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Colored channels for high-fidelity information transfer and processing between remote multi-branch quantum circuits

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Abstract – We present a protocol for high-fidelity information transfer and processing between remote multi-branch nonideal quantum circuits (QCs). A set of outputs of a QC is simultaneously coupled to the corresponding set of inputs of another, remote, QC through a single realistic nonideal data bus (DB). The normal modes of the DB are exploited to induce a Raman-like coupling on each colored output-input channel which enables the circuits to exchange information without effectively exciting the DB. Being only virtually excited, the nonidealities of the DB are substantially weakened, rendering a high-fidelity tunneling-like information transfer and processing between the remote multi-branch QCs.

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The simultaneous transfer and processing of parallel data streams between remote multiport quantum circuits (QCs) is a core requirement for the implementation of classical as well as quantum communication and computation. In this regard, perfect or high-fidelity transfer of quantum states has attracted much attention since its introduction at the beginning of the 2000s [1]. Aiming to optimize the control required for communication between distant nodes in a QC, the research effort devoted to state transfer has led to the necessary and sufficient conditions, within spin [2] and resonator networks [3], for it to demonstrate that perfect transfer can occur in an entire class of topologies [4]. State transfer through realistic noise channels has also been addressed within spin chains [5,6] and a protocol for quasi-perfect state transfer in a network of dissipative resonators [7,8] seems to broaden the perspective on the subject of decoherence-(quasi-)free subspaces [9]. In a more recent contribution [10], the process of quasi-perfect remote state transfer has been formally characterized as a nonlocal tunneling process where —by analogy with the tunneling effect in a double-well barrier— the overlap between distant sender and the receiver wave functions is indirectly mediated by the normal modes of the data bus (DB), *i.e.*, the transmission kernel of the network. Moreover, in the same study, it is demonstrated that this nonlocal tunneling enables not only the transfer of states (or excitations) from one system to another, but also the transfer of the whole system in a given state from one place to another. In other words, fermions can also undergo nonlocal tunneling between distant nodes of a quantum network.

Recent theoretical advances in high-efficiency state transfer rely on protocols that ensure resonance between the common frequency of the sender and the receiver (at the endpoints of a network) and a single normal mode of the DB [11–13]. Such a strategy leads to a three-body Hamiltonian —taking into account the sender, the receiver, and the "mathematical" system associated with the selected normal mode of the DB— which governs the perfect state transfer in the case of ideal networks. For nonideal networks, the perfect state transfer gives way to a process whose nonunity fidelity can be optimized through the above-mentioned nonlocal tunnelling mechanism [8,10], ensuring that the state goes directly from the sender to the receiver without populating the nonideal DB. As demonstrated in refs. [8,10], this mechanism works by tuning the degenerate sender and receiver out of resonance with all the DB normal modes, thus leading to an effective two-body (tunneling-like) Hamiltonian and causing the effects of incoherence in the DB to be substantially weakened. We finally stress that, apart from state transfer, there are proposals for the implementation of long-distance quantum gates, particularly those capable of generating entanglement between remote qubits [14,15]. Another proposal, based on an ideal spin chain data bus, has also been advanced by which the state of a sender can be transferred to one of different receivers, depending on both the frequency tuning between sender and receivers and the coupling strengths between them and the data bus channel [16].

The present study aims to extend the goals of refs. [8,10] to the simultaneous transfer and processing of parallel data between remote multi-branch nonideal QCs. Thus, instead of transferring a single state to a distant node in a network, we now proceed to transfer a set of output states of a QC to the corresponding inputs of another, remote, QC through a realistic nonideal DB. In fig. 1 we illustrate the process by sketching two distant QCs connected to each other through a DB, here assumed to be the (simplest) linear network of N coupled systems of natural frequencies ω_i (i and j run from 1 to N from here on). We are assuming that the degenerate output-input channels are, somehow, tuned to frequencies ϖ_ℓ (with ℓ running from 1 to M), each slightly out of resonance with a given DB normal mode Ω_i. These detuned normal modes are thus exploited to induce a Raman-like coupling between the ends of each output-input channel, enabling the circuits to exchange information without effectively exciting the DB. By taking advantage of such a nonlocal tunnelling mechanism [8,10], we thus demonstrate that as many states as the $M \leq N$ nondegenerate and sufficiently widely spaced DB normal modes can be simultaneously transferred with high fidelity between the remote circuits.

