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Robust quantum state transfer via topologically protected edge channels in dipolar arrays

C Dlaska, B Vermersch and P Zoller
1 Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria
2 Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria
3 These two authors contributed equally.

E-mail: benoit.vermersch@uibk.ac.at

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Abstract

We show how to realise quantum state transfer between distant qubits using the chiral edge states of a two-dimensional topological spin system. Our implementation based on Rydberg atoms allows to realise the quantum state transfer protocol in state-of-the-art experimental setups. In particular, we show how to adapt the standard state transfer protocol to make it robust against dispersive and disorder effects.

1. Introduction

Quantum state transfer aims at transferring the state of a first qubit to a second qubit, i.e. \((A |0\rangle_1 + B |1\rangle_1) \otimes |0\rangle_2 \rightarrow |0\rangle_1 \otimes (A |0\rangle_2 + B |1\rangle_2)\), and represents a basic building block of quantum communication and quantum information processing in a quantum network [1, 2]. Such a quantum network consists of nodes representing qubits as quantum memory, or in a broader context quantum computers, which are connected by quantum channels. Quantum networks are discussed both as local quantum networks connecting and thus scaling up small-scale quantum computers [3–5], or in quantum communication between distant nodes [1, 6]. The goal in a physical implementation of quantum state transfer is to achieve the transmission of a qubit with high fidelity through the quantum channel, i.e. avoiding decoherence. In a wide area quantum network, the natural carrier of quantum information will be photons as ‘flying qubits’ propagating in fibres or in free space as a physical realisation of the quantum channel, where a quantum optical interface allows storage in ‘stationary qubits’ represented by two-level atoms as quantum memory [7, 8]. Quantum state transfer between atoms stored in high-Q cavities connected by a photonic channel was reported in seminal experiments [9, 10] following the protocol described in [1]. A remarkable recent experimental development has been chiral quantum interfaces [11–14] in the context of chiral quantum optics [15], where two-level systems coupled to one-dimensional (1D) photonic nanostructures or nanofibers control the direction of propagation of emitted photons with a chiral light-matter coupling. This is illustrated in figure 1(a) as a two-level atom representing a first qubit \((\alpha = 1) |0\rangle \equiv |g\rangle, |1\rangle \equiv |e\rangle\), which decays from the excited state \(|e\rangle\) to the ground state \(|g\rangle\), emitting a photon into a 1D waveguide travelling unidirectionally to the right, which can then be restored into the second atom or qubit \((\beta = 2)\) achieving quantum state transfer. In nanophotonics, this chiral coupling occurs naturally due to spin-orbit coupling of light [15]. In local area or ‘on-chip’ chiral quantum networks, quantum state transfer can also be achieved via 1D phonon and spin channels [16]. In the latter case, magnons as spin excitations take the role of the ‘flying qubit’ [17], and a physical implementation of a chiral quantum interfaces between spins has been recently given in [18] for setups of Rydberg atoms arranged as 1D strings and ion chains.

In chiral quantum optics, the chiral light-matter interface selects the propagation direction of the travelling photon (or spin) wave packet (c.f. figure 1(a)), while the 1D waveguide supports both right and left going modes. Such a setup will thus not be protected against back-scattering from imperfections in the waveguide, as illustrated in figure 1(b). Instead, we concern ourselves with chiral quantum channels arising as chiral edge channels in two-dimensional (2D) topological quantum materials [19, 20] (c.f. figure 1(c)). Such topological...
quantum materials can be realised in condensed matter [21, 22] and be engineered as synthetic quantum matter with atomic systems [23–27], or in photonic setups [28, 29]. The distinguishing property of chiral edge channels is that they allow only unidirectional propagation around the edge of the topological quantum material. In the context of quantum state transfer, coupling a qubit to a chiral edge channel will thus not only provide us with an a priori chiral qubit-channel interface, but chiral edge channels are by their very nature immune against back-scattering [21, 22].

It is the purpose of the present work to study quantum state transfer of qubits via chiral quantum edge channels in a physical setting provided by dipolar arrays of Rydberg atoms. Motivated by recent experiments demonstrating dipolar Rydberg [30–34] and polar molecules [35] arrays, and building on recent proposals to engineer topological phases in spin systems realised by Rydberg atoms or polar molecules [36–38], we propose an implementation where the dipolar interactions are realised by weakly admixing Rydberg states to ground-state atoms via laser fields [39–41]. A key property of such a Rydberg-dressing implementation is that — with an appropriate spatial laser addressing — we can rearrange the edge of our engineered topological material, i.e. we can dynamically shape the edge channels to connect arbitrary pairs of qubits (c.f. figure 1(d)). Furthermore, our implementation provides a framework for illustrating in an experimentally realistic setup various features of quantum state transfer via topologically protected, and thus robust quantum channels, but also for realising a spectroscopy of chiral edge channels per se. Thus, we show how the measurement, by the qubits, of edge-state wave packets allows to realise high-fidelity quantum state transfer, robust against disorder and dispersive effects [16, 42].

Our manuscript is organised as follows. First, in section 2, we introduce our model of a quantum network with qubits connected via topological quantum channels. In section 3, we present an implementation of this model based on Rydberg-dressed atoms. In section 4, we numerically study the robustness of the quantum state transfer protocol and the role of disorder and dispersive effects. Finally, in section 5, we propose and assess the performance of a protocol, which exploits the chiral properties of the edge states, to achieve a perfect quantum state transfer, robust against static imperfections.

2. Model of a topological network and quantum state transfer using chiral edge states

In this section, we present our model of qubits, represented by a set of two-level atoms or spin-$\frac{1}{2}$, which can be coupled to an engineered 2D topological spin system [21, 22]. The setup we have in mind is illustrated in figure 2(a): the qubits are arranged on a quantum memory layer above the topological spin system (TSS) where chiral edge states play the role of the quantum channel. While in the present section we will define this model on
an abstract level, we will discuss a physical implementation of both qubits and the topological spin system with Rydberg atoms in section 3.

Quantum state transfer between a chosen pair of qubits $\alpha = 1$ and $\beta = 2$ on the quantum memory layer can be achieved by first arranging the dynamical chiral edge channels to connect the qubit pair and — again using lasers and dipolar interactions — swapping the state of the first qubit to a wave packet propagating in the edge channel, where it can be restored in the second qubit. This is illustrated in figures 1(c) and 2(a) for a pair of qubits at the edge of a square topological spin system.

