Integrated Photonics For Use In Higher State Quantum Networks

Warren McPhillips
Dept. of Computer Science
Georgia Southwestern University
Americus, Georgia 31709
wmcphill@gsw.view.usg.edu

Abstract – Highlight current challenges in developing quantum network communication. Specifically, state maintenance, error correction, and communication complications as a result of some properties that exist in quantum mechanics that classical computers do not experience. Then, propose a theoretical quantum network using integrated photonics via higher entangled states for transmission, "copying state" via quantum teleportation, and quantum error correction (QEC). I will visualize the various phases mentioned above using IBM' Composer, with code I wrote using IBM's Qiskit.

Keywords – Photonic Processor, Quantum Networks, Quantum Communication, Quantum Error Correction

I. CHALLENGES AND BENEFITS OF QUANTUM COMPUTING

In his 1948 paper, "A Mathematical Theory of Communication", Claude Shannon was able to quantify the amount of digital information that can be communicated in a channel. And for decades, this has been a reliable method for communication. However, unlike classical computing, quantum computing (qc) does not operate under the same principles as its classical counterpart, and has some challenges requiring solutions from various scientific fields.

While the classical computing systems are electrical, with electrical transistors being robust enough to guarantee the state of the switch, quantum systems are largely analog. And with analog processes, *noise*[1] in various forms effect the state of the system, impacting the fidelity of quantum bits (qubits), the fundamental storage element in qc.

Quantum fidelity is the measurement of *purity*[2] between two quantum states. Using IBM' Qiskit to exemplify noise, we can code a simple probabilistic coin flip. In classical computing, one can expect a binary output of roughly 50% of the time yielding heads or tails. The results in quantum computing however are not binary, and the outputs generated as a result of noise is just one of the many challenges scientists are trying to solve for.

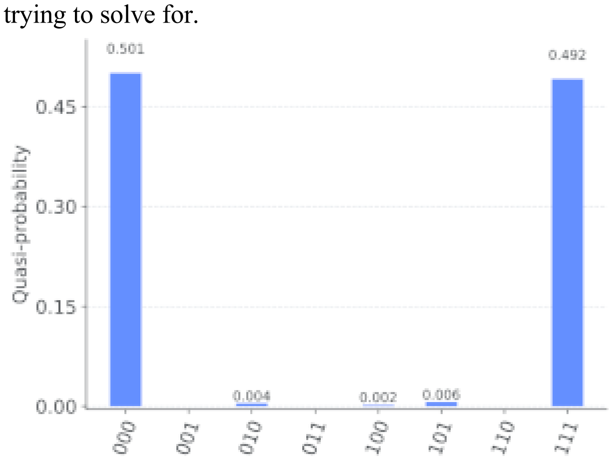


figure: Quantum coin flip after 4,000 iterations

While managing noise is an ongoing challenge, the general concensus among the scientific community is that noise is a problem that will be successfully managed in the future. Another challenge is timing. In qc, imperfect timing can cause errors. However, even with the growing list the challenges, the overall progress in qc is remarkable. In fact, scientists are already realizing the benefits qc can provide over its classical counterparts as some quantum systems are starting to exihibit quantum advantage: a point where quantum computing can outperform the classical counterpart.

The fundamental challenge for scientists is to understand and have the tooling and equipment reliable enough to control, measure, and create, in a quantum environment. Similarly to how man built ships, studied the stars and ocean currents to master the seas, we are in a quantum era trying to understand what tools we will need to master this "new" domain.

Physicists and mathematicians have spent decades studying quantum mechanics and have discovered some behaviors and properties in quantum mechanics that can be helpful in helping us understand and answer complex questions. Some of these beneficial quantum properties, specifically entanglement, superposition, and teleportation, are particularly useful in the realm of quantum computing; with the goal being able to leverage the capabilites of qc to achieve quantum advantage in applications such as code breaking. Quantum computing may perhaps even introduce applications for problems scientists have yet to discover.

In some current applications, scientists have already successfully tested performance on photonic systems that "on average, would take more than 9,000 years for the best available algorithms and supercomputers to produce, using exact methods, a single sample from the programmed distribution, whereas a photonic system (Borealis) was designed to specifically compute Gaussian boson sampling (GBS), in only 36 μs."[3] The performance of a photonic quantum system being able to quickly create and measure entangled pairs is how the system was able to perform these operations so quickly.