The network model. – As in ref. [10], our development applies to networks of bosonic and fermionic systems, such as networks of interacting resonators [17,18], coupled trapped ions [19], optical lattices [20,21] and spin chains [22], assuming in this last case the application of the Jordan-Wigner fermionization technique. The Hamiltonian governing the whole network is given by $H = H_{DB} + H_{\mathcal{O}/\mathcal{I}} + H_{\Re}$, where

$$H_{DB} = \sum_{i,j=1}^{N} \mathcal{A}_i^\dagger \mathcal{H}_{ij} \mathcal{A}_j$$

represents the DB, whose coupled components are expressed by the annihilation (creation) operators $\{\mathcal{A}_m\}$ ($\{\mathcal{A}_m^\dagger\}$) and, although only the nearest-neighbor couplings are shown in fig. 1, we address here the general case where each DB component interacts with all others, with strengths ζ_{mn}; any particular topology follows by an appropriate choice of the parameters defining the Hamiltonian $\mathcal{H}_{ij} = \omega_i \delta_{ij} + \zeta_{ij}(1 - \delta_{ij})$. The set of M output-input channels, described by the annihilation (creation) operators $\{\mathcal{O}_\ell\}$ and $\{\mathcal{I}_\ell\}$ ($\{\mathcal{O}_\ell^\dagger\}$ and $\{\mathcal{I}_\ell^\dagger\}$), as well as their respective couplings, of strengths λ_ℓ, to the first and the N-th DB components, are modeled by the Hamiltonian

$$H_{\mathcal{O}/\mathcal{I}} = \sum_{\ell=1}^{M} \Big[\varpi_\ell (\mathcal{O}_\ell^\dagger \mathcal{O}_\ell + \mathcal{I}_\ell^\dagger \mathcal{I}_\ell) + \lambda_\ell (\mathcal{O}_\ell^\dagger \mathcal{A}_1 + \mathcal{I}_\ell^\dagger \mathcal{A}_N + \text{H.c.}) \Big].$$

Finally, under the realistic assumption that all the systems enrolled on our network are coupled to their respective reservoirs, with coupling strength γ, the interactions are modeled by the Hamiltonian

$$H_{\Re} = \sum_{i,k} [\omega_{ik} c_{ik}^\dagger c_{ik} + \gamma_i (\mathcal{A}_i c_{ik}^\dagger + \text{H.c.})] + \sum_{\ell,k} \left\{ \omega_{\ell k} c_{\ell k}^\dagger c_{\ell k} + \gamma_\ell \left[(\mathcal{O}_\ell + \mathcal{I}_\ell) c_{\ell k}^\dagger + \text{H.c.} \right] \right\},$$

where the k-th mode ω_{qk} of the q-th reservoir ($q = i, \ell$) is described by the annihilation (creation) operator c_{qk} ($c_{qk}^\dagger$). Aiming to derive the network master equation, we diagonalize H_{DB} by applying the transformation $\Lambda_i = \sum_j T_{ij}^{-1} \mathcal{A}_j$, where the coefficients of the j-th column of the orthonormal matrix $\mathbf{T}$ ($\mathbf{T}^{-1} = \mathbf{T}^\intercal$) define the eigenvectors associated with the eigenvalues Ω_i [18]. After getting rid of the degrees of freedom of the reservoirs, we obtain the network reduced density operator