We emphasise that in this work we consider the limit of zero temperature where the precise control of the state of the quantum channel, which is not affected by the presence of thermal excitations, allows to achieve the quantum state transfer. This assumption is valid in particular for the Rydberg-dressing implementation presented in the next section, where the spin state of the TSS atoms are controlled with excellent precision \[34, 43\]. In contrast, for other platforms using for instance microwave waveguides or mechanical resonator arrays as quantum channel, temperature effects have to be included for a realistic description of the quantum state transfer \[44\].

The Hamiltonian associated with our model consists of three parts,

$$H = H_q + H_T + H_{qT},$$

(1)

corresponding, respectively, to the qubits, the topological spin system and the coupling between them. In the following, we first present the Hamiltonian of the qubits and the topological spin system (section 2.1) and then we show how to describe the coupling of the qubits to the chiral edge states of the topological spin system (section 2.2). Finally, we present the quantum state transfer protocol in our setting (section 2.3).

### 2.1. Two-level systems and topological spin system Hamiltonian

The qubits $\alpha = 1, \ldots, N_q$ forming the quantum memory layer, with ground state $|g\rangle$ and excited state $|e\rangle$, are located at positions $(x_\alpha, y_\alpha, z_\alpha)$. The qubit Hamiltonian is given by

$$H_q = \Delta_q \sum_{\alpha=1}^{N_q} \sigma_\alpha^0 \sigma_\alpha^-,$$

(2)

with $\sigma_\alpha^0 = |g\rangle \langle e|$, $\sigma_\alpha^- = (\sigma_\alpha^0)^\dagger$ and energy offsets $\Delta_q$. We note that in this model the qubits are not directly coupled, i.e. they can only interact via the topological spin system.

The topological spin system is represented by V-type three-level systems $j = (j_x, j_z)$ with

$$j_x = 1, \ldots, N_j, j_z = 1, \ldots, N_j,$$

where $|0\rangle_j$ denotes the ground state and $|1\rangle_j, |2\rangle_j$ the two excitation states of atom $j$, which are placed at fixed positions $(x_j, y_j, z_j = 0)$ in the $X, Y$ plane according to a square lattice of lattice spacing $a$. Similar to the Harper Hofstadter Hamiltonian \[45, 46\], which has been recently realised in cold atom experiments \[23–26\], a topological band structure is obtained by allowing the spin excitations $|1\rangle, |2\rangle$, also known as magnons, to acquire a phase when hopping around a closed loop in the lattice. The corresponding Hamiltonian is given by

$$H_T = \sum_{j=1,2} \sum_{j=1,2} \delta_{j,l} b_j^\dagger b_{j,l} + \sum_{j=1} b_j^\dagger h(\tau_{j,l}) b_j,$$

(3)

Here, we map the spin excitations to hard-core boson particles where the two-element vector $b_j = [b_{j,1}, b_{j,2}]$, with $b_{j,l} = |0\rangle_j \langle l|$, represents the two (hard-core boson) annihilation operators of the excitations at site $j$ and $\delta_{j,l}$...
is the corresponding energy offset. The matrix \( h(\mathbf{r}_j) \), with \( \mathbf{r}_{jk} = (x_j - x_k)\mathbf{X} + (y_j - y_k)\mathbf{Y} \), describes the transfer of an excitation between sites \( j \) and \( l \) and can be written as

\[
h(\mathbf{r}_{jl}) = \begin{bmatrix} t_1(\mathbf{r}_{jl}) & w(\mathbf{r}_{jl})e^{-i\phi(\mathbf{r}_{jl})} \\ w(\mathbf{r}_{jl})e^{i\phi(\mathbf{r}_{jl})} & t_2(\mathbf{r}_{jl}) \end{bmatrix},
\]

where the phases \( \phi(\mathbf{r}_{jk}) \) are responsible for the existence of Quantum Hall topological bands characterised by non-vanishing Chern numbers [37, 38] and thus chiral edge states [21, 22, 38] (c.f. figure 2(a)).

By considering for convenience the limit of an infinite number of atoms in one direction, \( N_Y \to \infty \), we obtain the dispersion relation of bulk and edge modes by Fourier transforming along the \( Y \) axis and diagonalising the TSS Hamiltonian (c.f. appendix \( A \)),

\[
H_T = \sum_m \int_{-\pi/a}^{\pi/a} dk \omega_m(k) b_{km}^+ b_{km},
\]

where \( \omega_m(k) \) denotes the dispersion relation corresponding to the TSS eigenmode \( b_{km} \). Figure 2(b) shows a typical example of dispersion relation curves \( \omega_m(k) \). The edge-state dispersion relation corresponding to \( m = a \omega_1(k) \) (blue line) represents localised modes propagating with group velocity \( v_g(k) \equiv \partial \omega_1(k)/\partial k \). Their chirality originates from the fact that the modes propagating with positive velocity are located on the left edge, while the modes moving in the other direction are located on the right edge (c.f. figure 2). At this point, we want to emphasise that the absence of counter-propagating modes (for example with a negative velocity on the left edge) guarantees the absence of reflections originated from local defects. We analyse in more detail the robustness of the edge-state channels in sections 4 and 5.

2.2. Coupling between qubits and topological spin system

The last part of the Hamiltonian \( H \) of our model corresponds to the coupling between the qubits and the topological spin system. To achieve the quantum state transfer, we are interested in coupling the qubits predominantly to the edge modes. This is achieved by positioning the qubits in the vicinity of the edge of the topological spin system and choosing the qubit transition frequency \( \Delta_q \) to match with an edge state \( b_{ka} \), where the resonant wave vector \( \mathbf{k}_a \) is defined via \( \omega_a(\mathbf{k}_a) = \Delta_q \). The coupling Hamiltonian is written as

\[
H_{QT} = \sum_{\nu=0,1} \int_{-\pi/a}^{\pi/a} dk \quad \mathcal{g}_\nu(\mathbf{r}_{\alpha\nu}) \quad b_{k\alpha}^+ b_{\alpha\nu} + \text{h.c.},
\]

where \( \mathcal{g}_\nu(\mathbf{r}_{\alpha\nu}) \) represents the coupling of an excitation \( |\epsilon\rangle_{\alpha\nu} \) of the qubit \( \alpha \) to a TSS excitation at site \( \nu \), encoded in one of the two levels \( \nu = 1, 2 \) and depends on the relative vector \( \mathbf{r}_{\alpha\nu} = (x_\alpha - x_\nu)\mathbf{X} + (y_\alpha - y_\nu)\mathbf{Y} - z_\alpha\mathbf{Z} \).

