Distributed quantum information processing with mobile electrons

Yuichiro Matsuzaki\(^1\) and John H. Jefferson\(^2\)

\(^1\)Department of Materials, University of Oxford, OX1 3PH, U. K.
\(^2\)Department of Physics, Lancaster University, Lancaster LA1 4YB, UK

In distributed quantum information processing, small devices composed of a single or a few qubits are networked together through shared entanglement to achieve a scalable machine. Typically, photons are utilized to generate remote entanglement between optically active matter qubits. In this paper, we consider another possibility for achieving entanglement between nodes: using mobile electron spins as mediators of the interaction between static qubits at each node. A strong interaction between electrons makes it feasible to couple the flying electron with the static electron. However, since the electrons easily interact with the environment, error accumulation during the entanglement operation could be more severe than with the other strategy using photons as flying qubits. We introduce a new scheme especially designed to minimize such error accumulation by using several distillation protocols. The conclusion is that a high fidelity entanglement operation can be constructed even under the effect of typical imperfections, and this suggestion therefore offers a feasible route for the realization of distributed quantum information processing in solid state systems.

The problem of scalability is a key challenge for practical quantum information. Recently, to overcome this problem, a new approach called “distributed quantum information processing” was suggested \([1–6]\). In this scheme, spatially separated qubits are entangled to make a network between small devices composed of a single or a few qubits. The distance between qubits in this scheme makes it easy to address the individual qubits and suppress decoherence caused by unknown interaction between them. So this scheme is considered to scale well for a large number of the qubits. To construct a high-fidelity entanglement operation (EO), many proposals using a photon to mediate interactions between the matter qubits have been suggested \([1–4, 7]\), because a photon is almost decoherence free due to the weak interaction with the environment and therefore is considered as an ideal flying qubit.

On the other hand, there is another possibility for a flying qubit: a mobile electron spin in solid state systems. The ability to coherently control an electron is at the heart of recent developments. A strong interaction between electrons makes it feasible to interact flying electron spins with static electron spins, so that distant static electron spins can exchange information with the help of the flying electron spins. So the investigation of flying electron qubits is an area of active study. A typical experimental setup is that a flying qubit injected in a one dimensional system passes between two distant matter qubits in order to mediate entanglement between them, and EO protocols in this setup have been investigated by many authors \([8–13]\). However, in such solid-state systems, the effect of error accumulation during the EO becomes more relevant than in the case of an optical flying qubit. If one uses an electron as a flying qubit, decoherence from the environment is inevitable, which results in the degradation of the entanglement. In addition, controlling interaction between the flying qubit and static qubit is still challenging with current technology, and imperfection of the control will be another source of errors. Although certain levels of error can be subsequently dealt with through techniques such as quantum error corrections \([14]\), keeping the errors as low as possible is still essential in order to make such techniques feasible.

In this paper, we suggest a new form of EO between matter qubits through a flying electron qubit. This scheme is especially designed to minimize the error accumulation through the method called distillation. By using imperfect entangled states as resources, one can generate a high fidelity entanglement through distillation protocols. In the (unrealistic) assumption of no decoherence and fine tuned parameters, our protocol provides a way to make a perfect Bell pair between static qubits with unit probability without measuring the flying qubit, while most of the previous schemes are probabilistic or require projective measurements to the flying qubit \([8–13]\). Since such measurements on the flying qubit are difficult to realize, our scheme may prove more feasible than the previous ones. Also, we estimate the error accumulation during the EO due to decoherence from the environment and typical experimental imperfections, and we show how to recover the fidelity by using distillation protocols. Since distillation protocols require more than two qubits per node, we assume that a few ancillary qubits are located near the static qubit. We show that even adding only one ancillary qubit at each node makes the EO robust against typical experimental imperfections.