$$\dot{\rho} = -i[\tilde{H}, \rho] + \sum_i (\Gamma_i/2)([\Lambda_i \rho, \Lambda_i^\dagger] + [\Lambda_i, \rho \Lambda_i^\dagger]) + \sum_\ell (\Gamma_\ell/2)([\mathcal{O}_\ell \rho, \mathcal{O}_\ell^\dagger] + [\mathcal{O}_\ell, \rho \mathcal{O}_\ell^\dagger]) + \sum_\ell (\Gamma_\ell/2)([\mathcal{I}_\ell \rho, \mathcal{I}_\ell^\dagger] + [\mathcal{I}_\ell, \rho \mathcal{I}_\ell^\dagger]), \quad (1)$$

where Γ_i and Γ_ℓ stand for the damping rates of the i-th DB normal mode and the ℓ-th output-input channel. The Hamiltonian $\tilde{H} = \tilde{H}_{DB} + \tilde{H}_{\mathcal{O}\mathcal{I}}$ sums the terms $\tilde{H}_{DB} = \sum_i \Omega_i \Lambda_i^\dagger \Lambda_i$ and $\tilde{H}_{\mathcal{O}\mathcal{I}} = \sum_{\ell=1}^{M} \{\omega_\ell (\mathcal{O}_\ell^\dagger \mathcal{O}_\ell + \mathcal{I}_\ell^\dagger \mathcal{I}_\ell) + \lambda_\ell \sum_{i=1}^{N} [(T_{1i} \mathcal{O}_\ell^\dagger + T_{Ni} \mathcal{I}_\ell^\dagger) \Lambda_i + \text{H.c.}]\}$, the latter describing the coupling of each of the M output-input channels to all the DB normal modes. Under the assumption of the weak-coupling limit: $\lambda_\ell, \zeta_{ij} \ll \omega_i, \varpi_\ell$, where all the couplings are significantly smaller than the frequencies, we have disregarded the cross-decay terms from eq. (1), which enable all the network components to lose excitation through each other [18].

Effective couplings between the output-input channel ends. – To engineer an effective interaction between the corresponding outputs and inputs of the two QCs, we first adjust each channel end (ϖ_ℓ) to be dispersively coupled to a single normal mode (Ω_j), or to a set of p-fold degenerate normal modes (Ω_j^p), thus being far out of resonance with all other modes Ω_i, such that $\left|\Omega_j^p - \Omega_i\right| \gg \lambda$. In both cases, the condition $\sqrt{\bar{n}_\ell} \lambda_\ell / \Delta_\ell \ll 1$ must be satisfied ($\bar{n}_\ell$ being the mean excitation of the ℓ-th output state and $\Delta_\ell = |\Omega_j - \varpi_\ell|$), while the coupling strengths λ_ℓ must be much smaller than those between the DB components ζ_{ij}, *i.e.* $\lambda_\ell \ll \zeta_{ij}$. Otherwise, the excitation of the state to be transferred would populate the DB, even under a large detuning Δ_ℓ. The above restrictions allow us to eliminate the DB variables adiabatically [23], rendering, up to the second order of the smallest network parameters λ_ℓ, the equation for the reduced density operator $\rho_{\mathcal{O}\mathcal{I}}$

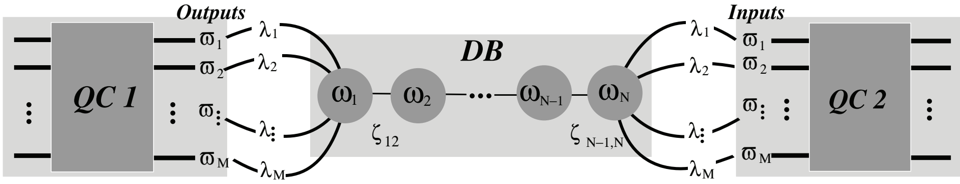

Fig. 1: A network for state transfer by nonlocal tunneling assuming symmetric QCs.