In qc, superposition allows a qubit to exist in multiple states, giving it the ability to perform two calculations at the same time, and when qubits are entangled, the processing power is exponential. So, for example, 3 entangled qubits can perform 8 simultaneous calculations; 300 qubits can perform more calculations in an instant, than there are atoms in the known universe.[4] In a classical sense, we can think of superposition and entanglement as a form of parallel processing.

II. THE PHOTONIC PROCESSOR

In the past couple of years, photonic systems have made great advancements in qc due to the use of pre-existing, over the counter telecommunications components that have also been in in use by various industries for some decades now.[4] Media like fiber optic cables to communicate information over optic channels and components like micro-ring resonators to split photons into entangled pairs have allowed scientists to create a quantum microchip with all of the components to generate entangled qubits on-chip, that also operates at room temperature. Operationally, photonic processors are a more stable system than other quantum systems. And, since a photons mass is measured as its energy, in a waveform, scientist's have figured out a way to store quantum information in various the spectrum's of light, surpassing the processing and storage capabilities of qubits (D≥2). Photonic generated qubits can exists as a vector of higher dimensions[4], aptly named qudits, by occupying these different bands within the spectrum. "In principle, a quantum computer with two, 32-state qudits, for example, would be able to perform as many operations as 10 qubits while skipping the challenges inherent with working with 10 qubits together."[4]

So, while qubits can exists as 0, 1 or both simultaneously, qudits can exists as $0,1^2,2^2..10^2..N^2$. In their paper, scientists created 2 entangled qudits supporting 10 states each, for a total of 100 dimensions.

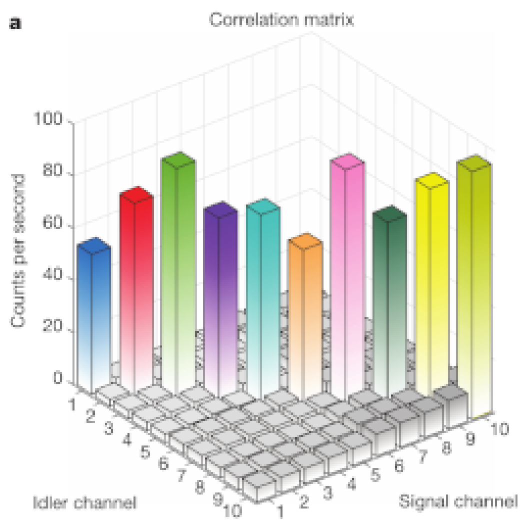
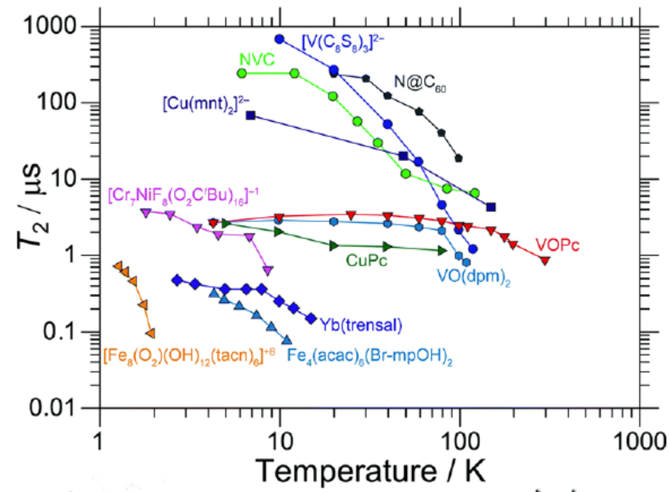


figure: 10 state qudit. The Idler and Signal channel each represent an entangled qudit.

This is more states than what 6 entangled qubits could generate, and the generation is all on-chip. "Many other quantum systems, cryogenic, magnetic, superconducting, etc. currently require more complex quantum circuitry to possibly achieve what a photonic system can using qudits."[4] and the authors believe larger dimension states can be achieved in the near future. This increased processing capacity can help solve what is arguably the most important limiting factor in realizing a quantum network: entanglement generation at scale, something I will discuss in section IV. Managing entangled states is difficult, and error-prone as entangled qubits can become unentangled for all sorts of reasons.