We consider a two-electron scattering model in a one dimensional system where one electron propagates and the other electron is in the ground state of a confining potential, introduced in \([15]\). For example, an electron injected into the conduction band of a carbon nanotube and an electron bounded by a potential well in the same band can be used as the flying and the static qubits \([16]\) respectively. One can construct a quantum well between electrodes in the nanotube, and the energy levels of the well are discrete due to the high degree of confinement in all three dimensions, which forms a quantum dot to accommodate the static qubit. Note that the relevant interaction between the electrons arises from Coulomb repulsion which has no dependency on the spins of the electrons and may be described by the effective Hamiltonian \([15]\):

\[
H = \frac{1}{2m} \hat{p}_a^2 + \frac{1}{2m} \hat{p}_b^2 + \hat{v}(x_a) + \hat{v}(x_b) + \hat{V}(x_a - x_b),
\]

where \(\hat{v}(x)\) is an effective one electron potential, \(\hat{V}(x_a - x_b)\)
is an effective two electron potential, and \( m \) denotes the effective mass of the electron. Since the total wave function of fermions should be anti-symmetric, the spin state becomes symmetric for an anti-symmetric spatial wave function while the spin state becomes anti-symmetric for a symmetric spatial wave function. So, even for the spin-independent Hamiltonian, the scattering process depends on the spin states of the two-body quantum systems. For the spin states of two electrons, there are three symmetric states (triplet) and one anti-symmetric state (singlet). The singlet is represented as \(|S\rangle = \frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle - \frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle\) and the triplets are represented as \(|T_1\rangle = |\uparrow\uparrow\rangle, |T_0\rangle = \frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\uparrow\rangle\), and \(|T_{-1}\rangle = |\downarrow\downarrow\rangle\). If the kinetic energy of the initial flying qubit is smaller than the energy difference between the ground state and the first excited state of the static qubit, the quantum state of the flying qubit after the scattering has the same magnitude of the momentum as the initial state, while the static qubit remains in the ground state. The state of the flying qubit after the scattering becomes a superposition of a reflected state and a transmitted state and, due to the Pauli exclusion principle, the amplitudes of reflection and transmission depend on the spin states. Furthermore, in this model and its extension to multiple static and propagating electrons, the total number of up spins and down spins are conserved throughout the interaction, reflecting conservation of total magnetization imposed by the Hamiltonian \((\mathcal{H})\). Therefore, for the initial state \(|\uparrow\downarrow\rangle_i\), we obtain \(|\uparrow\downarrow\rangle_i = \frac{1}{\sqrt{2}}(T_0|\uparrow\downarrow\rangle_i + r_s S|S\rangle_i)\) where \(U\) denotes a unitary operation by the Hamiltonian, \(|r\rangle_i, |t\rangle_i\) denotes the state of the reflected (transmitted) flying qubit, and \(|i\rangle_i\) denotes the initial state before the scattering. Also, \(r_s, t_s, r_T, t_T\) are complex numbers to denote the amplitudes of the reflection and transmission when the initial state is a singlet (triplet). These amplitudes can be determined by solving the spin-independent scattering problem where the orbital wave functions must be either symmetric or asymmetric. This two-electron system may be constructed such that a singlet is on resonance (with \(|t_s| = 1\)) while the triplet is off resonance (with \(|t_T| \simeq 0\)). This may be achieved by choosing the shape of the potential to give a large separation between singlet and triplet resonances and adjusting biases to bring the singlet on resonance \([15][16]\). In this case, if one were to projectively measure whether the flying qubit had been transmitted or not via charge detection, then the spin state between the transmitted flying qubit and the static qubit would be a near perfect Bell pair. The success probability to observe such transmission is 50% because the reflection probability becomes precisely equal to the transmission probability at this resonance in the limit of perfect triplet blocking, \(r_T = 0\). Also, we study a case of forward scattering where \(r_s, r_T \simeq 0\). We have \(U|S\rangle_i \simeq t_s S|S\rangle_i = e^{i\theta_s}|S\rangle_i\) and \(U|T\rangle_i \simeq t_T T|T\rangle_i = e^{i\theta_T}|T\rangle_i\). So we obtain \(U|\uparrow\downarrow\rangle_i \simeq e^{i\theta}(\cos \theta|\uparrow\downarrow\rangle_i + i \sin \theta |\downarrow\uparrow\rangle_i)\) where \(\theta' = \frac{\theta_1 + \theta_2}{2}\) and \(\theta = \frac{\theta_1 - \theta_2}{2}\). Similarly, we have \(U|\downarrow\uparrow\rangle_i \simeq e^{i\theta}(i \sin \theta|\uparrow\downarrow\rangle_i + \cos \theta |\downarrow\uparrow\rangle_i)\) and so, when the spins are anti-parallel, the quantum state after the interaction becomes a superposition of the non-spin flip state and spin-flip state. Furthermore, we have \(U|\uparrow\uparrow\rangle_i \simeq e^{i(\theta_1 + \theta_2)}|\uparrow\uparrow\rangle_i\) and \(U|\downarrow\downarrow\rangle_i \simeq e^{i(\theta_1 + \theta_2)}|\downarrow\downarrow\rangle_i\) and so spin flip processes do not occur when the initial spins are parallel. We now show how two static qubits are entangled through an interaction mediated by a flying qubit. We begin by describing a simplified case with fine tuned parameters and no decoherence and consider realistic imperfections later. Suppose that two static qubits (bound electrons) \(s1\) and \(s2\) are located in a one dimensional system. We assume that, due to the distance between them, the interaction between the static qubits is negligible. We prepare an initial state \(|\uparrow\downarrow\rangle_{f,s1,s2}\) and we will send a flying qubit as a mediator between the static qubits. For the forward scattering, we obtain

