164

$\langle G_6 \rangle$: 0.6340332

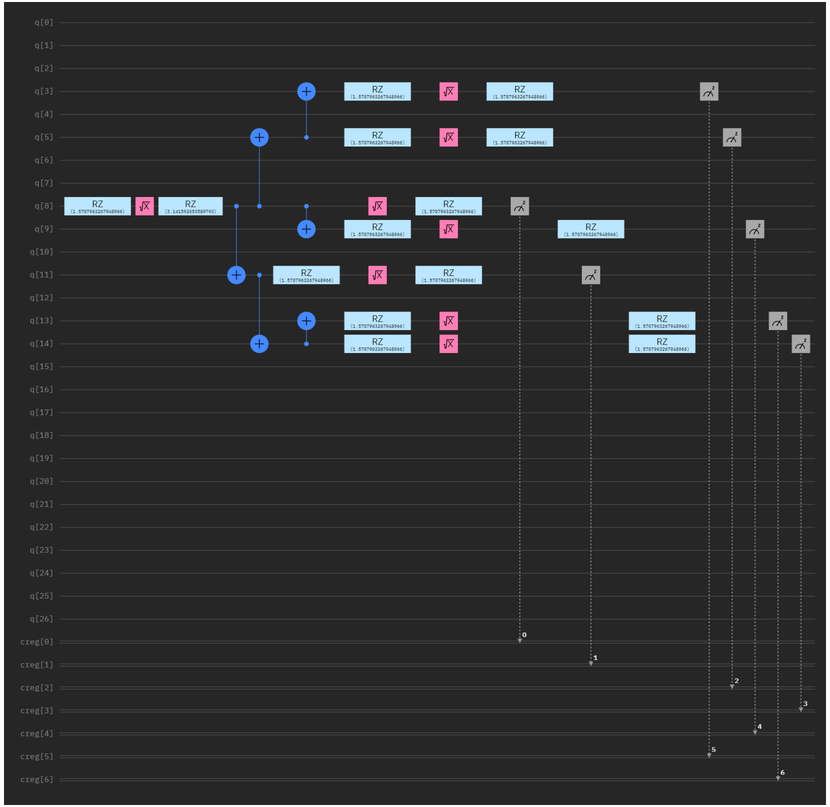
$\langle G_7 \rangle$: 0.58032227

I_S^7 : 8.459041083530476

Classical bound : 12



$$\langle G_1 \rangle$$



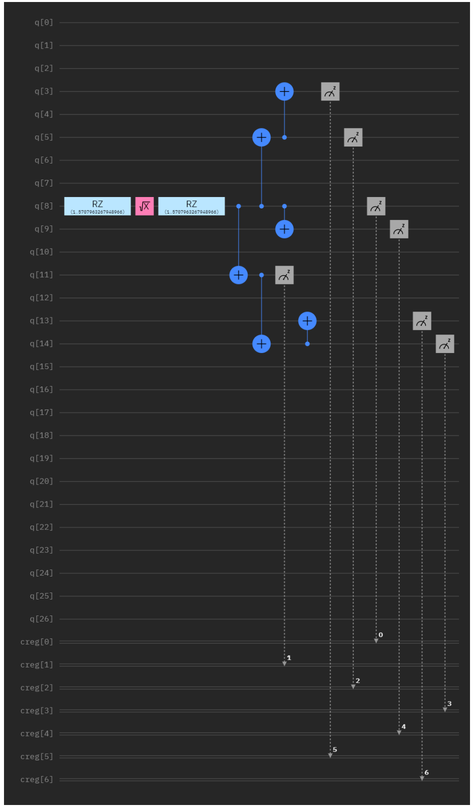
#CX-gate : 6

circuit depth : 10

測定値：

0.404541015625

$$\langle G_n \rangle (n \geq 2)$$

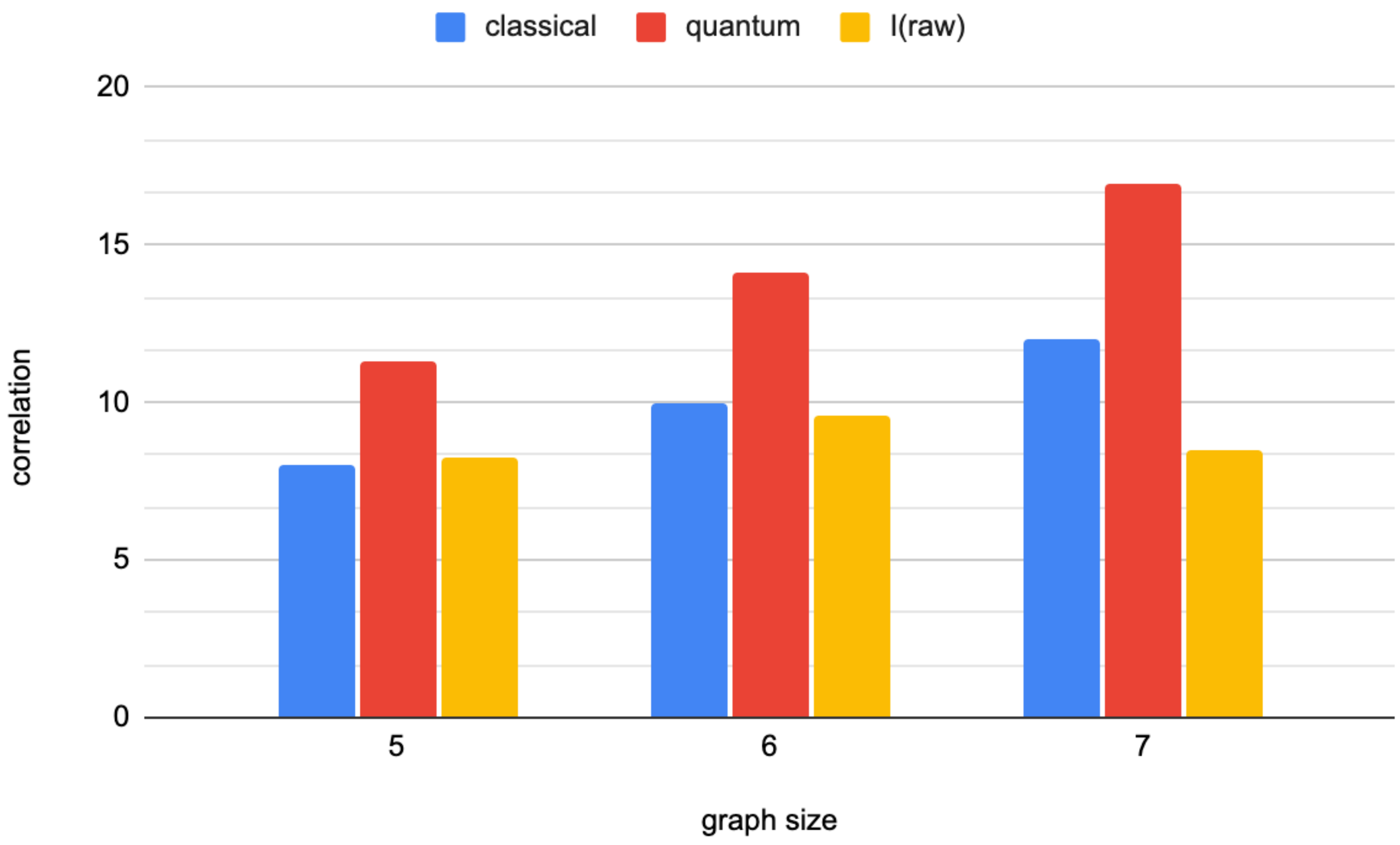


#CX-gate : 6

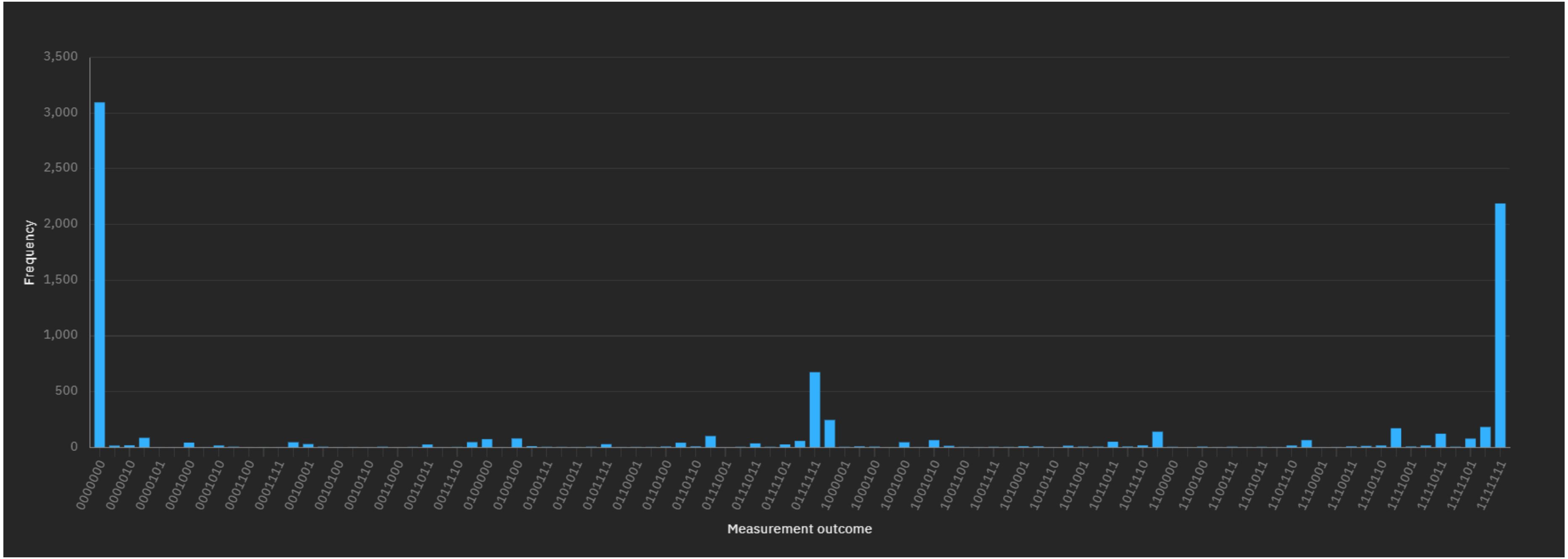
circuit depth : 7

測定値の平均：

0.5923665365


classical
quantum
I(raw)
20
15
10
5
0
correlation
5
6
7
graph size

Calibration of Readout Error



$\langle G_n \rangle (n \geq 2)$ を校正する (bit flip code)

校正前 (平均値)

5 star graph : 0.8226318359
6 star graph : 0.7559570313