describing the dynamics of all the output-input channel ends:

$$\begin{aligned}\dot{\rho}_{\mathcal{OI}} &= -i\,[H_{eff}, \rho_{\mathcal{OI}}] \\ &+ \sum_\ell (\Gamma_\ell^{(\mathcal{O})}/2)([\mathcal{O}_\ell \rho_{\mathcal{OI}}, \mathcal{O}_\ell^\dagger] + [\mathcal{O}_\ell, \rho_{\mathcal{OI}} \mathcal{O}_\ell^\dagger]) \\ &+ \sum_\ell (\Gamma_\ell^{(\mathcal{I})}/2)([\mathcal{I}_\ell \rho_{\mathcal{OI}}, \mathcal{I}_\ell^\dagger] + [\mathcal{I}_\ell, \rho_{\mathcal{OI}}^\dagger \mathcal{I}_\ell^\dagger]), \end{aligned} \tag{2}$$

where the Hamiltonian

$$H_{eff} = \sum_\ell \chi_\ell (\mathcal{O}_\ell^\dagger \mathcal{I}_\ell + \mathcal{O}_\ell \mathcal{I}_\ell^\dagger), \tag{3}$$

describes the effective couplings between the M output-input pair, with strengths $\chi_\ell = \sum_p \lambda_\ell^2 |T_{\ell 1}^p T_{\ell N}^p|/\Delta_\ell$, $T_{\ell 1}^p$ and $T_{\ell N}^p$ being the eigenvectors associated with the p-fold degenerate normal mode Ω_ℓ^p. Therefore, apart from the adiabatic elimination of the DB variables, we have also arranged the network parameters for the output-input channels not to interact with each other. We stress that H_{eff} is restricted to networks where $N \ll \Delta_\ell/\sqrt{\bar{n}}\lambda_\ell$, since its third-order correction is proportional to the factor $N\lambda_\ell^3/\Delta_\ell^2$ which has to be much smaller than $\lambda_\ell^2/\Delta_\ell$. Regarding the dissipative mechanisms of all the (adiabatically eliminated) DB elements, they are taken into account through the effective damping rates associated with each output-input pair, given by $\Gamma_\ell^{(\mathcal{O})} = \Gamma_\ell + \Gamma_j(\lambda_\ell^2/\Delta_\ell^2)\sum_p (T_{\ell 1}^p)^2$ and $\Gamma_\ell^{(\mathcal{I})} = \Gamma_\ell + \Gamma_j(\lambda_\ell^2/\Delta_\ell^2)\sum_p (T_{\ell N}^p)^2$ which, like χ, depend on the DB topology. The decay rate Γ_j of the j-th normal mode which is dispersively coupled to the ℓ-th pair of output-input ends is the one that takes place at the effective damping rates $\Gamma_\ell^{(\mathcal{O})}$ and $\Gamma_\ell^{(\mathcal{I})}$, and its contribution is exceedingly small ($\lambda_\ell/\Delta_\ell \ll 1$), owing to the tunneling nature of the output-input couplings. Finally, we note that the Lindblad form of the superoperator in eq. (2) follows from the condition that the DB constituents are initialized in their ground states. Otherwise, with an initially excited DB, we end up with additional temperature-like Lindblad terms, apart from correction (related to the DB), added to the Josephson-like structure in eq. (3).

Effective decay rates, fidelity and transfer times. – From here on we assume the particular case of a linear (first-neighbor coupling) degenerate DB whose components all have the same natural frequency ω and damping rate Γ. We also assume equal coupling strengths ζ between the DB elements, in the regime where $\lambda_\ell \ll \zeta \ll \omega$, adopted both to engineer the master equation (2) and to allow analytical results. Finally, equal damping rates are also assumed for all the output-input channel ends, so that $\Gamma_\ell = \tilde{\Gamma}$. With these restrictions on the parameters, we obtain the attenuated effective decay rates $\Gamma_\ell^{(\mathcal{O})} = \Gamma_\ell^{(\mathcal{I})} \sim \tilde{\Gamma} + \Gamma(\lambda_\ell/\Delta_\ell)^2$, while the excitation of the DB, $\mathrm{Tr}_{BD}(\rho_{DB}\sum_i \Lambda_i^\dagger \Lambda_i) \approx \sum_\ell (N\bar{n}_\ell \lambda_\ell^2/\Delta_\ell \zeta)t$, confirms that this channel is only virtually excited under the approximations used to obtain H_{eff} (see below).