For instance, the on-chip photonic processor, measured decay rates at 0.6μs[4], versus quantum systems with mass particles, e.g. superconducting, and magnetic achieving better decay times (see graph below). It is important to also note that while photonic decay seems faster than mass particles, photons are not as sensitive to environmental changes like other quantum systems. This makes detecting errors "easier" since photon loss is the leading cause for loss in such a system at the moment.

Measuring photon loss is fast, and require less complex error correcting code than other quantum systems and does not require cryogenic temperatures to maintain entanglement.



Source: https://doi.org/10.1021/acsaelm.3c00472

So even with the quicker decay rates, the benefits of on-chip processing with over the counter components achieved successful Bell measurements with fidelity of 88.5%, exceeding Bell inequality of 71%[4].

While this seems too good to be true, the authors do acknowledge that the manipulation/processing section from their micro-chip graphic below, still occurs off-chip which incurs some photon loss. But they anticipate this to be on-chip in the future. This is important to note because if there is enough loss of fidelity, the qudits will fail Bell inequality measurements.[4]

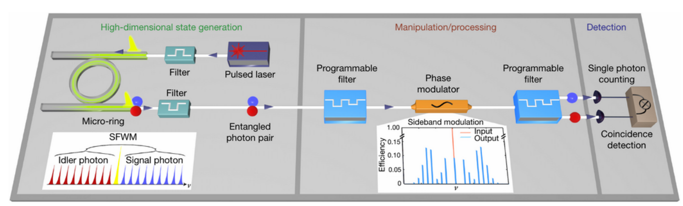


figure: photonic processor setup to to create, manipulate, and detect qudits

But, since its initial publication in 2017, programmable filters on-chip have been realized in the Borealis computing system mentioned earlier. What this means is that scientists are one step closer to having a complete quantum circuit that does not have to rely on the transfer and storage of quantum information as the gates can be updated programmatically, thus creating and manipulating more complex enanglements on-chip, as done with the Borealis system. This enables it to achieve a quantum advantage for its specific design[3] by reducing the need to physically expand the system with static gates when processing more complex problems: at scale where other quantum systems are not capable of achieving at the moment.

III. Quantum Network via Teleportation

In classical computing, bits can be copied, and repeated along a network channel, allowing for error correction, and information to travel longer distances. In phyics, superposition states that qubits can exist in multiple states at the same time, and its state is only know when read. And, because of this, the No-cloning thereom exists. The No-cloning thereom roughly states that a quantum state cannot be copied to create an identical version since reading the state will cause the entangled qubit pair to collapse: a process known as decoherance. However, while a quantum state can not be copied, it can be overwitten to a new state. This overwriting is what defines quantum teleportation: the transfer of information, not matter, between qubits.

In a very simplified example of quantum teleportation using the simulated protocol created, the below gates are used to create entangled qubits, q1 and q2, between two parties. Alice (q1) and Bob (q2), each receiving one of the entangled pairs. Alice wants to send some information to Bob via q0 some time later. To do this, Alice performs a Bell measurement on q0 and q1, which creates a new entangled pair but breaks the original entanglement between q1 and q2. According to Bell however, the newly entangled pair of q0 and q1 requires that q2 also have the same state as q0; thus overwriting, and completing the teleportation. *It is in repeating this teleportation process, that quantum repeaters can theoretically be built.*