Moreover, we consider the coupling terms \( \mathcal{g}_\nu(\mathbf{r}_{\alpha\nu}, t) \) to be time-dependent, which allows to form wave packets of edge modes propagating with a well-defined shape [1, 47]. In the basis of the eigenmodes \( b_{km} \), the coupling Hamiltonian takes the form

\[
H_{QT} = \sum_{m,\alpha} \int_{-\pi/a}^{\pi/a} dk \quad \mathcal{g}_{\nu,m}(k) \quad e^{-ik\cdot\mathbf{r}_{\alpha\nu}} b_{km}^+ b_{km} \quad + \text{h.c.},
\]

with the coupling strength \( \mathcal{g}_{\nu,m}(k) = (1/\sqrt{2\pi}) \sum_{\nu',\nu''} e^{-ik\cdot\mathbf{r}_{\nu',\nu''}} \nu''_{\nu'}(\mathbf{r}_{\alpha\nu}) \epsilon^{(k,m)}_{\nu',\nu''} \) describes the spatial properties of the eigenmodes and are given in appendix \( A \).

2.3. Quantum state transfer

Let us now apply our model to realise a quantum state transfer protocol [1] using chiral edge states [19]. The formal process we want to achieve is the transfer of any superposition state \( \langle \epsilon \rangle = A \langle g \rangle + B \langle c \rangle \) of a qubit \( \alpha = 1 \) to a second qubit \( \beta = 2 \) mediated by a wave packet propagating in the quantum channel (c.f. figures 1(a), (c))

\[
\begin{align*}
&\quad \langle \epsilon \rangle = A \langle g \rangle + B \langle c \rangle \\
&\quad A \langle g \rangle + B \langle c \rangle |0\rangle_T = |g\rangle_2 \\
&\quad |g\rangle_1 [A \langle 0 \rangle_T + B \int dk \quad \mathcal{a}_a(t) e^{-i\omega_1(t)k} b_{ka}^+ |0\rangle_T ] |g\rangle_2 \\
&\quad |g\rangle_1 |0\rangle_T [A \langle g \rangle_2 + B |c\rangle_1],
\end{align*}
\]

with |0\rangle_T = \prod_{\beta} |0\rangle_{j\beta} the excitation vacuum of the topological spin system. To derive the form of the coupling \( \mathcal{g}_{\nu,m}(k) \), which achieves the quantum state transfer, we write the general wave function

\[4\] This dispersion relation is only valid in the case of a single TSS excitation, where we can neglect the hard-core character of the boson operators \( b_i \).

\[5\] The precise position of the qubits we consider in the numerical examples is given in section 4.2.
|\psi(t)\rangle = \left(\sum_{\alpha} \varepsilon_{\alpha}(t) e^{-i(\Delta t)\sigma_\alpha^x} + \sum_m \int dk \varepsilon_{k,m}(t) e^{-i(\omega_m(k)t)k}b_k^\dagger\right)|V\rangle,

(9)

describing the propagation of a single excitation in the total system, with $|V\rangle \equiv |0\rangle_T \otimes \prod_{\alpha} |g_{0}\rangle_{\alpha}$. As presented in appendix B, the Wigner-Weisskopf treatment, valid in the weak coupling regime $h(\mathbf{r}_2) \gg g_{0}(\mathbf{r}_1,\mathbf{r}_2)$, eliminates the contribution of the TSS, resulting in the following set of equations for the qubit amplitudes:

$$\dot{c}_{e,1}(t) = -\frac{1}{2}\gamma_{a,1}(t)c_{e,1}(t)$$

$$\dot{c}_{e,2}(t) = \frac{1}{2}\gamma_{a,2}(t)c_{e,2}(t) - \sqrt{\gamma_{a,1}(t - \tau_a)\gamma_{a,2}(t)e^{i(\Delta t - (\tau_a - \gamma_1))}\gamma_{a,1}(t - \tau_a)},$$

(10)

(11)

where

$$\gamma_{a,\alpha}(t) = \frac{2\pi|g_{\alpha}^{a}(t)|^2}{|v_{a}(\mathbf{k}_a)|}$$

(12)

denotes the coupling of the qubit $\alpha$ to the edge mode $m = a, g_{\alpha}^{a}(t) = |g_{\alpha}^{a}(t)|e^{i\phi_a}, d = \gamma_2 - \gamma_1$ is the distance between the two qubits along the $Y$ axis and $\tau_a = d/|v_{a}(\mathbf{k}_a)|$ represents the time delay between the qubits. We emphasise that equations (10) and (11) illustrate the unidirectional coupling between the two qubits. Similar to the original proposal [1], the quantum state transfer protocol can be then realised with the time-dependent coupling [47, 48]

$$\gamma_{a,1}(t) = \frac{2\sqrt{\gamma_0 e^{-c(t-t_0)^2}}}{2\sqrt{c} - \sqrt{\pi}\gamma_0 \text{erf}(\sqrt{c}(t - t_0))},$$

(13)

which generates a Gaussian edge-state wave packet of temporal width $\sqrt{c}$. This symmetric pulse can be then reabsorbed by the second qubit via a time-reversed pulse $\gamma_{a,2}(t) = \gamma_{a,1}(\tau_a - t)$.