By tracing out the degrees of freedom of the QC1 outputs from the solution of eq. (2), we obtain the density operator for the inputs $\rho_{\mathcal{I}}(t)$ and, consequently, the fidelity for the state transferred to the ℓ-th input $\mathcal{F}^\ell(t) = \mathrm{Tr}_{\mathcal{I}}[\rho_{\mathcal{I}}(t)|\psi_{\mathcal{I}}^\ell(t)\rangle\langle\psi_{\mathcal{I}}^\ell(t)|]$, where $|\psi_{\mathcal{I}}^\ell(t)\rangle$ stands for the state transferred to the ℓ-th input under ideal conditions, which makes it exactly the same as the state coming from the ℓ-th output at $t = 0$, *i.e.*, $|\psi_{\mathcal{I}}^\ell(t)\rangle \equiv |\psi_{\mathcal{O}}^\ell(0)\rangle$. From the maximization of $\mathcal{F}^\ell(t)$, we derive the transfer time $\tau_\ell = (1/\eta_\ell)\cot^{-1}(\Gamma/4\eta_\ell) \approx \pi/2\eta_\ell$, where $\eta_\ell = \chi_\ell\sqrt{1-(\mathcal{C}_\ell/4)^2}$ is the renormalized output-input coupling strength, which depends on the cooperativity parameter $C_\ell = \Gamma_\ell^{(\mathcal{O})}/\chi_\ell \approx \Gamma/\Delta_\ell + \tilde{\Gamma}\Delta_\ell/\lambda_\ell^2$ [10] balancing the cost of the dissipation rate against the benefit of the effective output-input coupling strength. Note that with $\tau_\ell \approx 1/\chi_\ell$ we obtain, assuming $\zeta \approx \Delta_\ell$: $\mathrm{Tr}_{BD}(\rho_{DB}\sum_i \Lambda_i^\dagger \Lambda_i) \ll \sum_\ell \bar{n}_\ell/\lambda_\ell$.

Validity of the engineered master equation. – To demonstrate the simultaneous transfer of a set of output states from a QC to the corresponding input states of another remote QC, we next consider the case where $M = 5$ outputs are found to be Schrödinger-cat–like states $|\psi_{\mathcal{O}}^\ell(0)\rangle = N_\pm(|\alpha_\ell\rangle \pm |-\alpha_\ell\rangle)$. So as to use typical values from current experiments, we assume that the DB and the outputs and inputs of the QCs to be connected are composed of arrays of microcavities coupled by optical fibers [17]. The condition for dispersive coupling between the output-input channels and the DB normal modes can be fulfilled by first setting N and then adjusting the gap between the fibers and the microcavities so as to engineer the strength $\lambda_\ell \ll \Delta_\ell/N$. Fixing $N = M = 5$, with $\zeta = 10^6\,\mathrm{s}^{-1}$, and working in the microwave region with $\omega = 10^9\,\mathrm{s}^{-1}$, we next assume equal coupling strengths $\lambda = 10^5\,\mathrm{s}^{-1}$ between the QCs and the DB to derive the normal modes $\Omega_j = \{10^9 + 2\times 10^6\cos[j\pi/3]\}\,\mathrm{s}^{-1}$, enabling us to adjust the frequencies ϖ_ℓ in order to obtain the same detuning $\Delta_0 = |\Omega_j - \varpi_\ell| = 10^7\,\mathrm{s}^{-1}$ between all the output-input channels and their corresponding DB

