MCMit

Hardware-Software Co-Design for Mid-Circuit Measurement Error Mitigation

Emmanouil (Manos) Giortamis, Felix Gust, Aleksandra Świerkowska, Sandra Stankovic, Innocenzo Fulginiti, Yanbin Chen, Xiaorang Guo, Benjamin Lienhard, Martin Schulz, and Pramod Bhatotia

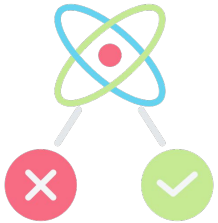
Technical University of Munich

ACM/IEEE MICRO'26, Athens, Greece

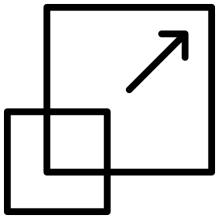
Two biggest quantum computing challenges

Noise

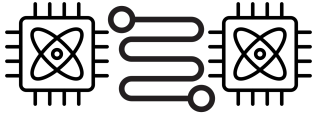
Quantum Error Correction (QEC)

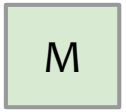


Scale



Distributed Quantum Computing (DQC)



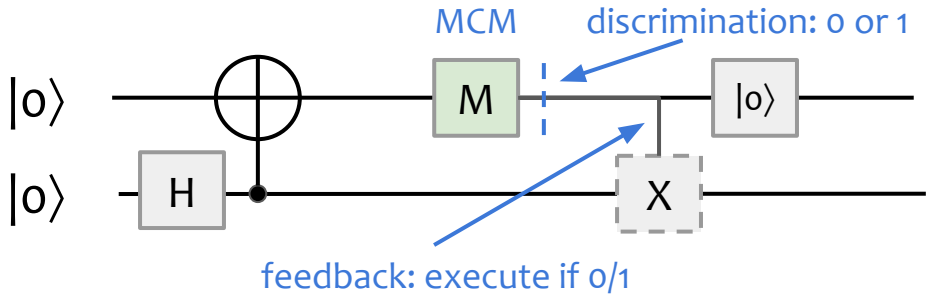


Mid-circuit measurements (MCMs)

Classical feedback

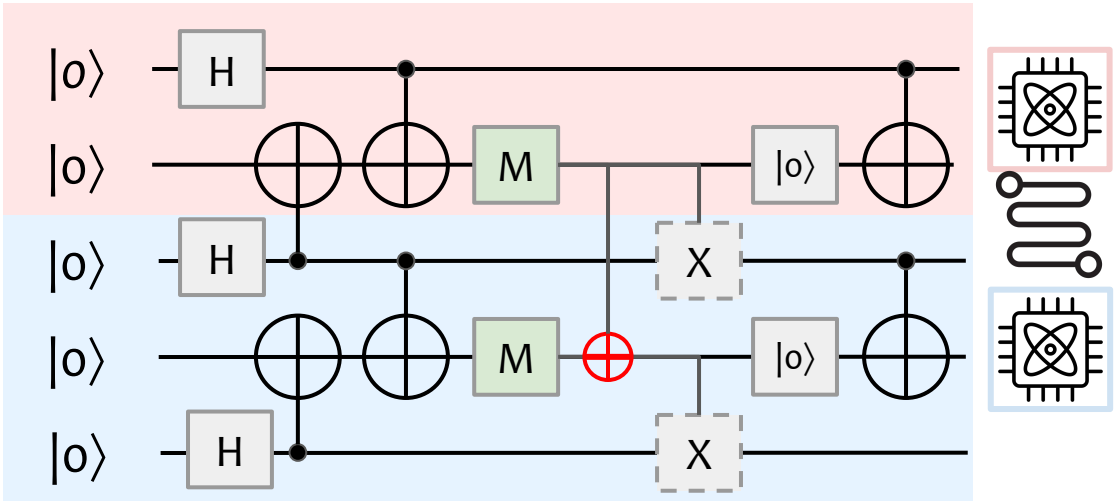
Images source: flaticon.com

What are MCMs and classical feedback?



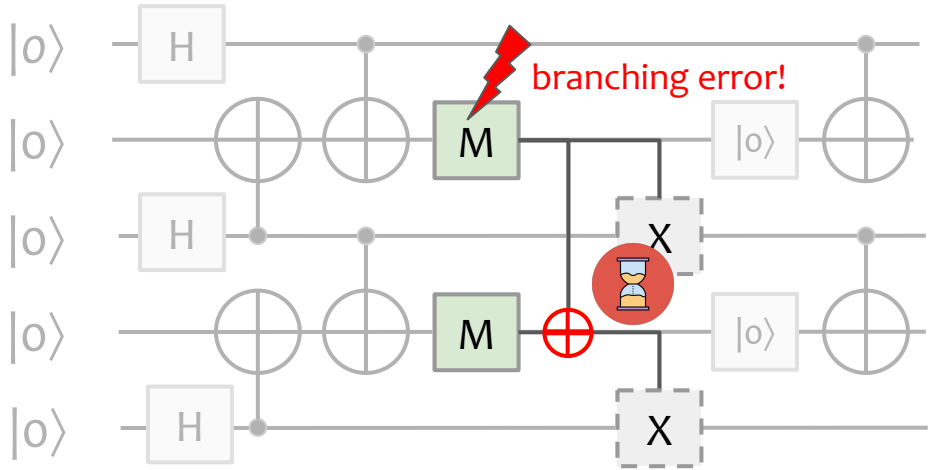
MCMs and classical feedback enable dynamic control flow

Why do MCMs and classical feedback matter?



