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Localization properties and high-fidelity state transfer in hopping models with correlated disorder

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ABSTRACT

We investigate a tight-binding chain featuring diagonal and off-diagonal disorder, these being modeled through the long-range-correlated fractional Brownian motion. Particularly, by employing exact diagonalization methods, we evaluate how the eigenstate spectrum of the system and how its related single-particle dynamics respond to both competing sources of disorder. Moreover, we report the possibility of carrying out efficient end-to-end quantum-state transfer protocols even in the presence of such generalized disorder due to the appearance of extended states around the middle of the band in the limit of strong correlations.

1. Introduction

In the past few decades, there has been a growing interest in investigating quantum transport properties of low dimensional disordered lattices [1–16], most of them based on Anderson scaling theory. In general lines, it is well established that there are no extended eigenstates in low-dimensional systems for any amount of uncorrelated disorder. The breakdown of standard Anderson localization theory was put forward about thirty years ago by Flores and Dunpap [17,18]. They pointed out that the presence of short-range correlations in the disorder distribution yielded the appearance of extended states in the spectrum of disordered chains. That could explain to a great extent some unusual transport properties of several types of polymers [17,18]. Right after this discovery, a handful of works came along to investigate the role of disorder correlations, either short- or long-ranged, in a wide variety of physical systems [19–40]. Particularly, it was shown in

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Refs. [19,21] that long-range correlated random potentials can actually allow for mobility edges in 1D disordered models. In Ref. [19], that specific kind of fluctuations was generated using the trace of a fractional Brownian motion whose intrinsic correlations decay following a power-law. Through numerical renormalization methods, it was show that this model exhibits a phase of extended states around the center of the band [19]. Tackling the same problem, the authors in [21] applied an analytical perturbation technique and came up with a direct relationship between the localization length and the characteristics of the intrinsic correlations in the disorder distribution. A few years later, the above results were validated through experiments carried out in microwave guides featuring correlated scatters [41]. The authors demonstrated that intrinsic long-range correlations within the scatters distribution ultimately improve the wave transmission. On the theoretical side, the Anderson model with long-range correlated hopping fluctuations (off-diagonal disorder) was studied in Refs. [20,32]. Likewise, it was found that strong correlations promote the appearance of a phase of extended states close to the center of the band.

In this work we provide further progress along those lines. In particular, we consider two sources of disorder acting simultaneously on the potentials as well as on the hopping strengths of the chain, both exhibiting long-range correlated fluctuations generated by the fractional Brownian motion. This model embodies a generalized disordered scenario which we aim to push on its capability of supporting extended states in the middle of the band thereby weakening Anderson localization. By looking at the participation ratio of eigenstates and also at the dynamics of the system through its mean square displacement for a delta-like initial state we find out that the chain allows for propagating modes if substantial long-range correlations are taking place in both sources of disorder. Looking forward possible applications in the field of quantum-information processing, we also investigate whether such a model of generalized disorder would allow for realizing standard quantum-state transfer protocols [42–49], particularly those relying on weak-coupled parties [44–46,48]. The point is that when designing chains for transmitting quantum states from one point to another – which is a crucial requirement in quantum networks [50] –one should take into account the possibility of undesired fluctuations taking place due to experimental errors [40,46,51–58], that including correlated noise [40,51,52,58]. Our calculations reveal that an electron (or a properly encoded qubit) can be almost fully transferred through the noisy bulk of the chain depending upon specific sets of parameters.

2. Model and formalism

We consider a N-site linear chain described by the electronic tight-binding Hamiltonian ($\hbar = 1$)

$$H = \sum_{n=1}^{N} \epsilon_n |n\rangle\langle n| + \sum_{n=1}^{N-1} J_n(|n\rangle\langle n+1| + \text{h.c.}), \tag{1}$$

written in the Wannier basis set $\{|n\rangle\}$ accounting for the electron position, where ϵ_n is the on-site potential and J_n is the hopping strength, those being the source of static disorder. Those parameters are here expressed in terms of energy unit $J \equiv 1$. Specifically, we assume that both quantities fluctuate such that their corresponding disorder distributions come with intrinsic long-range correlations modeled via the fractional Brownian motion [19,22,24,25]

$$\epsilon_n, J_n = \sum_{k=1}^{N/2} \frac{1}{k^{\gamma/2}} \cos\left(\frac{2\pi nk}{N} + \phi_k\right). \tag{2}$$

We emphasize that the sequence generated by the equation above exhibits a power-law spectrum $1/k^{\gamma}$ and ϕ_k represents a random phase uniformly distributed within the range $[0, 2\pi]$. For $\gamma = 0$, the sequence is fairly uncorrelated. On the other hand, $\gamma > 0$ brings about long-range correlations in the disorder sequence. Therefore, exponent γ stands out as a very important parameter since it controls the *degree* of correlations within the disordered sequence. Hereafter, Eq. (2) will be used for generating disorder distributions for both ϵ_n and J_n but with a few remarks: (i) for ϵ_n we attribute $\gamma \to \alpha$ and normalize the entire sequence so that $\langle \epsilon_n \rangle = 0$ and $\langle \epsilon_n^2 \rangle = 1$; (ii) for J_n we set $\gamma \to \beta$ and