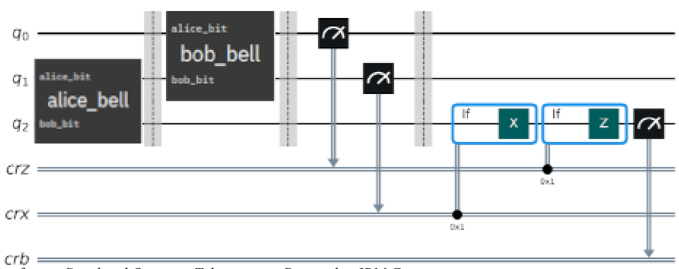


figure: Simulated Quantum Teleportation Protocol in IBM Composer

To summarize the protocol above via the code below, there are three (3) qubits, *q[3]* and two (2) classical bits, *crx*, and *crz,* with an additional register *crb,* that is used by Bob to compare the value of Alice' state after teleportation.

```
OPENQASM 2.0;
include "qelib1.inc";
// entangle Alice and Bob's information
// using Bell measurement.
gate alice_bell alice_bit, bob_bit {
h alice_bit;
cx alice_bit, bob_bit;
}
gate bob_bell alice_bit, bob_bit {
cx alice_bit, bob_bit;
h alice_bit;
}
// define the quantum and classical registers.
qreg q[3];
creg crz[1];
creg crx[1];
creg crb[1];

// Entangle q[1], q[2] – calls alice_bell()
// Alice gets q[1], Bob gets q[2]
h q[1];
cx q[1], q[2];

// Let's pretend that the two qubits are sent
// across a fiber optic channel (assume no errors)
barrier q[0], q[1], q[2];

// Alice now wants to send Bob a message.
// and puts the message in q[0]
// that breaks q[1] & q[2] entanglement.
// the classical bits are read by Bob
cx q[0], q[1];
h q[0];

barrier q[0], q[1], q[2];

measure q[0] -> crz[0];
measure q[1] -> crx[0];

// Bob has q[2], and after receiving the two
// classical bits, measures the bits to verify
// Alice' state.
barrier q;
// Bell's four states:
// 00 → Do nothing
// 01 → Apply the X gate
// 10 → Apply the Z gate
// 11 → Apply both XZ gates
if (crz == 1) z q[2];
if (crx == 1) x q[2];

//bob_bell() measures the qubits to verify the
//teleportation of Alice's qubits state.
measure q[2] -> crb[0];
// Bell probability results
// "000": 0.244140625,
// "001": 0.2568359375,
// "010": 0.2509765625,
// "011": 0.248046875
```

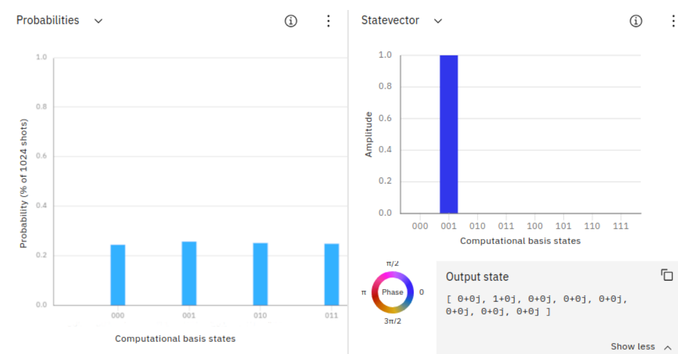


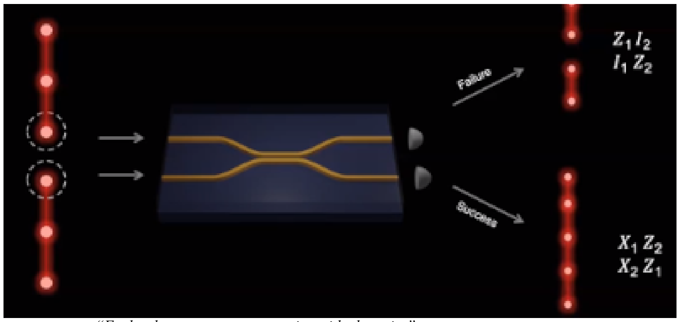
figure: Bell probability measurements and protocol output in IBM Composer

Note, this simulation is using classical correction, and classical communication to simulate the protocol in the quantum network. Actual implementation is significantly more complex, and the current state of the art is not yet reliable or error free. For example, this simulation does not account for error correction, checking along a fiber optical channel, and assumes a noise-free environment.

Forgiving the classical components, this code shows how an entangled qubit, *q[1]* and *q[2],* can be overwritten to a new entagled state, and using a Bell measurement, the new entangled state, *q[0]* and *q[1]*, by design, has to be in a state of the previous entangled pair.