MCMs and classical feedback enable DQC and QEC

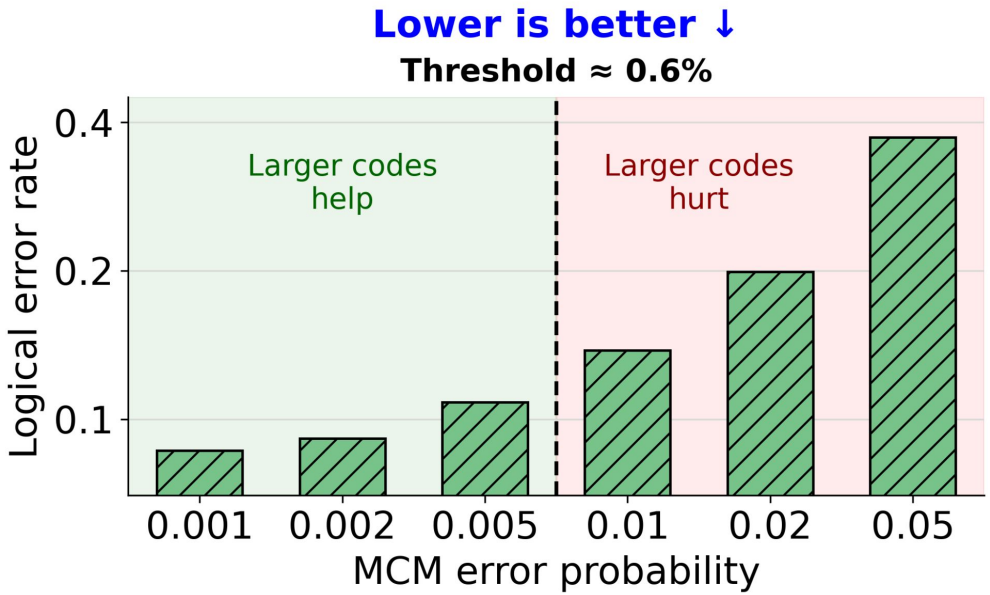
The limitations of MCMs and classical feedback



MCM errors

Classical feedback latency

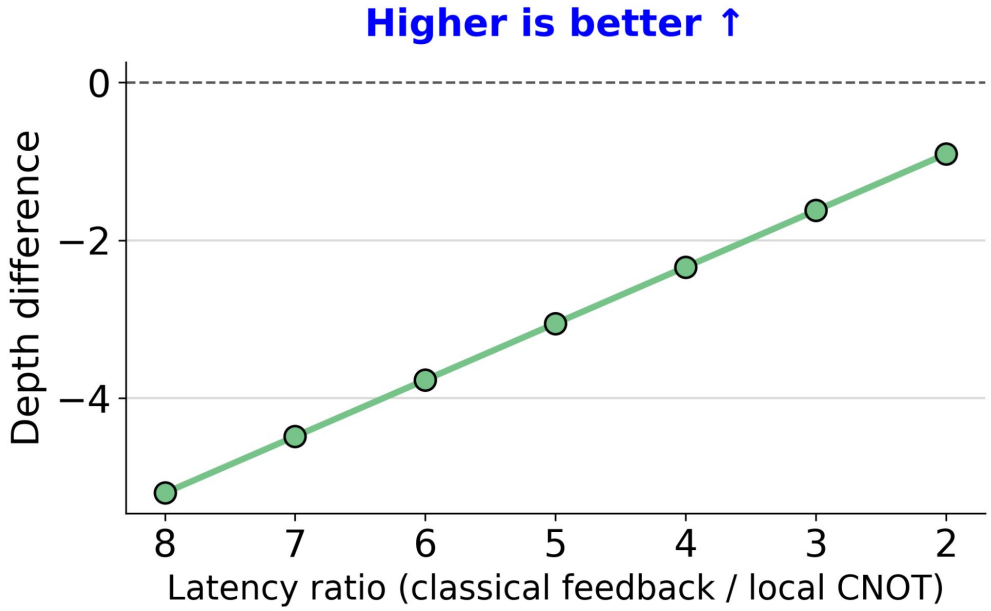
Impact of MCM errors on QEC



- Surface code
- Distance 11
- Circuit-level noise
- Google Sycamore

MCM errors degrade QEC performance by up to **4.3x**

Impact of classical feedback latency on DQC



- MECH compiler [1]
- Qiskit baseline
- Avg. of 4 apps.
- 3x3 grid chiplets

Classical feedback latency degrades DQC performance by up to **3.3x**

[1] MECH: Multi-Entry Communication Highway for Superconducting Quantum Chiplets, ASPLOS'24, Zhang et al.

The problem we are trying to solve

How to mitigate errors caused by erroneous and slow MCMs and feedback?