\[
U_2 U_1 |\uparrow\downarrow\rangle_{f,s1,s2} = e^{i(\theta_1' + \theta_2')} (\cos \theta_1 \cos \theta_2 |\uparrow\downarrow\rangle_{f,s1,s2} + i \cos \theta_1 \sin \theta_2 |\downarrow\uparrow\rangle_{f,s1,s2} + i e^{i\theta_2} \sin \theta_1 |\downarrow\downarrow\rangle_{f,s1,s2})
\]

(2)

where \(U_j (j=1,2)\) denotes a unitary operation for the interaction between the \(j\)th static qubit and the flying qubit. Note that, even when there is a finite reflection probability during the interaction between the flying and the first static qubit, one can get the same form via a postselection of transmission by using a charge detection. Since we are only interested in the quantum states of the static qubits, we trace out the flying qubit and obtain

\[
\rho_{s1,s2} = \left(1 - \frac{P_1 + P_2}{2}\right) |\downarrow\downarrow\rangle_{s1,s2} \langle \downarrow\downarrow| + \frac{P_1 + P_2}{2} |\chi\rangle \langle \chi|
\]

(3)

where \(|\chi\rangle = \sqrt{\frac{P_1}{P_1 + P_2}} |\uparrow\rangle_{s1,s2} + \sqrt{\frac{P_2}{P_1 + P_2}} i e^{i\theta_2} |\downarrow\rangle_{s1,s2}\), \(P_1 = 2 \cos^2 \theta_1 \sin^2 \theta_2\), and \(P_2 = 2 \sin^2 \theta_1\). We can calculate the the concurrence of this state as \(C = \sqrt{P_1 P_2}\). We have plotted this concurrence in the FIG 1 and obtain a perfect concurrence for \(\theta_1 = \frac{\pi}{4}, \theta_2 = \frac{\pi}{4}\), as can be seen directly from (2). For this choice, a Bell pair between the first static qubit

![FIG. 1: A concurrence of the entanglement between the static qubits is plotted. Here, \(\theta_1 (\theta_2)\) denotes the phase shift induced by the interaction between the first (second) static qubit and the flying qubit. Bell state for \(\theta_1 = \frac{\pi}{4}, \theta_2 = \frac{\pi}{4}\), as can be seen directly from (2).](image-url)
and the flying qubit is generated while the latter interaction plays a role of a SWAP gate between the flying qubit and the second static qubit. Surprisingly, a perfect Bell pair can be deterministically generated without any measurements, while most of the previous schemes are probabilistic or require spin-resolving measurements on the flying qubit [15, 16]. One of the ways to construct such gates is as follows. As already mentioned, for suitable parameters of the potential, one can make the energy of the singlet resonance far from that of the triplet resonance [15, 16], so that a Bell pair between the flying and the static qubits can be generated for a particular kinetic energy in a weak to intermediate correlation regime. This regime is suitable for our first gate between the flying and the static qubits. Conversely, in a strong correlation regime (wide dot) where electrons avoid each other to lower their Coulomb repulsion energy in the quantum well, transmission can be almost unity for both the singlet and the triplet [16]. This is due to the small single-triplet energy splitting and a small overlap between the wave functions of the flying and the static qubits in the quantum dot. Moreover, since the bound electron feels the Coulomb repulsion of the incident electron as it enters the dot, the bound electron is ejected and the incident electron becomes bound in the large quantum dot. Since this process represents an exchange between the static and flying qubits, an effective SWAP gate with almost unity transmission probability is performed in this process [16], which is suitable for our second gate. Although a reflection probability at the first gate is high (∼ 50%), such reflection error can be heralded by using a charge detector such as a single electron transistor [17] to check whether the flying qubit is transmitted.

