Distributed Quantum Error Correction
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I don’t care about quantum error correction.

I care about quantum computer system architectures.
A Quantum Multicomputer Node

quantum network

coherent microwave source

waveguide

classical control & measurement

to next node

node

qubit

transceiver qubit

dilution refrigerator
One Like This?
A Quantum Multicomputer
Multicomputer Research

- Architecture:
  # of nodes? Qubits/node?  
  Network topology? Link design?
- Software: applications, language design
- Error management:
  Quantum Error Correction (QEC), purification for teleportation
- Performance analysis

Link Design

multicomputer node
qubus connection
centimeters to meters
qubit

fiber or wave guide
serial connection
or parallel connection
transceiver qubit
node–internal qubit
qubus–qubit coupling
qubit–qubit coupling
Link Design

• Two levels of [[23,1,7]] code allow 1% physical teleportation failure when factoring a 1024-bit number
• Serial links work well when memory error rate 100x better than teleportation
  – Preferable for engineering reasons
• Creating and using distributed logical zeros is painful and unlikely to work well.

Small Nodes

Oi, Devitt, Hollenberg, PRA 74

Jiang et al., quant-ph/0703029

Kim & Kim, arxiv:0711.3866

14 qubits/node, one level of $[[5,1,3]]$

5 qubits/node, only 1 for data (1 measurement, 2 purification, 1 transceiver)

Kim & Kim, arxiv:0711.3866

Elementary Logic Unit (ELU)

(a) Measurement Optics
Integrated Optics For Beam Control

(b) MEMS mirror HR Coating Optical Fiber

(c) $N \times N$ Optical Crossconnect Switch (OXC)

Bell Detectors
Small Nodes

• Many technologies support small nodes, not the 3-5 thousand physical qubits we want

• At first glance, teleportation failure rates must meet standard threshold arguments
Partial Bell Measurement

\[ |\Phi^+\rangle \{ |000000000\rangle + |111111111\rangle \} \]

\[ \text{or} \]

\[ |00001111\rangle + |11110000\rangle \]
[[9,1,3]] Shor Code Stabilizer

X X X X X X I I I I I I
X X X
X X X
I I I
X X X
X X X

Z Z I II IZ IZ I II II I I I I I I I I I I
I I I I I I I Z Z I I Z Z I I I I I I I
I I I I I I I I I I I I I I Z Z I I Z Z
Shor Stabilizer in 3 Nodes

2 Bell pairs

+ 2 Bell pairs = 4 Bell pairs for one round of level one QEC

PBM uses one $|000000\rangle+|111111\rangle$, built & verified using two Bell pairs

Zero Bell pairs consumed!

PBM = Partial Bell Measurement
Concatenation

FTM = Full Transversal Measurement

9x2 Bell pairs x6

27x2 Bell pairs x2
• Single-data-qubit (5 phy qubit) nodes require
  \((5+6) \times 2 \times 9 + 9 \times 2 \times 6 + 27 \times 2 \times 2 = 414\)
  physical Bell pairs
• 3-data-qubit nodes (9 phy) require
  \(4 \times 9 + 9 \times 2 \times 6 + 27 \times 2 \times 2 = 252\)
  physical Bell pairs
  – approximately 1.6x for scaleup 5-->9 physical qubits/node
• 9-data-qubit nodes (20 phy) require
  \(9 \times 2 \times 6 + 27 \times 2 \times 2 = 216\)
  physical Bell pairs
  – but first level QEC will cycle faster
• Plus 81 Bell pairs per logical gate or teleportation
Observations

• All codes require entanglement btw nodes
  – Some syndromes purely local, some “hard”
• Mitigation approaches:
  – match to error type (biased error model)
  – reduce frequency in “hard” direction
  – relax constraints: Bacon-Shor?
• For detailed performance calculation, need to separate Bell pair creation from actual teleportation
Conclusions

- Small nodes not ideal, but usable
  - full logical qubits/node much better
    (how much depends on ratio of logical gates to QEC)
- At second level and above, the *interconnect* remains teleportation
http://www.sfc.wide.ad.jp/aqua/

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