Our proposal: MCMit

MCMit

A hardware-software co-design for mitigating mid-circuit measurement errors

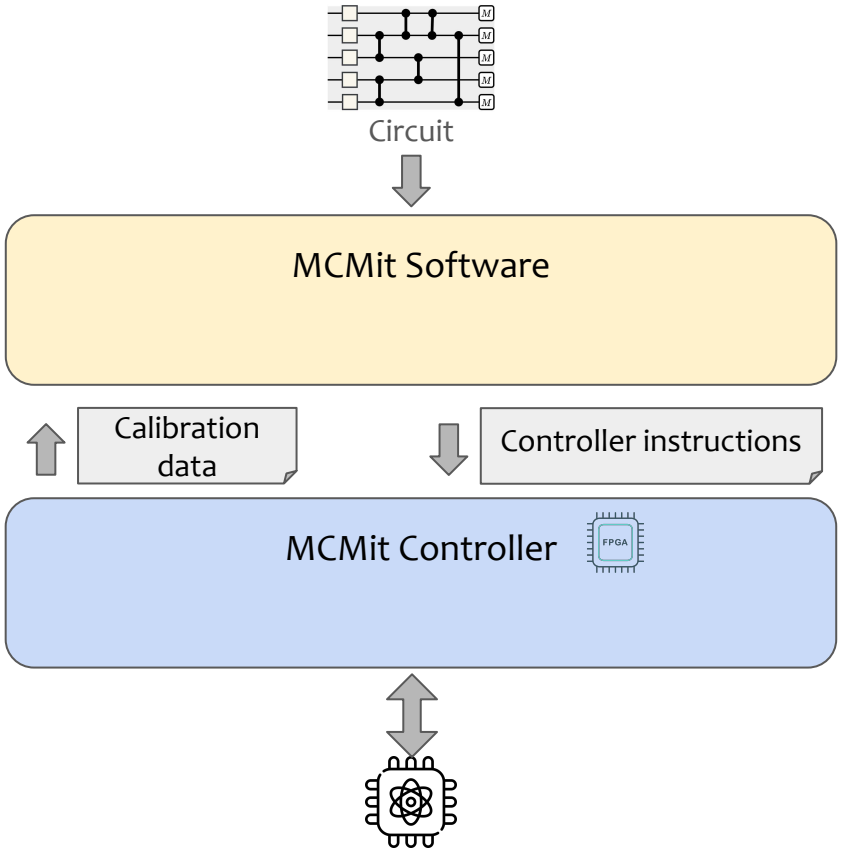
Design goals:

- **Cross-layer design:** S/W decisions are guided by H/W info and vice versa
- **Performance:** High fidelity, low logical error rates, and low latency
- **Efficiency:** Low hardware utilization & low software overheads