7 star graph : 0.5923665365

校正後

5 star graph : 0.468994140625
6 star graph : 0.471923828125
7 star graph : 0.395263671875

→効果なし

（理論値とのズレはbit flipのせいではない？）

$\langle G_1 \rangle$を校正する (Dynamic Decoupling by XX)

校正前

5 star graph : 0.635498046875

6 star graph : 0.603515625

7 star graph : 0.404541015625

校正後

5 star graph : 0.24658203125

6 star graph : 0.238037109375

7 star graph : 0.2412109375

$\rightarrow$効果なし

$\langle G_n \rangle (n \geq 2)$ を校正する (Dynamic Decoupling by XX)

校正前

5 star graph : 0.8226318359 (0.78417969 0.8215332 0.85107422 0.83374023)
6 star graph : 0.7559570313 (0.74902344 0.69018555 0.84838867 0.73681641 0.75537109)
7 star graph : 0.5923665365 (0.5534668 0.60058594 0.63085938 0.55493164 0.6340332 0.58032227)

校正後

5 star graph : 0.6336669921875 (0.72631836 0.59936523 0.5222168 0.68676758)
6 star graph : 0.6400390625 (0.64501953 0.72583008 0.59130859 0.53833008 0.69970703)
7 star graph : 0.6059977213541666 (0.60766602 0.71728516 0.59838867 0.52978516 0.48852539 0.69433594)

→効果あり！

$\langle G_1 \rangle$ を校正する (Dynamic Decoupling by RZ)

校正前

5 star graph : 0.635498046875

6 star graph : 0.603515625

7 star graph : 0.404541015625

校正後

5 star graph : 0.27490234375

6 star graph : 0.256591796875

7 star graph : 0.2724609375

→効果なし

$\langle G_n \rangle (n \geq 2)$ を校正する (Dynamic Decoupling by RZ)

