Quantum Networks for High Energy Physics

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Quantum networks of quantum computers and quantum sensors promise to yield new capabilities to simulate and test fundamental theories of nature, in addition to unprecedented network security, connectivity and modality. In particular, nontrivial demonstrator experiments to explore new physics are within reach during the next decade. In the near-term, we advocate for further theoretical development and testbeds to evaluate the feasibility and impact of potential experiments and discuss some key considerations.

Today's global distributed High Energy Physics Community depends on communications networks to share ideas, data and experimental facilities. Metcalfe's law attempts to quantify the value of such classical networks in stating that their value scales as the square of the number of connected nodes. Given the possibility of multi-node entanglement, it seems likely that the value of *quantum* networks will scale more favorably than classical networks, potentially yielding up to an exponential advantage and unprecedented connection modalities such as quantum sensor-computer links. If so, quantum networks of devices could dramatically increase their value compared to classical networked quantum devices, even for relatively modest quantum networks. Some application examples which have been suggested include the networking of telescopes [1, 2], and clocks [3, 4].

A major scientific challenge is to realize quantum networks of quantum devices to test scientific theories that are intractable with current techniques, and integrate them into existing extensive network infrastructures, for example, using integrative testbeds [5–7]. These networked quantum devices could perform computing, sensing, or a combination of computing and sensing (for example, distributed decision making to threshold interesting events). As quantum computing is considered elsewhere, for example, in [8], here we will consider quantum networks for science [9] in support of quantum sensing for high energy physics [10].

The physical size of potential quantum networks span many orders of magnitude, from chip-scale devices designed to test for micro-scale effects, to geosynchronous satellite networks. Depending on scale, these networks may be connected through combinations of on-chip wave guides, fiber optical, and free-space optical channels. Regardless of scale, subdivision of quantum sensor networks into smaller sub networks may give one the capability of determining interaction lengths and/or energy scaling of observed effects and how they propagate through the larger sensor network.

Due to an effect's propagation time, the physical size of the quantum network can be important for tests of new physics, for example, in gravitational wave detection. While the distance is an important consideration, the overall experimental transmission loss must also be considered as the quantum communications capacity is limited by the loss, forming fundamental quantum communications bounds [11]. This trade off was first discovered for quantum key distribution [12] and later generalized [11]. It may be important to consider this bound when considering the required network's size and the minimum resolvable signal relative to background noise.

To exceed the bounds developed in [11, 12], one needs quantum repeater technologies to enable "high-performance" quantum networks. One goal of the most advanced quantum repeater concepts is the fault-tolerant transmission of quantum information, where one can theoretically correct for both loss and imperfect quantum operations [13]. The development of a quantum repeater technology that enables continental-scale quantum network connectivity is an unsolved challenge which may not be ready for deployment in the next decade. As a result, initial demonstrator experiments to test new high energy physics should focus on repeater-less networks but, should be conceived in such a way that they can be scaled when quantum repeaters become available.

In addition to physical size and loss, another consideration is the energy scale to be sensed relative to quantum resources needed for networking. Free space and fiber optical carriers typically range from 3 eV to $\sim$0.75 eV of energy. In the case of a mismatch between a sensor's native energy scale and an optical carrier, it may be necessary to carry out an additional step of quantum transduction or quantum frequency conversion, which may need to be developed.

With these considerations in mind, collaboration between theorists and experimentalists who are subject matter experts in high energy physics, quantum sensors and quantum networks is critical to developing previously inaccessible tests of fundamental physics. Further concepts need to be developed showing that a quantum network enabled advantage is possible for quantum technology in the next decade, not only for relevant energy scales but also for relevant distance scales. This should be done with the goal of testing parameter regimes which are not tractable via conventional techniques.

We now describe some specifics related to quantum sensor networks. Holtfrerich *et al.* [14] is unique in that it transmits quantum correlations through distant plasmons on independent substrates, an example of a small quantum network.

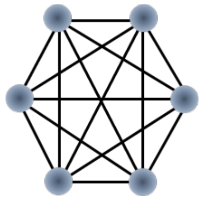

FIG. 1. A six node fully interconnected Hamiltonian graph representing a GHZ state. The nodes are optical modes while the edges represent the entangling interaction.

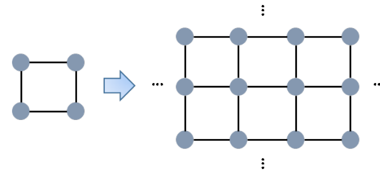

FIG. 2. Square cluster state graphs. The single tile (left) can be repeated to achieve long range order (right).