Outline

- ~~Introduction & motivation~~
- System design
- Implementation
- Evaluation

MCMit overview

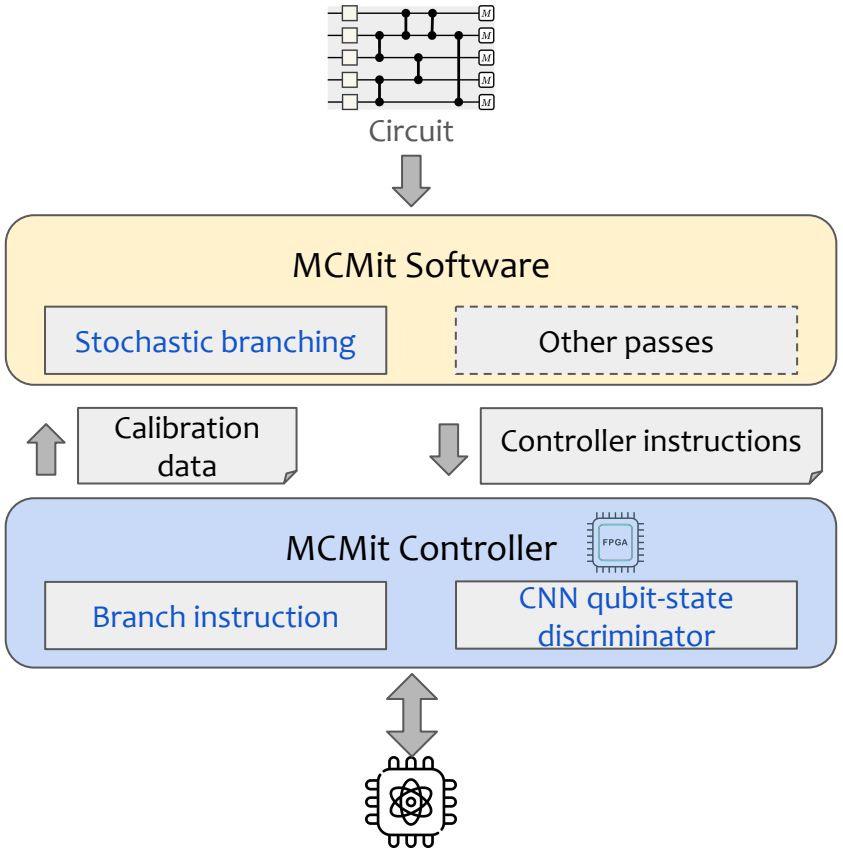


Key idea #1:
Branching error mitigation
based on MCM error probabilities

Key idea #2:
Single-instruction classical feedback

Key idea #3:
CNN-based qubit-state discrimination

MCMit overview

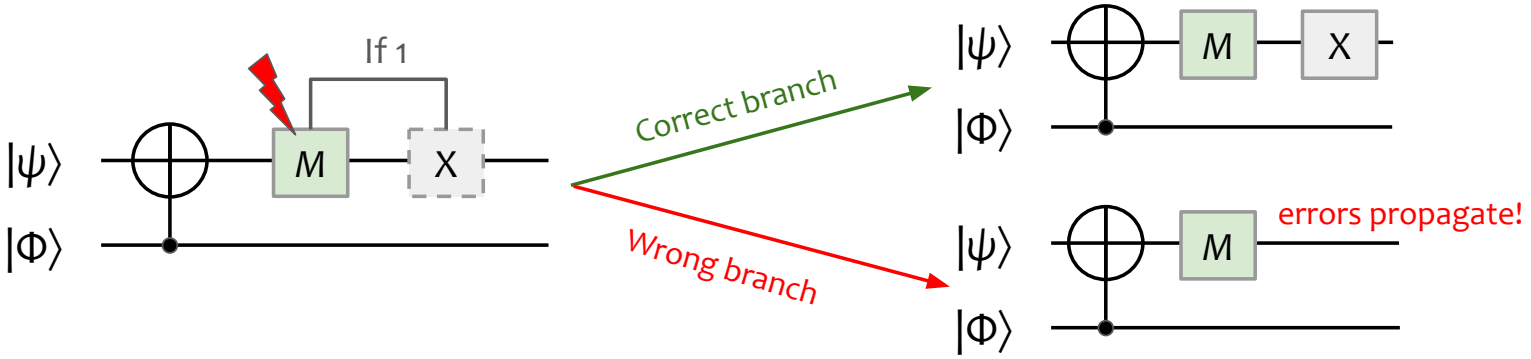


Key idea #1:
Branching error mitigation
based on MCM error probabilities

Key idea #2:
Single-instruction classical feedback

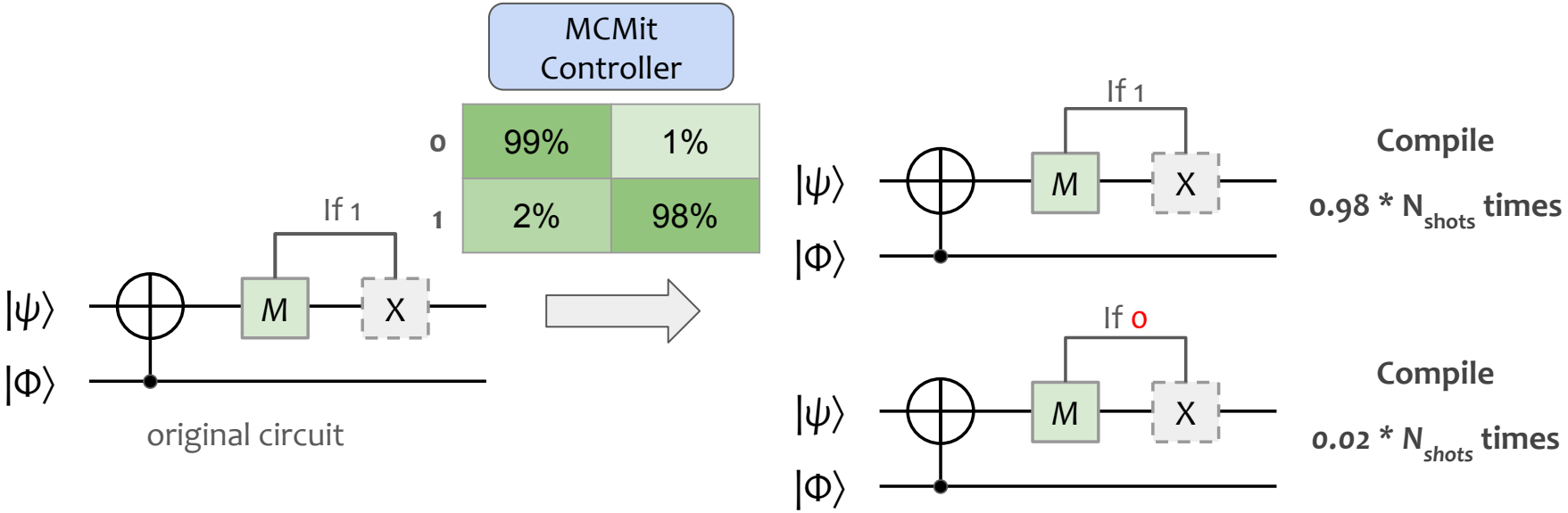
Key idea #3:
CNN-based qubit-state discrimination

What are branching errors and why are they hard?