IV. Quantum Error Correction (QEC)

Qubits are very sensitive to environmental changes, and such changes is what threatens a qubits state and encoded information. To smooth out the noise and errors, many physical qubits get encoded with the same information into what is known as a logical qubit. I will not discuss logical qubits in too much detail because there is no set definition since different quantum systems require a different number of physical qubits to make a logical qubit resilient enough to perform some meaningful calculations. Due to the nature of photonic systems, scientists think that photonic's may soon excel over other quantum systems in the generation of logical qubits. This is because errors in photonic's are commonly measured whether or not a photon is present (1) or not (0). So error correcting code is less encumbering, and entanglement is quick to measure success or failure. Designers of photonic systems hope this eventually leads to eliminate the dependency on classical computers to implement error correcting. [7]



source: "Fault-tolerant quantum computing with photonics"

In the pursuit of making more resilient qubits, one attempt to make error correction less dependent on classical hardware was to "entangle multiple photons, and encodes multiple physical qubits on individual photons, to produce error-protected qubits. We realize reconfigurable graph states to compare several schemes with and without error-correction encodings and implement a range of quantum information processing tasks. We observe a success rate increase from 62.5% to 95.8% when running a phase-estimation algorithm without and with error protection, respectively. Finally, we realize hypergraph states, which are a generalized class of resource states that offer protection against correlated errors."[8] It will still be some time before a standardized QEC scheme is accepted across different platforms. Once QEC is mastered, scientists can begin testing quantum networks.

V. Summary

Having a better understanding of advancements in photonic processing that allow scientists to solve difficult, specific problems; with the ability to create, process and measure entangled qudits on-chip, sets the stage for the next progression of quantum computing with networked systems. Due to the problem domains many scientists are trying to solve for, there may never be a "best of all" clear winner as different platforms are being built to solve problems for various fields, ie. photonic may excel in quantum networks, while ion traps may serve quantum chemistry better.

With proven entanglement over tens of kilometers using fiber optic cables, quantum systems can be designed like robots in automotive assembly lines with each system having the ability to perform a unit of work within its quantum circuit, then persisting results into a classical structure that is used as an input into another quantum system (a larger state machine).

Until practical quantum communication and a form of universal QEC can be achieved over microwave or other terrestrial signal, we will have to rely on classical computing to move data over any meaningful distance.

References

[1] Charles H. Henry and Rudolf F. Kazarinov. "Quantum noise in photonics". *Rev. Mod. Phys. Vol. 68, 1 July 1996*. pp. 801. https://doi.org/10.1103/RevModPhys.68.801

[2] K. Bartkiewicz, K. Lemr, and A. Miranowicz, "Direct method for measuring of purity, superfidelity, and subfidelity of photonic two-qubit mixed states," *American Physical Society, vol. 88 issue 5, Nobember 7, 2013*.

[3] Lars S. Madsen, Fabian Laudenbach, Mohsen Falamarzi. Askarani, Fabien Rortais, Trevor Vincent, Jacob F. F. Bulmer, Filippo M. Miatto, Leonhard Neuhaus, Lukas G. Helt, Matthew J. Collins, Adriana E. Lita, Thomas Gerrits, Sae Woo Nam, Varun D. Vaidya, Matteo Menotti, Ish Dhand, Zachary Vernon, Nicolás Quesada & Jonathan Lavoie. "Quantum computational advantage with a programmable photonic processor". *Nature 606 2022*, pp. 75−81. https://doi.org/10.1038/s41586-022-04725-x

[4] Michael Kues, Christian Reimer, Piotr Roztocki, Luis Romero Cortés, Stefania Sciara, Benjamin Wetzel1, Yanbing Zhang, Alfonso Cino, Sai T. Chu, Brent E. Little, David J. Moss, Lucia Caspani, José Azaña and Roberto Morandotti. "On-chip generation of high-dimensional entangle quantum states and their coherent control". *Nature Vol. 546, 2017*. https://doi.org/10.1038/nature22986

[5] A. Chiesa, F. Petiziol, M. Chizzini, P. Santini, and S. Carretta. "Theoretical Design of Optimal Molecular Qudits for Quantum Error Correction". *The Journal of Physical Chemistry Letters 2022 13* (28), 6468-6474. https://pubs.acs.org/doi/10.1021/acs.jpclett.2c01602

[6] Marcello Caleffi, "Optimal Routing for Quantum Networks". IEEE *October 16, 2017* https://doi.org/10.1109/ACCESS.2017.2763325

[7] Mercedes Gimeno-Segovia "Fault-tolerant quantum computing with photonics", *Proc. SPIE 11714, Quantum West, 1171407 March 9, 2021.* https://doi.org/10.1117/12.2593558

[8] Vigliar, C., Paesani, S., Ding, Y. et al. "Error-protected qubits in a silicon photonic chip." *Nat. Phys. 17, 1137–1143 (2021).* https://doi.org/10.1038/s41567-021-01333-w