3. Implementation with Rydberg atoms

Having introduced our model, we present an implementation using Rydberg-dressed ground-state atoms. Our proposal is based on the spin–orbit properties of the dipole–dipole interactions [36–38]. We show schematically the different constituents of our implementation in figure 3(a) while the full level structure and laser excitation scheme are detailed in appendix C. The atoms that form our 2D topological spin system, denoted as TSS atoms, are trapped in a square lattice along the $X$, $Y$ plane as realised in optical lattices [32, 33], optical tweezers [31, 49–51] or magnetic lattices [52, 53]. We encode the states $|0\rangle$, $|1\rangle$, $|2\rangle$ in different hyperfine ground states, for instance $F = 1, 2$ in the case of Rubidium atoms, where a magnetic field $Bz$ with direction $z = \sin \Theta X + \cos \Theta Z$ defines the quantisation axis. The qubit atoms (red spheres) are placed in the vicinity of the topological spin system, using the same level structure as for the TSS atoms with $|g\rangle \equiv |0\rangle$ and $|e\rangle \equiv |1\rangle$. We note that in figure 3, we consider the same bi-layer configuration as in figure 2. However, for experimental
reasons, it is also possible to realise the model presented in section 2 in the case where the qubits are placed in the same plane as the TSS atoms, along the edges of the square lattice. As depicted in figure 3(b) and written in detail in appendix C in the case of Rubidium atoms, TSS and qubit atoms are weakly excited by far-detuned laser fields to Rydberg states \{3\}, \{4\}, \{5\}, \{6\}, \{7\}, which are magnetic Zeeman states of the \(nS_{1/2}\) and \(nP_{1/2}\) fine-structure manifolds, respectively.

We first present the effective Hamiltonian governing the dynamics of TSS ground-state atoms obtained by eliminating the Rydberg states in perturbation theory (section 3.1) and then apply the same approach to the qubits (section 3.2). Finally, we check the validity of our implementation by assessing the relevant time scales and the sources of imperfections (section 3.3).

### 3.1. Topological spin system

The TSS Hamiltonian \(H_{\text{imp}} = H_\text{at} + H_\text{int}\) has two contributions. The first term \(H_\text{at}\), representing the energies of the levels and the laser excitation, can be written in a rotating frame determined by the laser frequencies

\[
H_\text{at} = - \sum_j \sum_{3 \leq i < 7} \Delta_3 |i_j\rangle \langle \tilde{i}_j| + \sum_j \left\{ \Omega_0 |0 \rangle \langle 0| + \Omega_1 |6 \rangle \langle 1| + \Omega_2 \left( |5 \rangle \langle 2| + \frac{\sqrt{2}}{2} |7 \rangle \langle 1| \right) \right\} + \text{h.c.},
\]

with the Rabi frequencies \(\{\Omega_0, \Omega_1, \Omega_2\}\), the laser detunings \(\Delta_3\) and \(|i_j\rangle\) the state \(i\) of atom \(j\). For simplicity, we consider in the following \(\Delta_3 = \Delta\).

As shown in appendix C, the second part of the Hamiltonian \(H_\text{int}\) representing the dipole-dipole interactions between Rydberg-excited states can be written as

\[
H_\text{int} = \sum_{j=1}^{N} \frac{C_j}{r_{j,1}^3} \sum_{\ell=1}^{4} \left( \hat{\mathbf{r}}_{j,\ell} \cdot \hat{\mathbf{d}}_{ij} \right) \phi_{j,\ell} c_i
\]

with the shorthand notation \(c_i = |i_j\rangle \langle j\rangle\), \(|6\rangle \langle 1|\), \(|5\rangle \langle 2|\), \(|7\rangle \langle 1|\) and \(\hat{\mathbf{d}}_{ij}\) a dimensionless \(4 \times 4\) matrix that depends on the spherical angles \(\theta, \phi\) of the relative vector \(\mathbf{r}_{j,1}\) with respect to \(z\). The radial coefficient \(C_j = \left( \int dr_0(r) r^2 R_0(r) \right)\) is a function of \(R_0\), the radial wave function associated with the \(S_{1/2}\) and \(P_{1/2}\) Rydberg states [43]. We emphasise that we consider the large distance limit \(C_j/r_{j,1}^3 \ll \Delta\) where only the resonant flip-flop processes of the type \(P_{1/2} \leftrightarrow S_{1/2}\) contribute.

In the perturbative (or dressing) regime, \(\Omega_{0,1,2} \ll \Delta\), the Rydberg states can be eliminated in perturbation theory, leading to an effective Hamiltonian governing the dynamics of the ground-state levels [39–41]. To do so, we apply the Van Vleck formalism [54] reducing the TSS Hamiltonian \(H_{\text{imp}}\) to the form of (3) with

\[
t_{\text{imp}}(\mathbf{r}_{j,1}) = (-1)^{\nu_{j}} \frac{C_j \Omega_{0}^2 \Omega_{2}^2}{r_{j,1}^3} \frac{9 \Delta^5}{2} (1 - 3 \cos^2 \theta_{j,1})
\]

and

\[
w(\mathbf{r}_{j,1}) = \frac{C_j \Omega_{0}^2 \Omega_{2}^2}{r_{j,1}^3} \frac{6 \Delta^3}{2} \sin(2\theta_{j,1}),
\]

and the second and fourth-order AC-Stark shifts

\[
\delta_1 = \frac{3 \Omega_{0}^2}{4 \Delta} - \frac{9 \Omega_{2}^2}{16 \Delta^2} + \frac{\Omega_{2}^2}{\Delta} = \frac{\Omega_{2}^2}{\Delta^2} - \frac{3 \Omega_{0}^2 \Omega_{2}^2}{2 \Delta^2} - \frac{\Omega_{0}^2}{\Delta} + \frac{\Omega_{0}^2}{\Delta^2}
\]

\[
\delta_2 = \frac{\Omega_{0}^2}{\Delta} - \frac{\Omega_{2}^2}{\Delta^2} = \frac{\Omega_{0}^2}{\Delta^2} + \frac{\Omega_{2}^2}{\Delta^2}
\]

where we set \(\delta_0 = 0\). To obtain a topological phase [38], it is important that the energy-splitting \(\delta_1 - \delta_2\) does not dominate over the flip-flop term (17). This condition can be achieved for example by choosing the ratio \(\Omega_{2}/\Omega_{0}\), \(\Omega_{1}/\Omega_{0}\) according to (18) in order to obtain \(\delta_1 = \delta_2 = 0\).

Finally, we emphasise that in our dressing implementation, the local and time-dependent control of the laser intensities \(\Omega_{0,1,2}\) allows to effectively disconnect atoms from the rest of the topological spin system and therefore to dynamically reshape the edges (c.f. figure 1(d)).