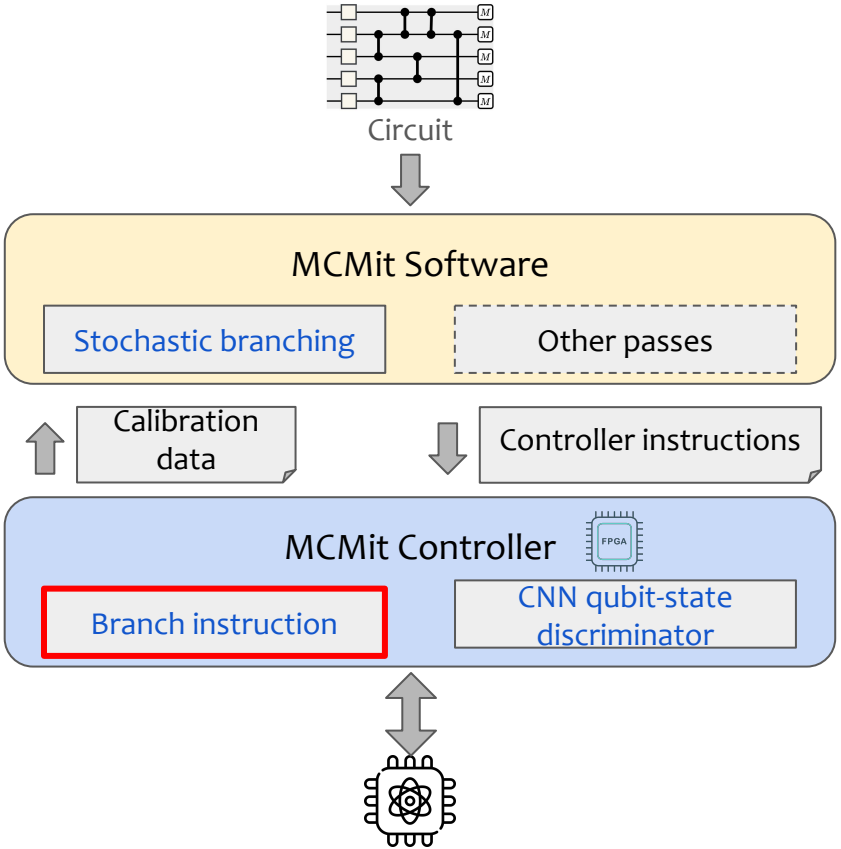
Existing readout error mitigation is not sufficient for MCMs

Stochastic branching leveraging confusion matrices

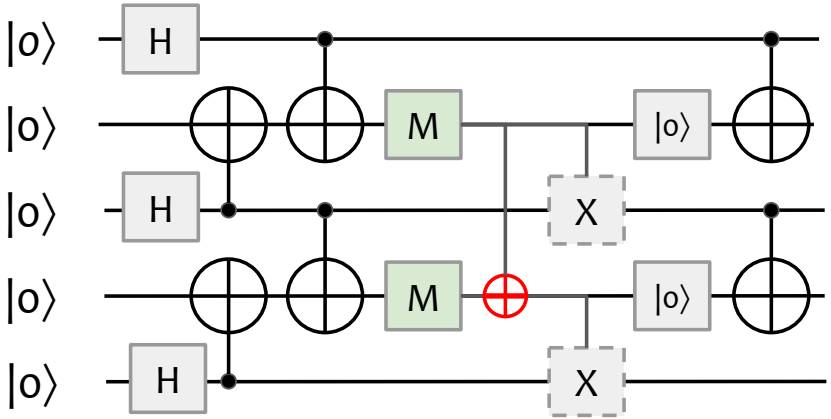


MCMit provides probabilistic branching error mitigation at negligible cost

MCMit overview



Existing QPU controllers' limitations



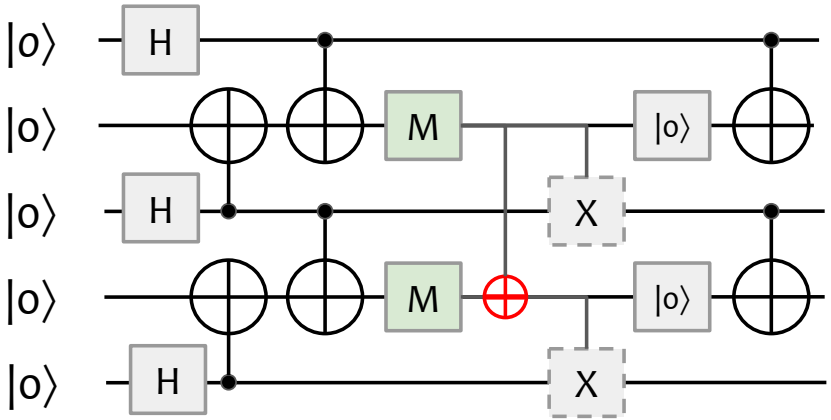
Linearly increasing XOR inputs

```
branch_fproc{
alu_op : 'eq',condition: 1, qubits: [1],
true: [
 branch_fproc {
  true: [
   branch_fproc {...}
  ]
 }
], false: []
}
```