In the actual implementation of the above scheme, a perfect Bell pair might not be generated due to imperfect control of the interaction between the static and flying qubits. In order to overcome such difficulty of controlling parameters, we adopt a two-step distillation protocol, which requires an ancillary qubit per node (See FIG. 2). Since we expect that the primary error sources are associated with the flying qubit, we assume that high fidelity local operations are possible between the static qubits within each node. We will show that adding only one ancillary static qubit makes our scheme robust against imperfections. After the flying qubit has passed the two static qubits, we obtain the state $\rho_{s1,s2}$ which is of the same form as the key state considered in [15, 18]. It follows that, if we have an ancillary qubit near the static qubit at each location, we can perform an efficient two round distillation protocol. We utilize the state $\rho_{s1,s2}$ as a resource to perform a parity projection on the ancillary qubits. Since the state $\rho_{s1,s2}$ is mixed, the parity projection is also imperfect. However, we can generate the state $\rho_{s1,s2}$ again through a transmission of another flying qubit and can utilize this state for performing the second parity projection on the ancillary qubits. From the measurement results of the two parity projections, we know whether the ancillary qubits are projected onto an entangled state or just projected onto separable states. As long as the errors caused by local operations in the node are negligible, this protocol constructs a perfect parity projection with success probability $P_s = \frac{P_1 P_2}{P_1 + P_2}$. Although errors in the local operations reduce the fidelity of the parity projection, it has been shown that this does not represent a major issue because only a few operations are necessary in this protocol [18]. Note that parity projection is one of the most commonly proposed EOs [2, 3, 4, 7, 18] to make useful multipartite entanglement such as a cluster state for quantum computation [19] and a GHZ state for a quantum magnetic sensor [20].

By using a projective measurement and a subsequent single qubit rotation, one can prepare any initial spin states. However, for a flying qubit, it would be difficult to construct a high fidelity measurement with the current technology and thus the initialization of the flying qubit could be imperfect. Importantly, this imperfection can be detected through the two round protocol and prevented from reducing the fidelity. Due to the imperfect initialization of the flying qubit, the initial state of the flying qubit can be represented as $(1 - \epsilon)|\uparrow\rangle_f + \epsilon|\downarrow\rangle_f$. Through the transmission of the flying qubit between the static qubits, the state of the static qubits will be $\rho_{s1,s2}' = (1 - P')|\downarrow\rangle_{s1,s2} + P'|\chi\rangle\langle\chi|$, where $|\chi\rangle = \sqrt{\frac{P_2}{P_1 + P_2}} |\uparrow\rangle_{s1,s2} + \sqrt{\frac{P_1}{P_1 + P_2}} |\downarrow\rangle_{s1,s2}$ and $P' = (1 - \epsilon)^2 P_2$. Therefore, one can perform a high fidelity parity projection between the ancillary qubits through the two round protocol. The success probability of this distillation is $P_\delta^{(c)} = \frac{1}{4}(1 - \epsilon)^2 P_1 P_2$, which means that the imperfection of the initialization just decreases the success probability of the EO without affecting the fidelity of the target entanglement.

Dephasing and relaxation are relevant error sources in solid state systems. Especially when the distance between the static qubits is long, the flying qubit will be affected by such errors due to the noisy environment. However, similar to the imperfect initialization, the relaxation process, which makes a spin-up state into a spin-down state, only decreases the success probability without affecting the fidelity of the EO. Therefore, we study especially how dephasing the flying qubit affects the fidelity of the EO, and also introduce a way to reduce the impact of this problem. We adopt a general dephasing model such that the state is acted on by a Pauli matrix $\sigma_z$ with a probability $\epsilon_z$ otherwise the state is unchanged. Note that dephasing does not change the initial state before the fly-