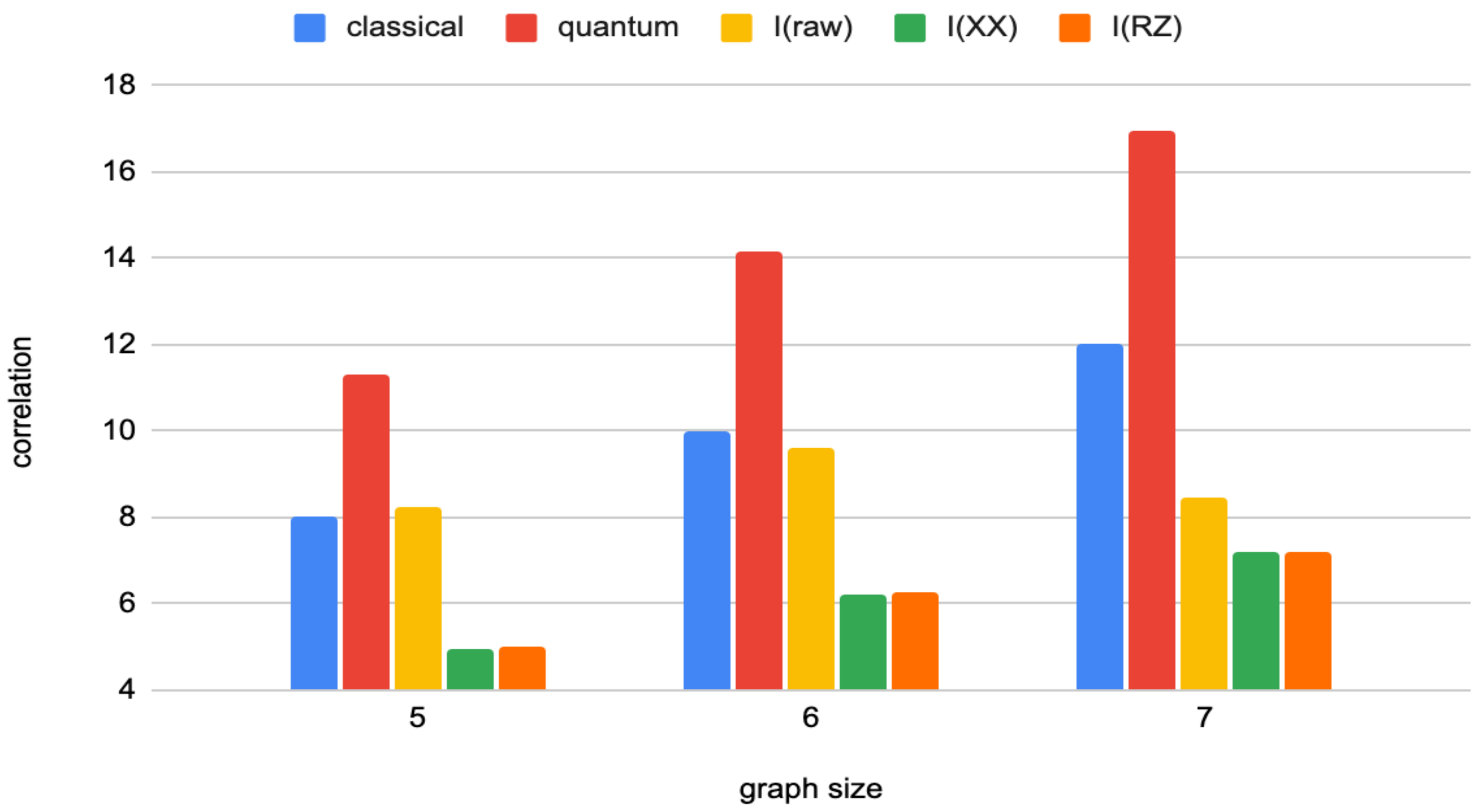
校正前

5 star graph : 0.8226318359 (0.78417969 0.8215332 0.85107422 0.83374023)
6 star graph : 0.7559570313 (0.74902344 0.69018555 0.84838867 0.73681641 0.75537109)
7 star graph : 0.5923665365 (0.5534668 0.60058594 0.63085938 0.55493164 0.6340332 0.58032227)