Each branch instruction costs 16ns

QPU controllers nest instructions, leading to linearly increasing latency

Single-instruction support for complex control flow

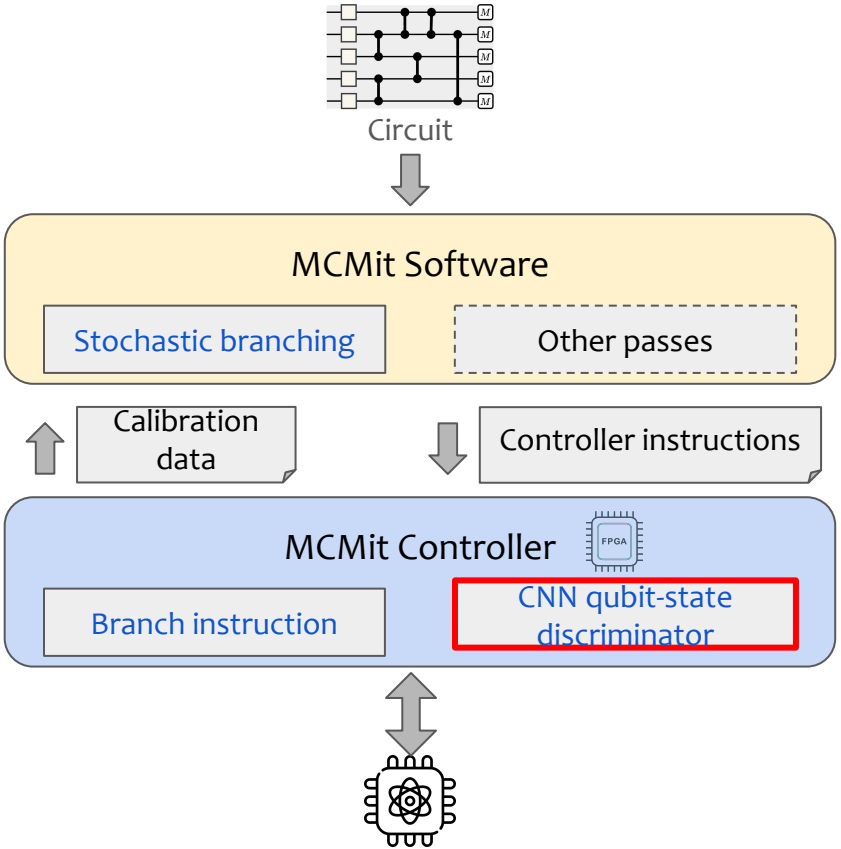



```
branch_reduce_fproc{
alu_op : 'xor', // maj, or, and
condition: 1,
qubits: [1, 3]
true: ['X'], false: []
}
```

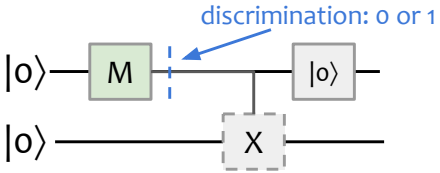
Single instruction: 16ns!

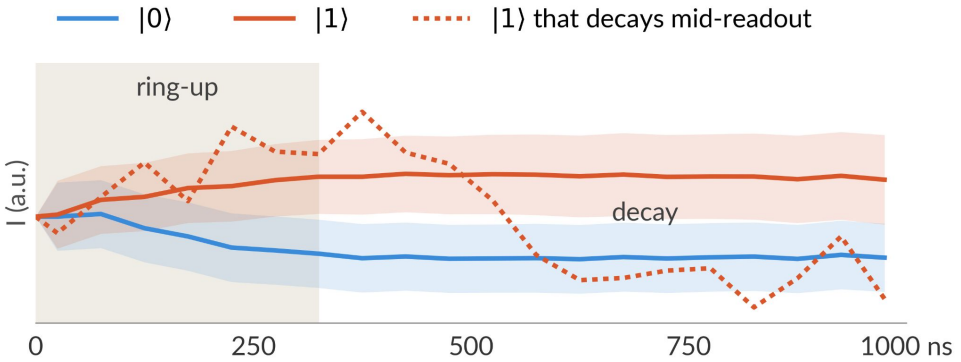
MCMit enables low- & constant-latency classical feedback

MCMit overview



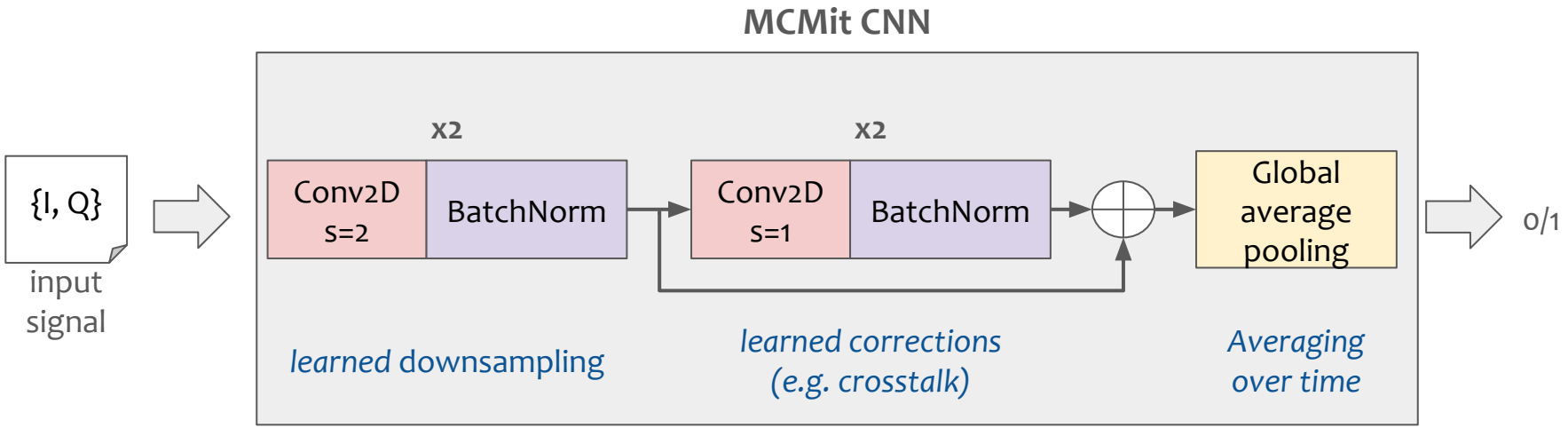
Why is qubit-state discrimination challenging?