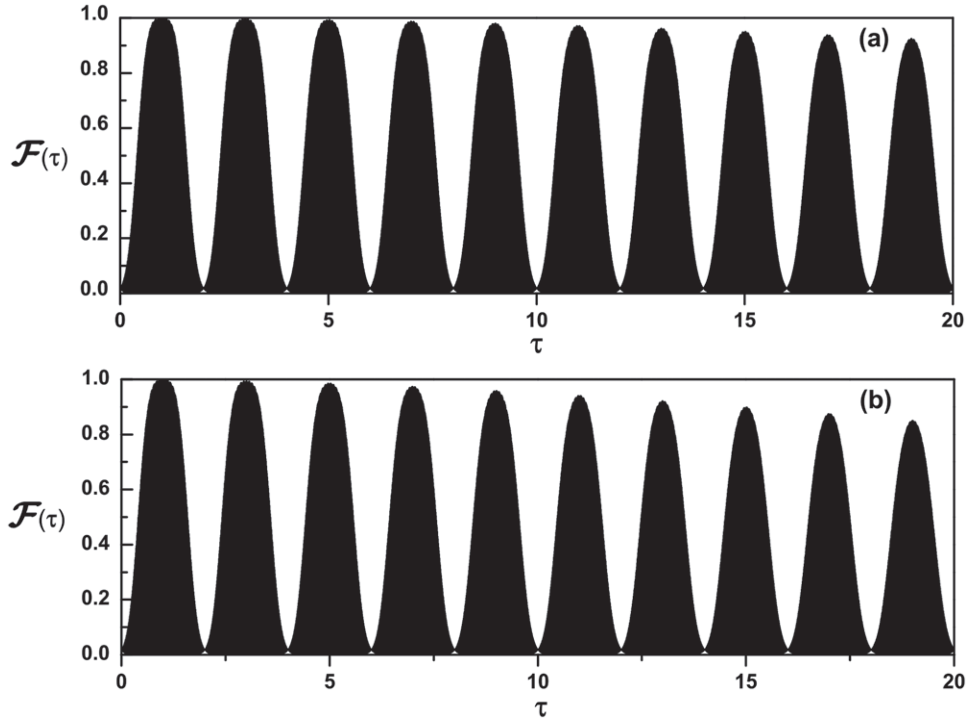

Fig. 2: Plot of the fidelity $\mathcal{F}(\tau)$ *vs.* the scaled time $\tau = t/\tau_\ell$, assuming $|\alpha_\ell|^2 = 5$, as computed from (a) the full (2) and (b) the effective (1) master equations.

normal modes. Finally, we choose high-finesse cavities for the output-input channel ends, with $\tilde{\Gamma} = 1\,\mathrm{s}^{-1}$, coupled to ordinary low-Q DB cavities, with $\Gamma = 10^4\,\mathrm{s}^{-1}$.

Adopting the above regime of parameters, in fig. 2(a) we plot the fidelity $\mathcal{F}(\tau)$ *vs.* the scaled time $\tau = t/\tau_\ell$, which turns out to be the same for all output-input channels, since $\lambda_\ell = \lambda$. Assuming $|\alpha_\ell|^2 = 5$, we find that even after ten consecutive transfers of the output states to the inputs, which takes the time interval $\tau = 20\tau_\ell = 20\pi\Delta_\ell/\lambda^2$, the fidelity $\mathcal{F}^\ell(\tau) \approx (1 + \mathrm{e}^{-10\pi|\alpha_\ell|^2\mathcal{C}_\ell/2})/2 \approx 0.92$ is still considerably high since, for the parameters given above, the cooperativity $\mathcal{C}_\ell \approx 10^{-3}$ is very small.

In order to analyze the validity of the engineered interaction (3), we plot in fig. 2(b) the fidelity $\mathcal{F}(\tau)$ as computed from the master equation (1) under the regime of parameters specified above for a microcavity array, which justify the effective coupling (3). We see that the two plots in figs. 2(a) and (b), generated by eqs. (2) and (1), respectively, are very close for the first few swap operations and, even after $\tau = 20\tau_\ell$, the fidelity is still around 0.85, thus confirming the accuracy of the whole set of approximations carried out. Evidently, by adopting a more stringent regime of parameters, we could get a much better agreement between the effective and real dynamics.