![FIG. 2: Schematic of a construction of a high fidelity parity projection between distant static qubits where each node supports two qubit storage. Transmission of the flying qubit could generate only impure entanglement between the static qubits due to experimental imperfections. One can use the additional ancillary qubits for a distillation protocol to guarantee that an ideal EO is performed.](image-url)
ing qubit interacts with the static qubits, and also the flying qubit will be traced out after the flying qubit has passed the two static qubits. So the dephasing effect is only important when the flying qubit is between the static qubits. The final state of the static qubits is then represented as $\rho_{s1,s2} = (1 - \epsilon_f)\rho_{s1,s2} + \epsilon_f \sigma_z^{(s1)} \rho_{s1,s2} \sigma_z^{(s1)}$ from (3). For an initial state $|+\rangle_{a1,a2}$, we can perform the two round protocol by using the state $\rho_{s1,s2}$ and we obtain $\rho_{a1,a2} \approx (1 - 2\epsilon_f)|\psi^{(+)}\rangle\langle\psi^{(+)}| + 2\epsilon_f|\psi^{(-)}\rangle\langle\psi^{(-)}|$ where $|\psi^{(+)}\rangle = \frac{1}{\sqrt{2}} |\uparrow\rangle \pm \frac{1}{\sqrt{2}} |\downarrow\rangle$. This means that, due to the dephasing, the fidelity of the EO decreases to $1 - 2\epsilon_f$. Fortunately, an efficient distillation protocol to reduce the effect of the dephasing has been suggested \[21\], and this protocol requires only an additional qubit at each node. So, if we have a second ancillary qubit, we can reduce the impact of the dephasing as follows. First, we prepare the imperfect bell state $\rho_{a1,a2}$ between the first ancillary qubits by the two round protocol. Since this two round protocol is probabilistic, we repeat this process until successful. Second, we perform local operations (including measurements) between the first and second ancillary qubits at each node. By repeating the first and second steps, the state of the second ancillary qubits converges to a high fidelity entangled state. In this process, one obtains a series of measurement results. The fidelity of the EO becomes a function of the measurement results and follows a biased random walk which converges rapidly to unity \[21\]. For example, with a dephasing rate $\epsilon_f = 0.089$, one can obtain a high fidelity $F \approx 1 - 10^{-4}$ entangled state by performing this protocol 10 times on average \[21\]. Importantly, this protocol does not require postselection and hence one can perform an EO deterministically with no risk of damaging previous entanglement for performing a new EO. So this EO has the advantage of reducing the time resource needed especially when one tries to generate multipartite entanglement.

In order to generate a large entangled state, one has to prepare a significant number of static qubits in the one dimensional system and needs to perform EOs between two specific static qubits \[2\]. Here, we describe how to perform such selective EOs via a flying qubit. Suppose that one prepares a state $|\psi^{(+)}\rangle_{s,1} \otimes |\psi^{(+)}\rangle_{s,2} \otimes |\psi^{(+)}\rangle_{s,3} \otimes |\psi^{(+)}\rangle_{s,4}$ and try to perform an EO between the down-spin static qubits at $i$ and $i+1$. For the triplet resonance, the flying qubit $|\psi^{(+)}\rangle_{f}$ has spin-preserving, unity transmission probability with a static qubit $|\psi^{(+)}\rangle_{s,i}$, hence the flying qubit arrives at the $i$-th static qubit without affecting the previous static qubits. After the flying qubit interacts with the $i$-th and $i+1$-th static qubits, the flying qubit can continue to transmit until it reaches the end of the one dimensional system through the SWAP gate with a unity transmission probability in the strong correlation regime. As a result, one obtains the target state $\rho_{a1,a2}$ between the $i$-th and $i+1$-th static qubits and, by using this state, one can perform an EO to the ancillary qubits.

Finally, we discuss a possible experimental realization for the distillation protocols. Molecular spin systems could be attached externally to the nanotube to provide ancillary qubits. For example, Sc@C$_{62}$ has an unpaired electron spin in the highest occupied molecular orbital with a long decoherence time of 200 $\mu$s, which can be utilized as a qubit \[22\]. Moreover, since the electron spin exists mainly on the fullerene cage, there is expected to be a large exchange coupling between the electron spin and the static qubit in the quantum dot \[23\]. Furthermore, instead of using a quantum dot for a static qubit, Sc@C$_{62}$ could itself provide both the static qubit and the ancillary qubit, the latter being provided by a nuclear spin. This would allow two-qubit gate operations between the nuclear and the electron spins through hyperfine coupling \[24\]. So these properties of Sc@C$_{62}$ may be suitable for performing our distillation protocols, although further research is needed to assess its suitability as a future generation technology. In conclusion, we have suggested a way to construct a high fidelity EO between spatially separated static qubits by using a flying qubit in solid state systems. Although there are several types of error, we have shown a robust way to perform a high-fidelity EO by making use of a distillation protocol, suggesting constitutes a feasible route for the realization of distributed quantum information processing in solid state systems. Authors thank Simon C. Benjamin and Joseph Fitzsimons for useful discussions.

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