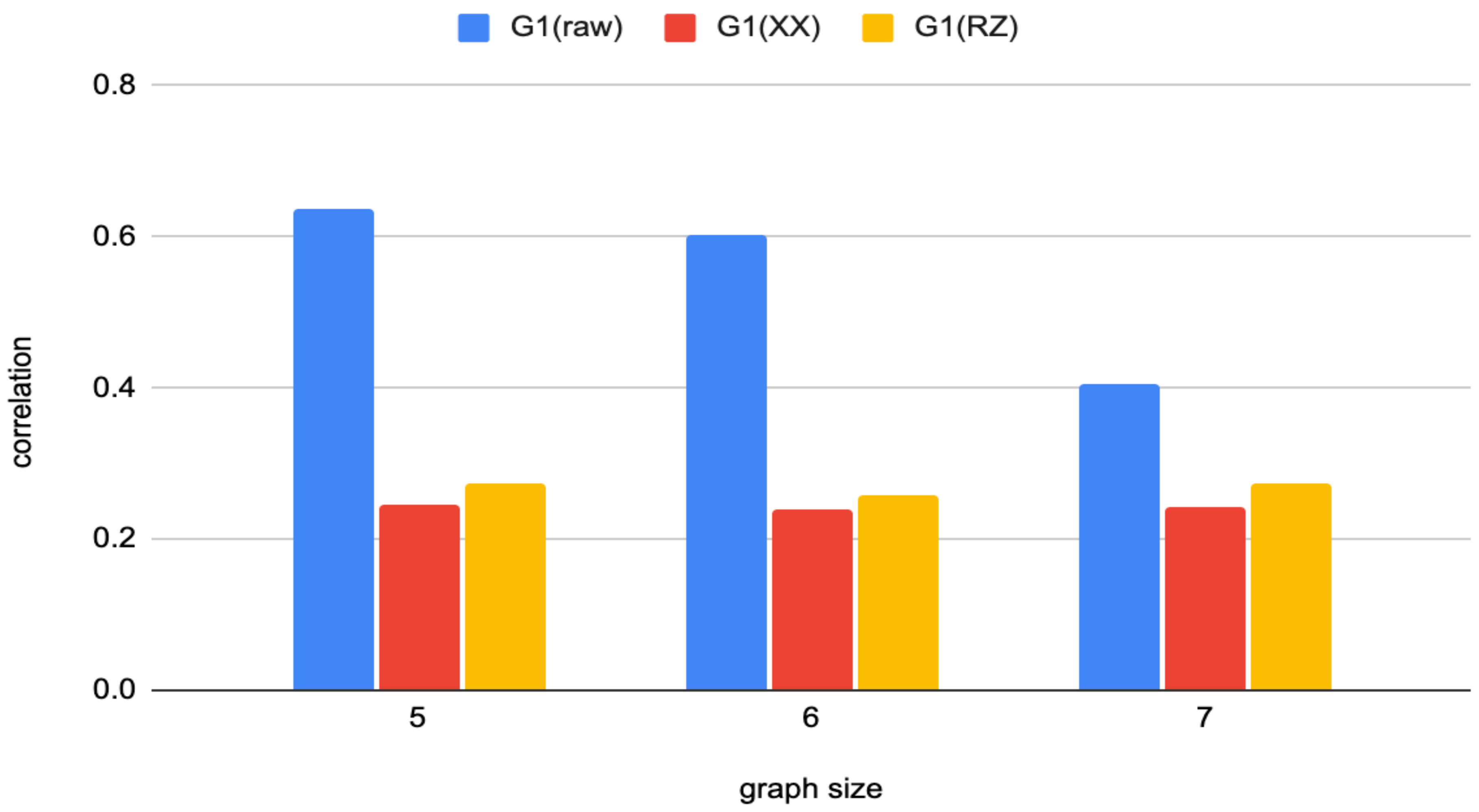
校正後

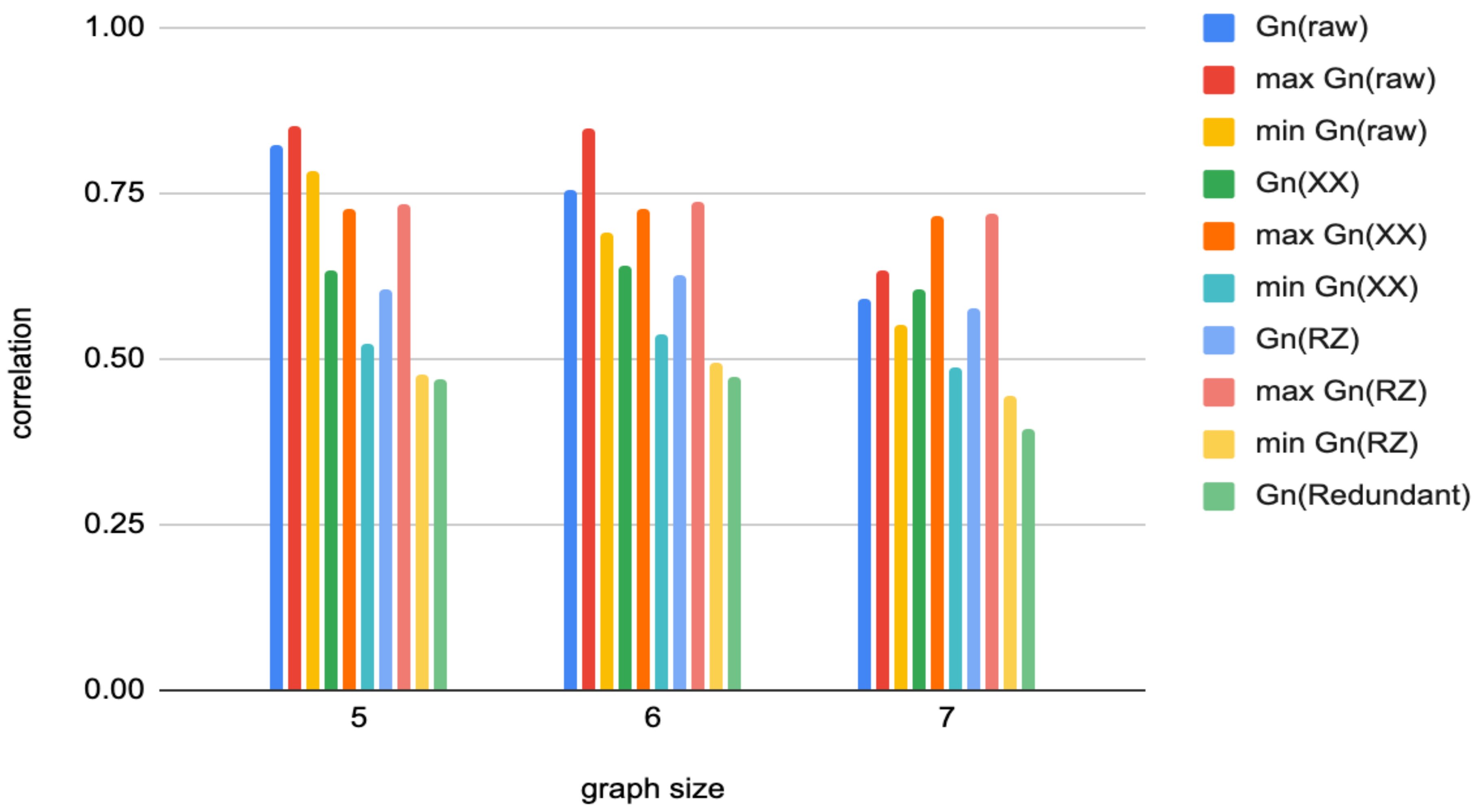
5 star graph : 0.6065673828125 (0.7355957 0.484375   0.47827148 0.72802734)
6 star graph : 0.62646484375 (0.66967773 0.73828125 0.49560547 0.51098633 0.71777344)
7 star graph : 0.5771077473958334 (0.64257812 0.72119141 0.48193359 0.45581055 0.44287109 0.7182617)

→効果あり！



classical
quantum
I(raw)
I(XX)
I(RZ)
18
16
14
12
10
8
6
4
correlation
5
6
7
graph size


G1(raw)
G1(XX)
G1(RZ)
0.8
0.6
0.4
0.2
0.0
correlation
5
6
7
graph size



1.00
0.75
0.50
0.25
0.00
correlation
5
6
7
graph size
Gn(raw)
max Gn(raw)
min Gn(raw)
Gn(XX)
max Gn(XX)
min Gn(XX)
Gn(RZ)
max Gn(RZ)
min Gn(RZ)
Gn(Redundant)

考察

- Readout error は少なくとも bit flipによるものではない
- Crosstalkは恐らく発生していて、Dynamic Decouplingによって発生を減らすことができる。

- Readout errorはphase flipによるものだと思うので、QREM以外の訂正方法を探して試してみたい。
- なぜ $\langle G_1 \rangle$ の測定値をDynamic Decouplingによって改善できなかったのか考える。

Reference

- Siyuan Niu, Aida Todri-Sanial, Analyzing Strategies for Dynamical Decoupling Insertion on IBM Quantum Computer (2022), arXiv:2204.14251v1
- Bo Yang, Rudy Raymond, Hiroshi Imai, Hyungseok Chang, Hidefumi Hiraishi, Scalable Bell Inequalities for Quantum Graph States on IBM Quantum Devices (2021), arXiv:2101.10307v1
- Gary J. Mooney, Charles D. Hill & Lloyd C. L. Hollenberg, Entanglement in a 20-Qubit Superconducting Quantum Computer (2019), scientific reports (2019)9:13465
- F. Baccari , R. Augusiak, I. Šupić, J. Tura, A. Acín, Scalable Bell Inequalities for Qubit Graph States and Robust Self-Testing (2020), physical review letters 124, 020402