### 3.2. Qubits and coupling to the topological spin system

The implementation of the qubits is similar to the one of the TSS atoms, with the difference that the level \(2\) is energetically excluded from the dynamics (for instance via the second-order AC-Stark shifts). Following the same procedure as for the derivation of the TSS Hamiltonian, we obtain the coupling Hamiltonian in the form of (6) with
of the two edge states which share the same chirality. The existence of two edge modes offers in principle the advantage of for the numbers given in section 3.3. The two edge-state channels have the same chirality, i.e., they propagate in the same direction along each edge. The existence of two edge modes offers in principle the advantage of...
performed multiplexing protocols but also gate operations based on spin-spin collisions (see [16] in the context of spin chains). However, in the following we consider that one edge-state mode \( m = a \) is predominantly excited, which can be achieved by exploiting the spin and localisation properties of the edge states (c.f. figure 4(b)).

4.2. Quantum state transfer

The quantum state transfer protocol relies on effective time-dependent couplings of the form of (13), which in the context of our implementation can be achieved by dynamically varying the qubit Rabi frequencies \( \Omega_{0,0}(t), \Omega_{1,0}(t) \) according to (12), (19) and (20). We study the performance of the protocol by numerically calculating the corresponding dynamics governed by (1) with the initial condition \( |\Psi(t = 0)\rangle = \sigma_0^\dagger |V\rangle \). As an example, we choose the two qubits to be separated by a distance \( d = y_0 - y_1 \) and position them with respect to the closest TSS atom \( j|\alpha\rangle \) with \( x_j |\alpha\rangle = 0 \) via \( V|\alpha\rangle = b(Z - X) \), with \( b = 8.1 \mu \text{m} \). For this geometric configuration, we obtain a dominant coupling \( \gamma_0 \) to the edge state indicated in red in figure 4.

The results of the quantum state transfer protocol are shown in figure 5, where we represent the fidelity of the quantum state transfer \( F = |c_{a,2}(t_f)|^2 \) for a final time \( t_f = 8 \) ms. In panel (a), we study the effect of the finite size of the topological spin system by representing the fidelity \( F \) for different TSS sizes \( N_X, N_Y \), a distance \( d = 6a \) and \( \gamma_0 = 2\pi \times 0.64 \) kHz. For large TSS sizes \( N_X, N_Y \gg 10 \), the fidelity converges towards a constant value \( F \approx 0.95 \), showing that the dispersion relation that we derived under the assumption of a semi-infinite topological spin system is relevant to describe the quantum state transfer in large but finite systems. To explain the cause of the deviation from the ideal fidelity \( F = 1 \), we represent \( F \) as a function of \( d \) and \( \gamma_0 \) in panel (b). At short distances and small coupling strengths, we observe state transfer with a small error that we attribute to the influence of the second edge-state channel \( m = b \) and to the off-resonant contribution of the bulk modes \( m = a, b \). At large distances, the fidelity is a decreasing function of \( d \) and of the coupling strength \( \gamma_0 \) indicating the onset of dispersion effects [16] that distort the edge-state wave packet while propagating.

Furthermore, we study the influence of disorder, which in cold atom experiments typically manifests by an on-site probability \( P \) for TSS atom vacancies. The fidelity \( F \) as a function of \( P \) is shown in figure 5(c) for a fixed distance \( d = 26a \) and coupling \( \gamma_0 = 2\pi \times 0.64 \) kHz. Despite the absence of back-scattering in our topological quantum channel, the presence of disorder distorts wave packets of edge states, affecting the fidelity of the quantum state transfer. Moreover, considering the individual disorder realisations shown as red circles, we notice that the robustness of the protocol crucially depends on the position of the vacancies.

To summarise this section, we demonstrated the potential of using a Rydberg-dressing implementation of chiral channels for quantum state transfer. We studied the role of dispersion and disorder as sources of

![Figure 5](image-url)
imperfection, the latter having a crucial influence on the fidelity despite the topological character of the edge modes. In the next section, we show that these limitations can be overcome by performing a protocol based on the spectroscopy of the transmission channel.

5. A robust state transfer protocol for the effects of dispersion and disorder

The goal of this section is to present a state transfer protocol that is robust against dispersive and disorder effects. In contrast to the standard protocol that assumes that the wave packet propagates without deformation according to a linear dispersion relation, here we simply treat the quantum channel as a ‘black box’ that conveys the information from the first to the second qubit. This section is organised as follows. In section 5.1, we show how to realise spectroscopy of the quantum channel via the qubits, i.e. to measure the phase and amplitude of the distorted wave packet. We then use this information in section 5.2 to derive the protocol which achieves the quantum state transfer. Finally, in section 5.3, we illustrate the efficiency of our method using two toy models.

We emphasise that our protocol is based on the assumption of perfect chirality of the quantum channel, i.e. it relies on the fact that all the emission of the first qubit is transmitted toward the second qubit. It thus applies in the context of the topological spin system presented in this previous sections but also in the context of chiral 1D waveguides [16] subject to dispersive effects. Finally, our protocol is only robust against static imperfections, i.e. we assume that the Hamiltonian describing the quantum channel is time-independent and can thus be characterised before we realise the quantum state transfer.

5.1. Quantum channel spectroscopy using the qubits

We now present the different steps of the spectroscopy of the quantum channel. As depicted in figure 6, we consider the first qubit $\alpha = 1$ to be initially excited and to emit for times $t < 0$ a wave packet with a well-defined shape which is then distorted while propagating. At time $t = 0$, the wave packet reaches the second qubit, whose dynamics, following appendix B, are given by

$$\dot{c}_{e,2}(t) = \left( -\frac{\gamma(t)}{2} + i\delta(t) \right) c_{e,2}(t) + \sqrt{\gamma_{e,2}} f(t),$$

(21)

with $f(t) = -i\int\left( K_{21}(k) e^{ik\cdot r} + K_{12}(k) e^{-ik\cdot r}\right) c_{e,1}(k,0)\,dk$ where $c_{e,1}(t) = \int\limits_{\mathbb{R}^2} dk\, e^{i\theta(k)} c_{e,1}(k,t)$ represents the wave packet amplitude in real space and we assume $c_{e,1}(0) \approx 0$. In contrast to the standard state transfer protocol that supposes that a wave packet propagates without deformation [1], we assume here that the second qubit receives an unknown wave packet $f(t)$ whose amplitude $|f(t)|$ and phase $\Phi(t) \equiv \arg(f(t))$ are both unknown. The time-dependent quantity $\delta(t)$ (c.f. figure 6) allows to change the transition frequency of the second qubit dynamically, which is assumed not to modify the coupling $\gamma_{e,2}(t)$. As explained in section 5.2 the chirp $\delta(t)$ is a crucial ingredient to realise the quantum state transfer.

