A switching approach for perfect state transfer over a scalable network architecture with superconducting qubits[1]

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Abstract. We develop a network architecture for Perfect State transfer (PST). It is known that PST is possible for antipodal vertices of a hypercube. We extend this result for any pair of nodes for memory enhanced hypercube, by switching-off-edges. This is accomplished by determining a sub-hypercube with a desired pair of end-point vertices. This is further extended to any number of nodes in where PST is possible for any pair of nodes of the network where PST is at most a two-step process. Finally, we establish that the procedure of switching-off-edges can be realized using superconducting transmon qubits with tunable couplings.

Keywords: perfect state transfer, architecture, hypercube, edge switching

In quantum computation, it is often required to transfer an arbitrary quantum state from one site to another. Quantum state transfer with 100% fidelity is known as perfect state transfer (PST) [2]. A quantum architecture can be designed purely in graph-theoretic fashion (determining the qubits' mutual connectivity) and can be realized by physical systems. PST in graphs is a rare phenomenon. The task is to find graph structures which support PST for as many pair of vertices as possible and possibly grow under some operation (scalability of networks).

PST scheme established in [3] and [4] allows PST over arbitrarily long distances with the use of the manifold Cartesian product of one-edge and two-edge path graphs which support PST under the XY as well as Heisenberg interaction of spins. This enables PST between antipodal vertices of hypercubes on $n = 2^k$ nodes at the same time $t = t_0$ as for the 'seed' graphs. The first shortcoming in this model is that of the impossibility of routing [5]. This would involve constructing a very large network just to enable PST between a pair of antipodal qubits. Second, is that this architecture scales the number of qubits with the factor of 2 or 3 which will be a very large jump for the larger dimensional hypercubes as the network scales up. This motivates for finding a quantum computing architecture that would allow us routing to any given vertex of the graph as well as enables an arbitrary number of vertices n while still preserving perfect fidelity and routing to any vertex starting from any other given vertex. Therefore, we propose a network architecture on $n = 2^k$, and $2^k < n \leq 2^{k+1}$, for some positive integer k.

First, we prove that it is possible to find a sub-hypercube of a lower dimension ($d \leq k$) i.e. on 2^d nodes such that a pair of desired vertices of the original hypercube are antipodal vertices of this sub-hypercube. Thus, a PST is possible. This is accomplished by switching-off all other edges in the network that are not part of the sub-hypercube. Note that the vertices of a hypercube on 2^k vertices are nothing but strings of 0, 1 of length k. Hence a corresponding canonical k -qubit state can be stored in a quantum memory register attached to each vertex.

The second case $2^k < n \leq 2^{k+1}$ is dealt with by partitioning the vertices as $n = 2^k + m$, where additional nodes need to be connected to an existing hypercube. If we follow the binary labelling in sequence for all vertices (with the length $k + 1$), then an interesting property arises. If the desired vertices belong to this complete hypercube of 2^k vertices, then by previous proof, a PST is possible. However, if one vertex belongs to the complete hypercube and other in the additional nodes, the PST can be performed by a 2-step PST process in time $2t_0$. And the same argument follows for all partitions within this set of m qubits. Therefore, a PST is possible between any qubits for any arbitrary number of qubits in a maximum time of $2t_0$. And hence, the scalability of this protocol. Our results hold both for XY-coupling as well as the Heisenberg interaction Hamiltonian.

We also put forward a possible physical system for the realization of our PST protocol system that can allow the graph edge switching using superconducting transmon qubits with tunable couplings [6] with XY type coupling. Qubits $|i\rangle, |j\rangle$ are coupled with an effective coupling $\tilde{g}_{ij}$ which is a contribution of direct qubit-qubit couplings and an indirect interaction via ancilla couplers associated with each edge. $\tilde{g}_{ij}$ can be tuned as a continuous real number to a range of values, always featuring a bias point $\tilde{g}_{ij} = 0$, by the detuning of ancilla couplers. In this way, edges can be switched-off/on when desired, for a task of PST between any pair of qubits.

We also propose the idea of PST assisted quantum computation where PST can be used in contrast to a large number of swap gates between any two physically distant qubits when the quantum circuit depth is very high, thereby reducing the complexity of a large quantum circuit. This involves PST over the computational qubits of a quantum processor.

References

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