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Realization of quantum information processing in quantum star network constituted by superconducting hybrid systems

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HIGHLIGHTS

- We extend traditional one-dimensional quantum network to star structure, mainstream QIP schemes can be carried out in parallel in this network.
- We realize controllable effective coupling between arbitrary superconducting qubit and bus by only tuning their detuning.
- Effective quality factor can be greatly improved although only the bus has a high quality factor.

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ABSTRACT

In the framework of superconducting hybrid systems, we construct a star quantum network in which a superconducting transmission line resonator as a quantum bus and multiple units constituted by transmission line resonator and superconducting qubits as the carriers of quantum information. We further propose and analyze a theoretical scheme to realize quantum information processing in the quantum network. The coupling between the bus and any two superconducting qubits can be selectively implemented based on the dark state resonances of the highly dissipative transmission line resonators, and it can be found that quantum information processing between any two units can be completed in one step. As examples, the transmission of unknown quantum states and the preparation of quantum entanglement in this quantum network are investigated. At last, we exhibit our simulation results and complete the relevant discussions in order to show the advantages of this kind of quantum network.

1. Introduction

Networked information processing is an ultimate requirement in quantum information processing (QIP) [1]. Especially in recent years, the developing researches about complex quantum algorithm and quantum communication are increasingly dependent on distributed quantum many-body systems with controlled information exchange [2,3]. A lot of schemes about multiphoton quantum communication [4,5], quantum network coding [6], quantum network teleportation [7,8] and quantum walks [9–11] have been proposed continuously in last decade. Besides, some investigation issues in classical networks, such as synchronization [12–14] and parameter identification [15], are also extended into quantum regime. Meanwhile, thanks to the advances of quantum mechanics and related theories, the quantum network schemes have been discussed in various quantum systems. The most representative works are optical quantum network [5,16–18] and hybrid solid quantum network in the framework of superconducting systems [19–21]. For now, experimental advances have

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successfully achieved the collective coupled cavity (or cavity optomechanical) array [17] and two-dimensional Josephson junction networks [19], which provide a promising platform for mature quantum network technology.

Compared to the classical network, the quantum network is considered to be efficient owing to the existence of quantum acceleration. However, some unique properties or requirements in quantum mechanics also bring difficulties for achieving the quantum network. Firstly, interaction between device and nodes is restricted to some fixed forms (e.g. beam splitter or X–X interaction), and the Hermitian Hamiltonian excludes all forms of unidirectional coupling in quantum regime. Basically, this property causes that most commonly used coupling graphs, for example dissipative condition in classical small-world and scale-free networks [22–26], could not be found a reasonable correspondence in quantum network. Moreover, analyses of many-body quantum interaction and quantum correlation are still open issues in quantum information science. For these restrictions, most of the existing quantum networks only have a one-dimensional network structure and the QIP in such kinds of networks can only be completed between adjacent nodes [12,19,21,27–29]. Besides the obstacle of quantum interaction, quantum network is more susceptible to environment and thermal noise than classical network since QIP requires long coherence time, which means that all nodes should be placed in a low temperature quantum environment or non-Markovian environment [30,31].

The aim of this work is to address the above problems. In particular, we consider a quantum star network in the framework of superconducting hybrid systems. The network is composed of a superconducting transmission line resonator (TLR) as a quantum bus and multiple units constituted by TLRs and superconducting qubits (SQs) as the carriers of quantum information. We find that star structure is quite suitable for quantum network. On the condition of large detuning, the Hamiltonian of the whole network can be simplified as two selected SQs coupling with the quantum bus. Therefore, a node or a unit can establish QIP with any other nodes under the help of quantum bus, however, the rest nodes will not disturb this QIP. Though designing effective interaction strength and dissipation rate, we find that only the bus requires a high quality factor and low temperature environment, which greatly reduces the requirement for removing thermal noise. Therefore, we believe that this quantum network is both parallel and practical.

We organize this paper as follows: in Section 2, we introduce the network model adopted in this work and give an effective Hamiltonian to describe the interaction between quantum bus and the selected SQs. In Section 3, we discuss the QIP scheme in this network. As examples, we respectively analyze how to transfer unknown quantum states and how to prepare maximally entangled states between arbitrary SQs. In Section 4, we give the feasibility analysis to estimate whether the used parameters are experimentally achievable. At last, a brief summary of our conclusions is completed in this section.

2. Network model and effective Hamiltonian

The schematic diagram of the quantum network topology is sketched as Fig. 1. Each TLR with coupling multi-superconducting qubits (SQs) is considered as an information processing unit, and the interaction potential between TLR and SQs is standard Jaynes–Cummings interaction with coupling intensity g [32,33]. The excitation space of SQ is restricted to 2×2 and the corresponding self-energy can be tuned locally. As a carrier of quantum information, the quantum state of a SQ corresponds to a result of quantum computation or a quantum information to be transferred. After the second quantization, the kth information processing unit can be described by following Hamiltonian:

$$H_k = \omega_k a_k^\dagger a_k + \sum_{m=1}^{N} \frac{\omega_m}{2} \sigma_{z,m} + g\left(a_k^\dagger \sigma_m^- + a_k \sigma_m^+\right), \tag{1}$$

where a_k ($a_k^\dagger$) is the annihilation (creation) operator of the TLR in unit k. For the mth SQ, $\sigma_{z,m}$ and $\sigma^- = (\sigma^+)^\dagger = |g\rangle\langle e|$ respectively denote the Pauli spin operator and the lowering operator. ω_k is the frequency of the fundamental TLR mode and ω_m is the frequency difference of the two lowest energy levels of a SQ. A special TLR with the highest possible quality factor (Q-factor) is selected as a quantum bus and correspondingly, the TLRs in different units connect the bus by collectively coupling a current-biased Josephson junction (CBJJ). Here the bus Hamiltonian $H_{bus} = \omega_b a_b^\dagger a_b$ is the standard free Hamiltonian of a TLR and the node–bus interaction can be simplified as beam splitter Hamiltonian $H_{coupling} = \sum \lambda_k (a_b^\dagger a_k + H.c.)$ after adiabatically eliminating the CBJJs. The total Hamiltonian of whole network can be written as a sum of Hamiltonians respectively belonging to the bus, each node and interaction between bus and node, i.e., $H_{total} = H_{node} + H_{bus} + H_{coupling}$. We emphasize here that, except for the bus, the rest TLRs do not require a higher Q-factor in this network. Moreover, such a system can also be considered as a cavity quantum electrodynamics system consisting of optical cavities and atomic ensemble system.

We find that some common point to point QIP schemes can be implemented in our network. In order to construct a QIP between two SQs in different units, it is necessary to couple two target SQs selectively. Compared to the previous work in which the local external flux thread of each SQ is needed to adjust, such a directional coupling can be realized by a quite simple operation in this network. The strategy is the following: all SQs are initially set in the same frequency $\omega_m = \omega_k$, i.e., a perfect match with the TLR; the site energies of the two target SQs are tuned to ω', which corresponds to a large detuning with TLR ($|\omega' - \omega_k| \gg g$). Under the large detuning condition, the interaction between the corresponding TLR and target SQs is a virtual process. Therefore, target SQs will not be disturbed by other SQs and TLRs. After an adiabatic elimination, one can find that only the target SQs have effective interaction with the quantum bus. Compared to the previous works, this kind of adjustment is simple.