Qubit-state discrimination is challenging at *short* readout traces

MCMit Convolutional Neural Network (CNN)



This architecture can achieve high accuracy even at *short* readout durations

Outline

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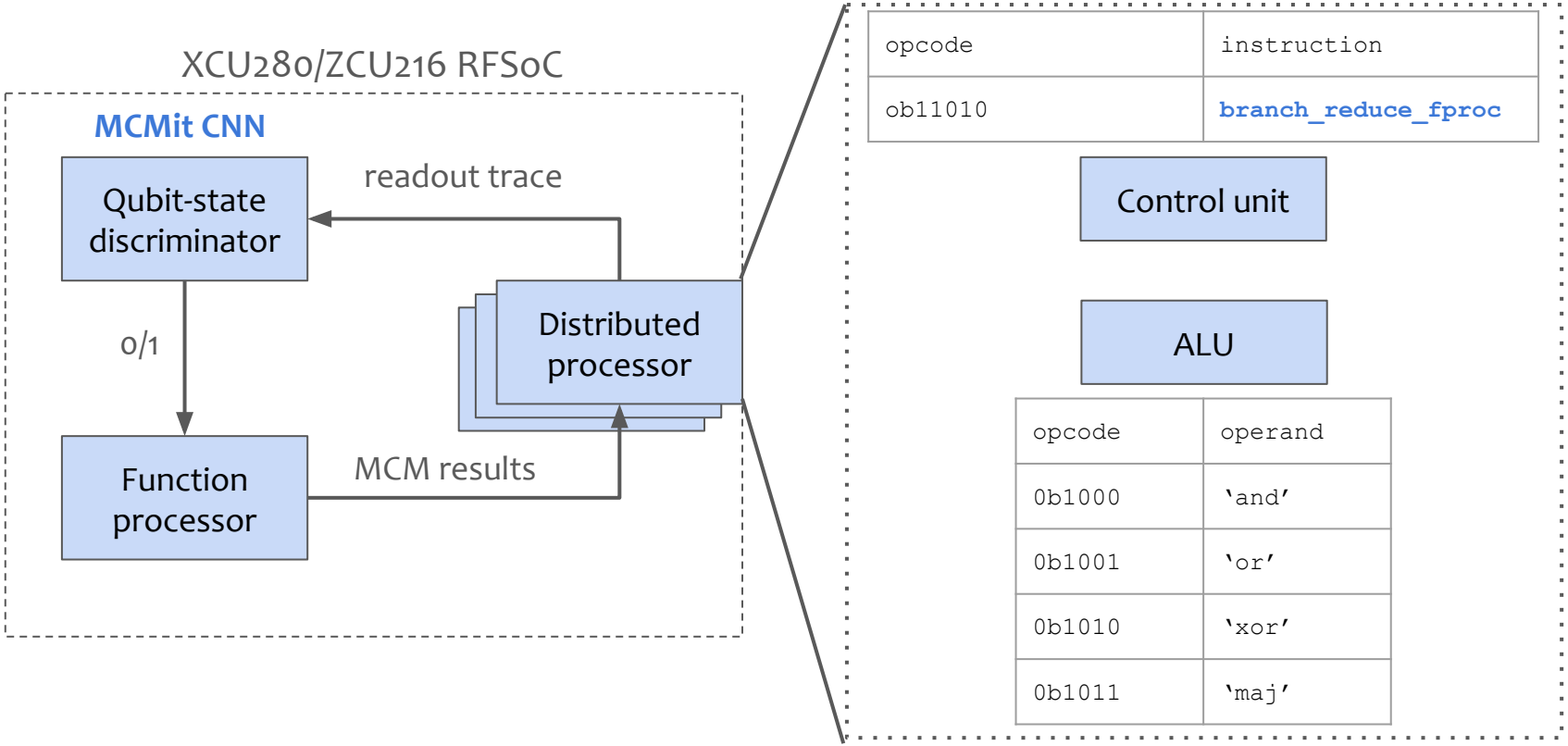
FPGA implementation of MCMit controller



Outline

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Research questions

RQ #1

Fast readout:
Can MCMit shorten the MCM length and how does this affect LERs?

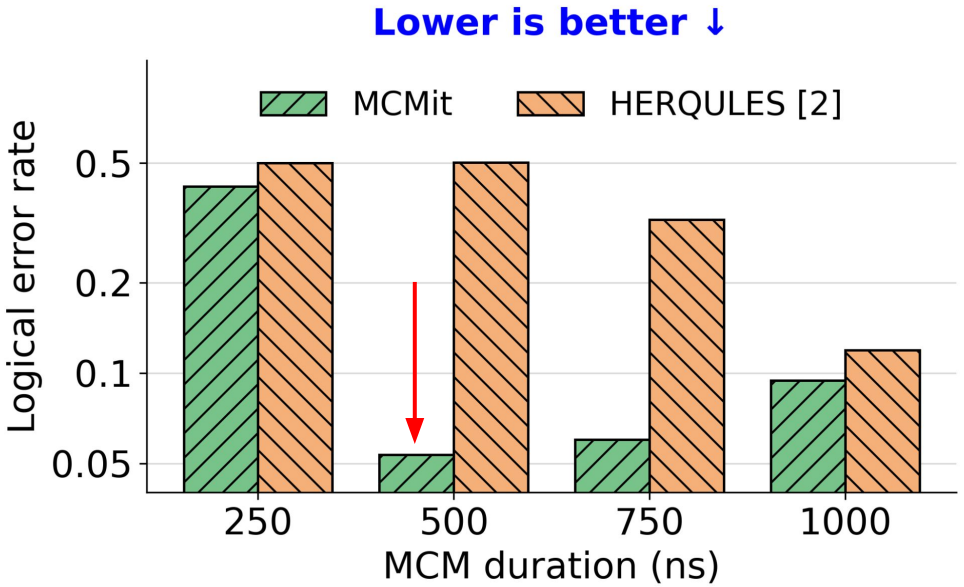
RQ #2

Branching errors:
Can MCMit mitigate branching errors caused by MCM errors?