We now show how to measure the wave packet $f(t)$. Using the ansatz $d(t) = e^{\gamma_{e,2}^{\prime}t/2} c_{e,2}(t)$, (21) becomes

$$\dot{d} = -i\delta d + \sqrt{\gamma_{e,2}} e^{\gamma_{e,2}^{\prime}t/2} f(t).$$

(22)

In a typical experimental setup, we only have access to the population of the qubit, and thus to the modulus $r \equiv |d(t)|$ while the phase $\theta \equiv \arg(d(t))$ cannot be directly measured. Therefore, it is not possible to extract the

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1 In this case, however, the channel is not protected against back-scattering.

2 Originated for instance from dispersion effects.

3 Note that the assumption of perfect chirality of the quantum channel implies $\int dt \, |f(t)|^2 = 1$. 

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Figure 6. Robust state transfer with static imperfections: the first qubit emits a symmetric wave packet towards the second qubit. Its unknown final shape can be measured by the second qubit using a chirped transition frequency $\gamma_{e,2}^{\prime} + \delta(t)$. We use this information to derive the pulse shape $\gamma_{e,2}^{\prime}(t)$ and chirp $\delta(t)$ realising the quantum state transfer.

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function \( f(t) \) via (22) with a single measurement of the qubit population. However, the measurement can be repeated for different (time-independent) \( \delta \) leading to the response \( d(t) \) and consequently \( f(t) \). A simple option is to realise two measurements of the qubit population: (i) the first measurement gives the function \( r_0 \) for \( \delta = 0 \) and (ii) the second measurement, performed at a small constant value \( \delta = \hat{\delta} \), leads to the knowledge of \( r_0' \equiv (\partial r/\partial \delta)_{\delta=0} \) via finite differentiation. We can then eliminate \( f(t) \) using (22) and obtain

\[
\begin{align*}
\dot{r}_0' - \hat{\delta} u &= 0 \\
\hat{\delta} r_0' + \dot{u} + r_0 &= 0, \tag{23}
\end{align*}
\]

with \( \theta_0' \equiv (\partial \theta/\partial \delta)_{\delta=0}, u = r_0 \theta_0' \). Knowing \( r_0 \) and \( r_0' \), (23), (24) can be integrated to find \( \theta_0 \) and finally \( f(t) \) using (22). As we are interested here in studying deviations from the ideal case where the function \( f(t) \) is real, we solve the differential equations (23), (24) iteratively in \( \theta_0 \), the zeroth order \( \theta_0(t) = -r_0'(t) \int_0^t d\tau r_0(\tau') \) in the examples below will be a good approximation. This concludes the spectroscopy of the quantum channel: comparing the Fourier components of the propagating wave packet.

5.2. Pulse shapes
Under the assumption of static quantum channel imperfections, the knowledge of the wave packet \( f(t) \), which reaches the second qubit, can be used to realise a robust state transfer protocol. To do so, we realise, after the first two measurements related to the quantum channel spectroscopy, a third experiment with time-dependent couplings \( \gamma_{a,2}(t) \) and chirp \( \delta(t) \). For a perfect absorption of the entire wave packet \( f(t) \) with the evolution \( c_{a,2}(t) = e^{i\Phi(t)} \sqrt{\int_0^t dt' |f(t')|^2} \), we obtain the conditions

\[
\begin{align*}
\gamma_{a,2}(t) &= |f(t)|^2/\int_0^t dt' |f(t')|^2, \\
\delta(t) &= -\Phi(t), \tag{25}
\end{align*}
\]

where we used (21). The first condition (25) resembles the typical pulse shape obtained in the standard state transfer protocol [1, 47, 48] with a real envelop \( f(t) \) (c.f. (11) in the Gaussian case). The second ‘phase-matching’ condition allows to compensate for the existence of the phase \( \Phi(t) \) by a ‘chirped’ frequency \( \delta(t) \). In this way, the frequency of the second qubit is dynamically synchronised with the evolution of the phase \( \Phi(t) \).

5.3. Results
We now apply our protocol based on the spectroscopy of the channel, using two toy models. First, in section 5.3.1, we consider a 1D quantum channel subject to dispersive effects while we present in section 5.3.2 the results obtained in the case of a disordered topological spin system. In both models, we assess the efficiency of the protocol by numerically simulating the dynamics of the combined system formed by the qubits and the quantum channel, similar to the study presented in section 4.

5.3.1. Compensation of dispersion effects in structured 1D waveguides
We consider a unidimensional waveguide (\( N_x = 1 \)), where the excitations are encoded in a single excited state |1\>. The matrix \( h(r_{j,l}) \) (c.f. (3)) is a simple scalar with nearest neighbour interactions \( h(r_{j,l}) = -J \delta_{j,l,\pm 1} \). This model was studied in detail in [16], showing dispersive effects similar to the ones presented here in section 4. In this case, the dispersion relation has an analytical expression \( \omega(k) = -2 J \cos(\kappa a) + \delta_c \), where we choose \( \delta_c = 0.5 J, \Delta_0 = 0 \). The fidelity of the quantum state transfer protocol is shown in figure 7(a). The blue curve corresponds to the standard quantum state transfer protocol, showing how dispersion affects the quantum state transfer at large distances \( d/a \). The green curve represents the case where the coupling of the second qubit has been adapted according to (25), whereas the red curve also includes the ‘chirp’ condition (26). The second condition is the crucial requirement to obtain a robust state transfer protocol. For a distance \( d = 400a \), we obtain a fidelity of 96\%, corresponding to a reduction of the error of 90\% compared with the standard state transfer protocol. The robustness of the protocol simply comes from the fact that the chirp compensates for the phases accumulated by the Fourier components of the propagating wave packet.

