Quantum Internet: Networking Challenges in Distributed Quantum Computing

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In recent years, quantum computing has become more and more of a reality. The newest problem that computer scientists are looking to solve is how to connect these quantum devices together. This concept – the Quantum Internet – as well as the problems with implementing it, is what is explored in this paper by Cacciapuoti, et al. In the past, quantum communications mechanics were only used to send classical information using bits, with quantum mechanics simply enhancing the exchange [1]. However, what the Quantum Internet hopes to achieve is to share information by sharing quantum states, using qubits. A qubit, or a quantum bit, is a two-level state, which can have two orthogonal basis states: the one, or the excited state, and the zero, or the ground state.

The Quantum Internet must use and work around quantum mechanics in order to function. One such factor of quantum mechanics that the Quantum Internet must deal with is the superposition principle [1]. Due to this, a qubit can be in a superposition of the two basis states. Therefore, while the classical bit can only encode one of n states, the qubit can encode all 2n states at one time. However, once the qubit is measured, the states collapse into only one bit, with whether it is a one or a zero depending on the previous superposition of the qubit. Finally, the biggest difference between the classical internet and the Quantum Internet is the concept of entanglement. When two qubits in a superposed state are entangled, once one of them is measured, both qubits instantly collapse into one state, no matter how far away they are. They will both yield the same measurement, either a one or a zero.

One major problem with the Quantum Internet, however, is that due to the no-cloning theorem of quantum mechanics, qubits cannot be copied, nor can they be measured without collapsing the qubits to one bit [1]. Because of this, if a photon carrying this qubit were to get lost are damaged, there would be no way to recover the qubit. The ability to resend data if it is lost is essential in classical networking; therefore, a workaround for this had to be developed.

The Quantum Internet employs quantum teleportation to transmit qubits [1]. This strategy employs Bell-State Measurement (BSM) and an entangled pair of particles that are shared between the source and the destination to send an unknown qubit. First, the entangled pair is created and sent to both the source and the destination. One qubit is then measured, destroying both members of the entanglement. The result of the measurement (2 classical bits) is then sent to the destination using a classical channel, and the original qubit is remade.

Several physical entities are vital for the operation of the Quantum Internet [1]. There are the quantum nodes – the quantum devices that being connected to each other – and the classical and quantum links connecting them. The Entanglement Generator is what created the two entangled particles, which are then distributed to the quantum nodes using quantum links. Lastly, there are the quantum memory and measurement devices, which are used to store the quantum states that need to be sent and to measure the quantum pair during the BSM process, respectively.

There are several challenges to be overcome when designing the Quantum Internet [1]. The first one is with the functionalities of the network. For instance, as stated before, due to the no-cloning theorem, a copy of a qubit cannot be made. Because of this, classical error-correction cannot be done, as it usually assumes a copy of the information is available, and new error-correcting strategies must be devised. The no-cloning theorem has a corollary, called the no-broadcasting theorem, stating that quantum information cannot be sent to multiple places at once. This means that the Quantum Internet cannot use classical network protocols such as medium access control and route discovery which take advantage of broadcasting. Classical routing algorithms also cannot be used due to how complicated the physical structures of the Quantum Internet are.

Another big problem is decoherence, where the qubit gradually loses information the longer it interacts with its environment [1]. A perfectly isolated qubit remains unchanged; this is, of course, not feasible in the Quantum Internet, as the qubit must be interacted with in some way for the communications to take place. Errors in the information being transmitted can also occur due to random fluctuations and imperfections when an operation is performed on the qubit. Quantum technologies must be able to handle not only bit-flip errors, but also phase-flip errors and simultaneous bit-flip and phase-flip errors. This further complicates the design of quantum error correcting protocols.

Long distance distribution of entangled pairs is another key issue since the entanglement distribution rate decays the more the particles are away from each other [1]. A possible solution to this is the use of Quantum Repeaters. They use a concept known as entanglement swapping, where 2 pairs of entangled particles are created. The source and the destination receive one particle of each pair, and the other two particles are sent to an intermediate node. When a BSM is performed on the particles at the node, the entanglements swap, and the particles at the source and destination become entangled with each other.

Entanglement distribution affects how several of the layers of the network stack are implemented [1]. In the physical layer, the entanglement gradually decays due to decoherence. The techniques used to distribute entangled pairs must have vigorous error correction, which is a problem that has not yet been solved. Multiplexing must be implemented in the link layer so that more than one quantum device can be connected on one quantum channel. For the network layer, new routing methods must be designed for optimal path selection. The teleportation process destroys the entanglement; thus, a new entangled pair must be created for every qubit that needs to be sent. This is something else that must be accounted for in the design of the network layer of the Quantum Internet.

An interface between the matter qubit – the qubit used for computing and storing information in quantum devices – and the flying qubit – the qubit used to actually transmit information – must be created [1]. A transducer is used for converting matter qubits into flying qubits. There are several ways of creating a matter qubit; therefore, multiple types of transducers must be designed.

Finally, there is the issue of deploying the Quantum Internet [1]. These include the current technological limit on quantum technology and quantum communications, the need of using both expensive cryo-cables and fiber optic cables or free space photonic links, and the fragility of qubits making quantum networks must create new networking protocols and quantum and classical algorithms. There will also be challenges involving the integration of classical and quantum communication technologies.

In conclusion, this article shows that there is an exciting future for the world of networking. The Quantum Internet will likely have far-reaching influences all throughout the computing world, taking computer communications to the next level. However, as illustrated throughout this paper, the computing community will have to come together to overcome the various challenges in the implementation of the Quantum Internet before it can actually be put to use.

[1] Cacciapuoti, Angela Sara, et al. 2020. “Quantum Internet: Networking Challenges in Distributed Quantum Computing”. IEEE Network. vol. 34, no. 1, pp. 137-143, January/February 2020, DOI: 10.1109/MNET.001.1900092.