We observe that high rates of fidelity are still achieved when the DB components are assumed to be initially excited, or the coupling between them and their natural frequencies show some degree of randomness. With the same parameters as in fig. 2, in fig. 3(a) we plot the fidelity (1) when each component of the DB is initially in a coherent state $\beta = 1$. When this plot is compared with that in fig. 2(b), it is clear that the first cycles of state transfer and recurrence are hardly affected by the initial excitation of the DB, the fidelity at $\tau = 20\tau_\ell$ being 0.8. Also with the same parameters as in the above cases, in fig. 3(b), we plot the fidelity (1) when ζ has random values distributed uniformly within the interval $[0.8, 1.2] \times 10^6\,\mathrm{s}^{-1}$. Again, despite the significant range of the random coupling strength, the fidelity is only weakly affected, leading to about the same value as that from the real dynamics, thus demonstrating the robustness of our protocol against experimental fluctuations. One difference between this latter case and the others is that, as expected, the transfer time is affected by the inhomogeneity of the couplings between the DB components.

Additional effective interactions and logic operations. – It is straightforward to engineer additional effective interactions from the network scheme proposed above. For example, assuming R degenerate output–input pairs, such that $\varpi_1 = \varpi_2 = \cdots = \varpi_R = \varpi$, eq. (3) is substituted by

$$H_{eff} = \sum_{\ell'=1}^{R}\sum_{\ell''=1}^{R} \chi_{\ell'\ell''}\left[\mathcal{O}_{\ell'}^\dagger\left(\mathcal{O}_{\ell''} + \mathcal{I}_{\ell''}\right) + \mathrm{H.c.}\right] + \sum_{\ell=R+1}^{M} \chi_\ell(\mathcal{O}_\ell^\dagger\mathcal{I}_\ell + \mathrm{H.c.}), \tag{4}$$

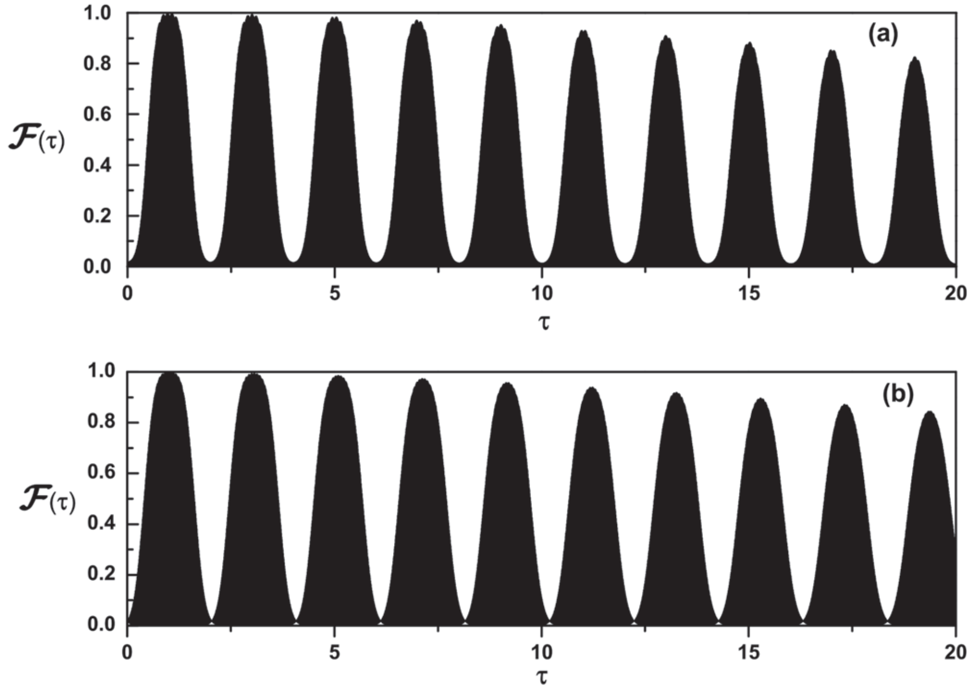

Fig. 3: Plot of the fidelity $\mathcal{F}(\tau)$ *vs.* the scaled time $\tau = t/\tau_\ell$, computed from the full master equations (2), when each component of the DB is initially in a coherent state $\beta = 1$ (a), and when ζ has random values distributed uniformly within the interval $[0.8, 1.2] \times 10^6\,\mathrm{s}^{-1}$ (b).