5.3.2. Robustness against disorder in a topological spin system
Finally, we study the robustness of the protocol in the case of a disordered topological spin system. For simplicity, we consider a model which, in contrast to the Rydberg implementation in section 3, includes a single edge-state channel [57]. The Hamiltonian is commonly written in terms of Pauli matrices
are not affected by the disorder of the quantum state transfer, while adding a chirp term is vacant. This is illustrated in figure 7. Correction of (a) dispersion effects in the case of a spin chain and of (b) disorder with a topological spin system. In each case, the first qubit emits a Gaussian wave packet according to (13) with $\gamma_0 = 0.3 J$. In panel (b), the fidelity has been averaged over 50 realisations of the disorder. We represent in blue the standard state transfer protocol $[\{10\}, \{11\}]$, in green the correction of the pulse shape and in red the case where the chirp is also applied. In the case of the spin chain (a), the chirp is an essential ingredient to compensate for dispersion effects. With disorder and a topological spin system, green and red curved overlap showing that the chirp is not needed. Finally, the orange curve representing the averaged fidelity where the coupling sites $j\{1\}$ are not affected by the disorder shows that the protocol only applies when the disorder does not affect the couplings $\gamma_{\alpha\beta}$ of the qubits to the waveguide.

\[
H_T = \sum_j \left( b_{j+1,j}^\dagger \sigma_z + i \sigma_x, b_{j+1,j} + b_{j,j+1}^\dagger \sigma_z - i \sigma_x b_{j,j+1} + \text{h.c.} \right) + m \sum_j b_{j,j+1}^\dagger \sigma_z b_{j,j+1},
\]

(27)

where we fix in the following $m = -1$. Moreover, the two qubits are coupled to a single TSS atom $j\{1\}$ (with $j\{1\} = 0$) according to (6) with $g_{a\alpha}^\dagger (\mathbf{r}_{a\alpha}, t) = -i f(t) (-1)^{j} \sqrt{2} \delta_{b,j\{1\}}$.

The results of the protocol are shown in figure 7(b) with the same graphical conventions as in figure 7(a). The comparison between the different curves shows that adapting the coupling pulse according to (25) increases substantially the fidelity $F$ of the quantum state transfer, while adding a chirp term (c.f. (26)) is in this case not required. Our interpretation is that in contrast to dispersion effects, the effect of missing atoms mainly leads to a time-delayed absorption of the wave packet, corresponding to the time needed by the wave packet to ‘avoid’ the defects. Finally, we note that our protocol is not robust when the coupling between the qubits and the edge-state channel is affected by the disorder, which in this example occurs if one site $j\{1\}$ is vacant. This is illustrated in figure 7(b) by the orange line, which represents the averaged fidelity for disorder realisations where the two sites $j\{1\}, j\{2\}$ are both occupied and corresponds to a much higher fidelity compared to the red curve.

6. Conclusion

In summary, we have studied a model of a quantum network where qubits can interact via chiral edge states. Our implementation based on Rydberg-dressed ground-state atoms allows to demonstrate the different ingredients of quantum state transfer using a topologically protected spin system in state-of-the-art experimental setups, and can be easily adapted to other dipolar systems such as polar molecules. Furthermore, after having numerically studied the role of static imperfections in the standard protocol $[\{10\}, \{11\}]$, we have presented an original approach, based on the spectroscopy of the quantum channel, achieving high-fidelity quantum state transfer even in the presence of dispersive and disorder effects.

In a broader context, our model of chiral quantum network in dipolar arrays can be applied to realise various robust quantum operations using the chiral edge states as topologically protected quantum channels. With directional spin chains, the hard-core nature of spin excitations makes it possible to implement entangling gates between distant qubits [16, 58]. In the case of dipolar topological spin systems, where the equilibrium phase diagram includes a Fractional Chern insulator [19], the role of topology in the collision dynamics of multiple edge-state excitations and the opportunities for realising entangling gates represent fundamental questions for quantum information processing in quantum networks, which we plan to address in a future work.

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Appendix A. Diagonalisation of the TSS Hamiltonian

In this section, we show how to obtain the dispersion relation describing the topological spin system. To do so, we consider the system to be in the Y direction, while remaining finite in the X direction and diagonalise the TSS Hamiltonian (3). The presence of at most one excitation in the TSS, $\sum_{k,\nu} \langle b_{k,\nu}^\dagger b_{k,\nu} \rangle \approx 1$, allows us to treat the hard-core boson operators $b_{k,\nu}$ as genuine bosonic operators. Using the transformation $b_{k,\nu} = (1/\sqrt{2\pi}) \int_{-\pi/\nu}^{\pi/\nu} dk \ e^{i j k} b_{x,0,k}$, we obtain

$$H_T = \sum_{x,j} \int dk \ b_{x,j,k}^\dagger \hat{h}(x_j - x_1, k) b_{x,j,k} \quad (A.1)$$

where $b_{x,j,k} = [b_{x,j,k,0}, b_{x,j,k,1}]$, $k$ is the wave vector associated with a plane-wave moving along the Y direction and

$$\hat{h}(x_j - x_1, k) = \sum_y e^{-i j k} h((x_j - x_1)X + yY), \quad (A.2)$$

with $h(0) = 0$. Finally, the TSS Hamiltonian (A.1) can be written in the quadratic form of (3) using the operators $b_{x,j,k} = \sum_{\alpha,\nu} \langle \phi_{n,\alpha,\nu} | b_{x,j,k} | \phi_{n,\alpha,\nu} \rangle \phi_{n,\alpha,\nu}$ representing the eigenmodes of the Hamiltonian and $\omega_{\alpha}(k)$ the corresponding dispersion relation.