RQ #3

Feedback latency:
Can MCMit keep feedback latency constant as the number of MCMs grows?

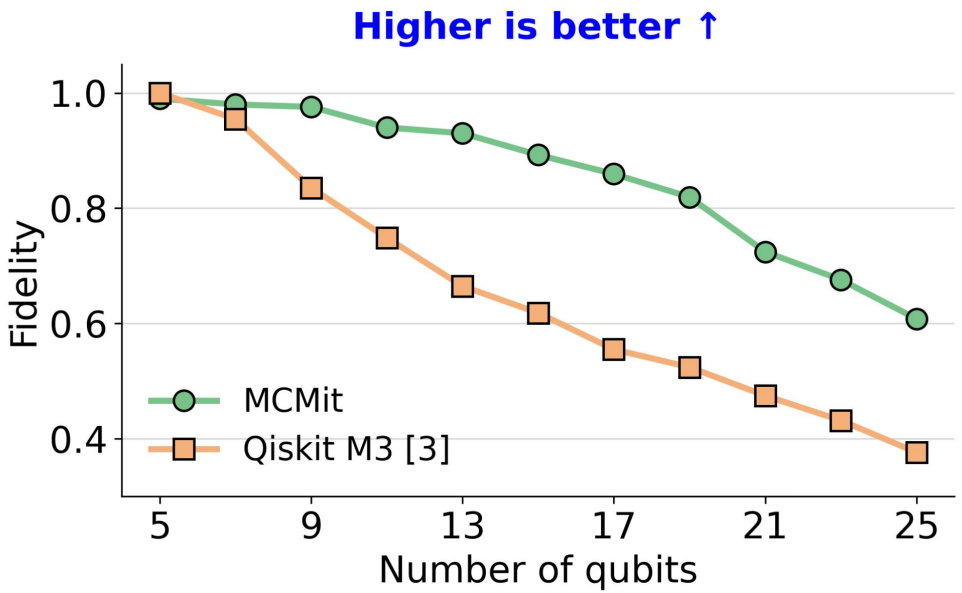
#RQ1: Fast readout



MCMit reduces LERs by **9.4x** for 500ns readout compared to the SOTA

[2] Scaling Qubit Readout with Hardware Efficient Machine Learning Architectures, ISCA'23, Mauyra et al.

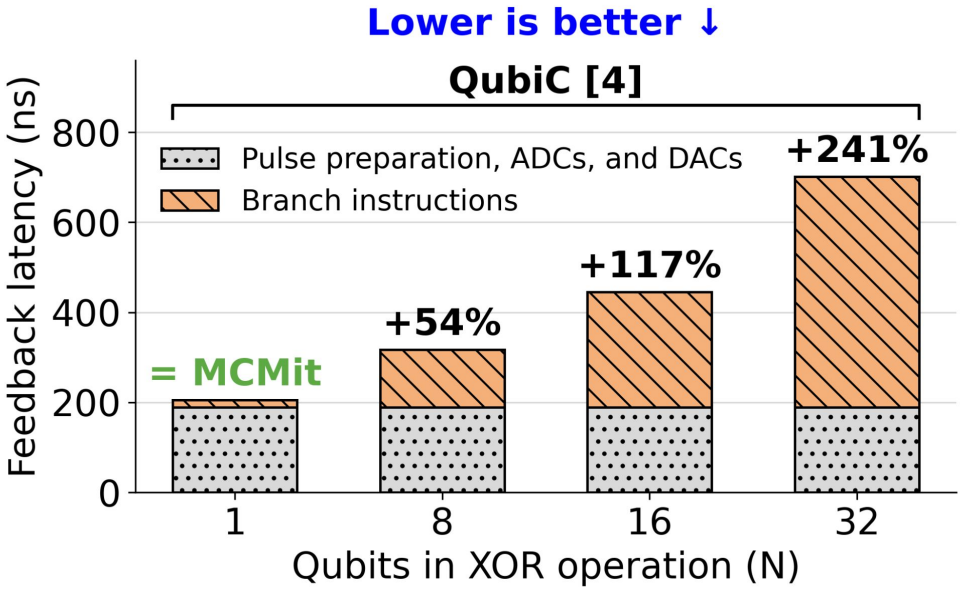
#RQ2: Branching errors



MCMit achieves **37%** higher fidelity, on average, compared to the SOTA

[3] Scalable Mitigation of Measurement Errors on Quantum Computers, PRX Quantum 2, Nation et al.

#RQ3: Feedback latency



MCMit improves classical feedback latency by up to **~70%**

[4] QubiC 2.0: A Flexible Advanced Full Stack Quantum Bit Control System, QCE'23, Huang et al.

Conclusion

How to mitigate errors caused by slow MCMs and classical feedback?

MCMit:

A hardware-software co-design for MCM error mitigation

Impact:

- Mitigates MCM and branching errors
- Reduces MCM and classical feedback latency
- Helps to open the way to DQC and QEC

Source code

Personal website

emmanouil.giortamis@tum.de