with $\chi_{\ell'\ell''} = \sum_p \lambda_{\ell'}\lambda_{\ell''}|T^p_{\ell'1}T^p_{\ell'N}|/\Delta_{\ell'}$, which enables us to generate n-bit quantum logic gates and to prepare entangled cluster states. A method for achieving a two-qubit entangling gate between arbitrary distant qubits in a network was recently proposed using uniform cold-atom chains [15]. Assuming that all the outputs (inputs) are coupled to the DB components with the same strength $\lambda_\ell = \lambda$, and starting with a state in which only one output contains a single excitation while all the others are in the vacuum state, then after the interaction time $\chi\tau = \pi/4$, we reach the W state $\sum_{\tilde{\ell}=1}^{2R} \mathrm{e}^{\Phi_\ell} |\delta_{\tilde{\ell}1}, \ldots, \delta_{\tilde{\ell}R}, \delta_{\tilde{\ell},R+1}, \ldots, \delta_{\tilde{\ell},2R}\rangle/\sqrt{2R}$ [24], where the first R positions in the product state refer to the outputs while the last R refer to the inputs. Apart from phase factors, this W state is thus composed of all the totally symmetric states involving $2R-1$ zeros and 1 excitation; for $R = 2$, we have $(|1000\rangle - i|0100\rangle - |0010\rangle - i|0001\rangle)/2$.

Considering the case where the output-input pairs are two-level systems described by the Hamiltonian (3), and assuming that laser pulses are used to rotate the output-input pairs, we may engineer, at the transfer time τ_ℓ, the evolution operator

$$U_{\mathit{eff}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \mathrm{e}^{i\varphi} \end{pmatrix},$$

which can be used, by adjusting the laser parameters supplying the phase factor φ, to implement long-distance two-bit universal quantum gates (with the output-input pairs), apart from performing the discrete quantum Fourier transformation of output to input states [25].

Finally, in the case where all output-input pairs are degenerate two-level systems ($\varpi_\ell = \varpi$) with $\lambda_\ell = \lambda$, it is easily verified that interaction (4) reduces to the simple form $H_{\mathit{eff}} = \chi S_+ S_-$, with $S_+ = \sum_{\ell=1}^{R}(\mathcal{O}_\ell^\dagger + \mathcal{I}_\ell^\dagger)$ and $S_- = \sum_{\ell=1}^{R}(\mathcal{O}_\ell + \mathcal{I}_\ell)$, which has been engineered in spatially confined atomic and spin samples. In our network, in contrast, the inputs are spatially distant from the corresponding outputs and direct manipulation of each network node is assumed. The interaction S_+S_- can be used to generate a plethora of states, such as entanglements, Schrödinger cats and spin-squeezed states [26].

We have advanced a proposal for the simultaneous transfer of a set of states between remote quantum circuits through a single realistic nonideal DB. The protocol applies to networks of bosonic and fermionic systems and can be used equally for the preparation of entangled states and for performing logic operations between remote QCs. The tunneling nature of the output-input couplings enables the high-fidelity transfer of the whole set of output states of a QC to the inputs of another remote QC, as well as the high-fidelity implementation of logic operations between these channel ends. Regarding the sensitive issue of how to tune the degenerate output-input channels to the vicinity of the DB normal modes, *i.e.*, the engineering of the required colored output-input channels, we mention that frequency-tunnable resonators have recently been realized experimentally [27].

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