Quantum optical networks are collections of physically separated optical modes related by a generalization of two-mode squeezing. In particular, quantum networks take advantage of the entanglement that two-mode squeezed states naturally exhibit. For globally distributed signals which affect multiple nodes that are entangled, networked quantum sensors present an advantage over averaging independent sensors [15]. For this reason, networks of quantum sensors have been proposed as a natural way to obtain the Heisenberg limit in sensing, where noise scales inversely with the number of nodes on the network. Several types of quantum networks are possible, depending on the nature of the entanglement. Here, we describe two general networks. The first network type is called a Hamiltonian graph [16]. The simplest implementation consists of a two-mode squeezed state with maximum squeezing. This configuration, also known as an Einstein-Podolsky-Rosen (EPR) state [17], is a maximally entangled state. Hamiltonian graphs that are fully interconnected with equal weights describe Greenberger-Horne-Zeilinger (GHZ) states. In this case, the interaction between two fields, forming the edge of the graph, is given by $e^{-i\hbar\chi_{ij}(a_i^\dagger a_j^\dagger - a_i a_j)}$.

The equations of motion for the network in the Heisenberg picture can be written in matrix form:

$$\dot{\mathbf{A}} = \boldsymbol{\kappa}\cdot\mathbf{A}^\dagger, \tag{1}$$

where $\boldsymbol{\kappa} = \kappa\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}$ for example, for two modes. Here $\boldsymbol{\kappa}$ is an adjacency matrix. This network can easily be generalized to more than two modes by considering concurrent interactions between n modes in the network:

$$H = i\hbar\sum_{i=1}^{n}\sum_{j\neq i}^{n}\kappa_{ij}\left(a_i{}^\dagger a_j{}^\dagger - a_i a_j\right). \tag{2}$$

The above Hamiltonian implies that all optical fields interact with specific strengths with all other fields in the network. For instance, six fields have a graph as shown in Fig. 1. Any connectivity can be represented by tuning the adjacency matrix, which amounts to specifying a new Hamiltonian.

Another useful network type is called a cluster graph. In this network, the edges represent different interactions, known as quantum nondemolition operators [18, 19]. The edges in a cluster graph are defined by $e^{i\hbar(\chi_{ij}X_iX_j)}$, where X and P are the amplitude and phase quadratures of each node on the graph.

The nodes in the cluster graph represent each field after a degenerate nonlinear interaction, which reduces the phase. That is, $P_i \to 0$. However, it is possible to represent the nodes on a cluster graph as equivalent to those in the Hamiltonian graph with a redefinition of the phase of a single field. An example with long-range order is shown in Fig. 2.

For cluster states, a node's phase depends on its neighbors' amplitudes, while neighboring amplitudes are independent. The equations of motion yield solutions $X_i(t) - P_j(t) = e^{-\kappa t}P_j(0)$ and $P_i(t) - X_j(t) = e^{-\kappa t}P_i(0)$. Applying a Fourier transform to one node of a cluster graph transforms it to a Hamiltonian graph. Under $X \to P$ and $P \to -X$ we have

$$X_1(t) + X_2(t) = e^{-\kappa t}P_2(0), \tag{3}$$

$$P_1(t) - P_2(t) = e^{-\kappa t}P_1(0). \tag{4}$$

As $t \to \infty$, Eqs. (3)-(4) are equivalent to EPR operators up to an arbitrary, semantic, and local definition of quadrature which has no effect on graph topology. This property is important because it allows one to generate the more tractable network, and then adjust the measurements to produce either a GHZ state or a cluster state, depending on the application.

Multimode squeezing can be used to produce a network as shown in Fig. 2. Extending squeezing measurements to more than two modes is straightforward. For example, the GHZ state, which is a maximally entangled state, shows quantum noise reduction for specific quantum operators found by diagonalizing the adjacency matrix $\boldsymbol{\kappa}$. For a k-mode GHZ state, the squeezed operators are

$$(k-1)X_1 - \sum_{i=2}^{k}X_i, \tag{5}$$

$$\sum_{i=1}^{k}P_i. \tag{6}$$

Thus, a signal to noise advantage for a distributed phase signal could be obtained by joint phase sum measurements.

In the case of multimode squeezed spin networks, this measurement scheme is optimal [20]. In the same way that two mode squeezed states use a reference which shares correlations with the signal beam, quantum networks can maintain large portions of the network as references (half of the nodes, for example, while half or more transduce a global signal). With these ideas in mind, we see that quantum networked sensing is a straight forward extension of sensing with two mode squeezed states, and indeed the latter is a simple form of a quantum network. This realization provides a plausible path forward to the next generation of quantum sensing: multimode quantum noise reduction distributed across a network topology.

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