Appendix B. Wigner-Weisskopf treatment of qubits coupled to edge modes

In this section, we consider the model introduced in section 2 to derive general expressions for the dynamics of the qubits (c.f. (10), (11)). Starting from the Wigner-Weisskopf ansatz (9) and plugging it into the Schrödinger equation $d |\psi(t)/dt = -i (H_0 + H_T + H_{GW}) |\psi(t)|$ leads to a set of coupled differential equations for the amplitudes

$$\dot{c}_{\alpha,0}(t) = -i \sum_m \int d\tau \langle \phi_{\alpha,m}(t) | b_{\alpha,0}(t') c_{\alpha,0}(t') e^{-i \omega_{\alpha}(k) \tau} \rangle \quad (B.1)$$

$$\dot{c}_{k,m}(t) = -i \sum_\alpha \langle \phi_{\alpha,m}(t) | b_{\alpha,0}(t') c_{\alpha,0}(t') e^{-i \omega_{\alpha}(k) \tau} \rangle \quad (B.2)$$

Formal integration of (B.2)

$$c_{k,m}(t) = -i \sum_\alpha \int_0^t d\tau' \langle \phi_{\alpha,m}(t') | b_{\alpha,0}(t') c_{\alpha,0}(t') e^{-i \omega_{\alpha}(k) \tau'} \rangle \quad (B.3)$$

and (B.3) plugging into (B.1) gives with $\gamma_{\alpha,\beta} \equiv \gamma_{\alpha} - \gamma_{\beta}$

$$\dot{c}_{\alpha,0}(t) = -\sum_{m,\beta} \int_0^t d\tau' \langle \phi_{\alpha,m}(t') | b_{\alpha,0}(t') c_{\beta,0}(t') e^{-i \omega_{\beta}(k) \tau'} \rangle \quad (B.4)$$

If we assume that the qubit timescales are slow compared with the bath timescales (weak coupling regime $\hat{h} (r_{x,0}, r_{0,0}) \gg g_{\alpha} (r_{0,0})$), we can linearise the dispersion relation for a particular edge mode $\omega_{\alpha}(k)$ around the qubit resonance $\omega_{\alpha} (k_\alpha) = \Delta_{\alpha}$

$$\omega_{\alpha}(k) \approx \Delta_{\alpha} + (k - k_\alpha) \nu_{\alpha} (k_\alpha). \quad (B.5)$$

Furthermore, the weak coupling approximation allows us to assume that $g_{\alpha,\beta}(t)$ is independent of $k$ around the resonant wave vector $k_\alpha$, such that $g_{\alpha,\beta}(t) \approx g_{\alpha,\beta}(k_\alpha)$. This leads to the following expressions for the qubit amplitudes

$$\dot{c}_{\alpha,0}(t) = -\sum_{\beta} \int_0^t d\tau' \delta (t - \gamma_{\alpha,\beta} / \nu_{\alpha} (k_\alpha) - t') \quad (B.6)$$

$$\times \delta (t - \gamma_{\alpha,\beta} / \nu_{\alpha} (k_\alpha) - t')$$

$$= -\frac{1}{2} \gamma_{\alpha,\beta} (t) c_{\alpha,0} (t)$$

$$- \sum_{\beta=\alpha} \Theta (\gamma_{\alpha,\beta} / \nu_{\alpha} (k_\alpha)) \Theta (t - \gamma_{\alpha,\beta} / \nu_{\alpha} (k_\alpha)) e^{i (k_\alpha \nu_{\alpha} - \nu_{\alpha}) t}$$

$$- \sum_{\beta=\alpha} \Theta (\gamma_{\alpha,\beta} / \nu_{\alpha} (k_\alpha)) \Theta (t - \gamma_{\alpha,\beta} / \nu_{\alpha} (k_\alpha)) e^{i (k_\alpha \nu_{\alpha} - \nu_{\alpha}) t}$$

$$= -\sum_{\beta=\alpha} \Theta (\gamma_{\alpha,\beta} / \nu_{\alpha} (k_\alpha)) \Theta (t - \gamma_{\alpha,\beta} / \nu_{\alpha} (k_\alpha)) e^{i (k_\alpha \nu_{\alpha} - \nu_{\alpha}) t}$$
It is important to note that for the timescales of our implementation, the hyperfine interaction between Rydberg states is negligible so that the nuclear spin $m_F$ behaves as a spectator in the dynamics.
\[ V^{(1)}_{dd} = \frac{d^{(1)} d^{(1)} - 3 (d^{(1)} n) (d^{(1)} n)}{r_{jl}^3}, \] (C.1)

where \( d^{(1)} \) is the dipole operator of atom \( j \). The projection of the dipole-dipole potential onto the Rydberg states manifold can be written as

\[ H_{int} = \frac{1}{2} \sum_{j=1}^{N} p V^{(1)}_{dd} p_j, \] (C.2)

with the projection operator \( P = \sum_{j=1}^{N} | j \rangle \langle j | \). Neglecting non-resonant processes (of the type \( S_{1/2} S_{1/2} \rightarrow P_{1/2} P_{1/2} \)), the Hamiltonian reduces to

\[ H_{int} = \sum_{j=1}^{N} c_j \hat{h}_{dd}(\theta_{jl}, \phi_{jl}) c_j, \] (C.3)

with the shorthand notation \( c_j = \{ [5]_{j} [3], [6]_{j} [3], [5]_{j} [4], [6]_{j} [4] \} \) and the \( 4 \times 4 \) matrix \( \hat{h}_{dd}(\theta_{jl}, \phi_{jl}) \) given by

\[ h_{dd}(\theta_{jl}, \phi_{jl}) = \begin{bmatrix}
  f_1(\theta_{jl}) & f_2(\theta_{jl}, \phi_{jl})^* & f_3(\theta_{jl}, \phi_{jl}) & -f_4(\theta_{jl}) \\
  f_2(\theta_{jl}, \phi_{jl}) & -f_1(\theta_{jl}) & -f_3(\theta_{jl}, \phi_{jl}) & f_4(\theta_{jl}) \\
  f_3(\theta_{jl}, \phi_{jl})^* & -f_2(\theta_{jl}, \phi_{jl}) & -f_1(\theta_{jl}) & f_4(\theta_{jl}) \\
  -f_4(\theta_{jl})^* & f_3(\theta_{jl}, \phi_{jl})^* & f_2(\theta_{jl}, \phi_{jl}) & f_1(\theta_{jl})
\end{bmatrix}, \] (C.4)

with \( f_1(\theta_{jl}) = (1 - 3 \cos^2 \theta_{jl}) / 9, f_2(\theta_{jl}, \phi_{jl}) = e^{i \phi_{jl}} \sin 2 \theta_{jl} / 6, f_3(\theta_{jl}, \phi_{jl}) = e^{2i \phi_{jl}} \sin^2 \theta_{jl} / 3 \).

Finally, an example for an excitation transfer process according to our dressing scheme is depicted in figure C1(b).

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