Non-Markovian effects in waveguide-mediated entanglement between qubits

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Abstract

During last years, intense efforts have been made to control and tailor the coupling between quantum emitters and the electromagnetic field. One of the areas in which this research is very promising is quantum information, where quantum entangled states of two emitters (or qubits) are the basis of quantum cryptography, quantum teleportation and other quantum operations. Short-distance entanglement is available in many optic, atomic, and molecular systems. However, for information transmission purposes, it is necessary to entangle emitters separated by a long distance. In order to achieve this goal, and also to control the field-matter interaction, waveguides arise as a very promising system. Their broader band for Purcell enhancement, the high beta factors, and the low dimensionality allow to have strong photon-qubit interaction in a similar way as cavity QED. Moreover, waveguides offer interesting possibilities such as entangling photons via evanescent coupling. Finally, the fact that photons are directly usable (in opposition to cavity systems) suggests that these systems are good candidates for the design and implementation of circuit QED devices.

Recently, long distance entanglement between two qubits mediated by surface plasmon polaritons in a one-dimensional plasmonic waveguide (Fig. 1) has been reported [1]. It has been shown that, for specific distances between qubits, a collective symmetric / antisymmetric entangled configuration can be practically decoupled from the dynamics of the rest of states, thus giving rise to very small decay rates. This results in a long lifetime of the entangled state, even if the beta factor associated with the waveguide is smaller than unity. The dependence of the coupling parameters with the inter-qubit distance makes it possible to tune the degree of entanglement desired.

The above mentioned calculations are based in a density matrix formalism, which is widely used in quantum optics. This method traces out the electromagnetic degrees of freedom within the Markovian approximation. In this work [2] we present a complete QED solution of the hamiltonian, which allows us to study the system outside the Markovian regime. In the real space formalism we use [3], the photonic degrees of freedom are also considered in the dynamics. This is a key feature for quantum plasmonics purposes, as intrinsically photonic properties such as nonclassical correlations could now be calculated. In our study, we obtain a new branch of quasi-localized eigenstates which plays a key role in the time evolution of the qubit populations. With this complete solution we are able to recover the Markovian results for low qubit-waveguide coupling [Fig. 2 (a)]. Our results show, however, that Markov approximation is not valid when the qubit-waveguide coupling is increased. The one-dimensional character of the system makes it to be non-Markovian in this regime, as photons undergo sucessive reflections between both qubits. In contrast to what intuition suggests, a stronger coupling between qubits and guided photonic modes decreases the role of the collective effects, as well as the entanglement properties [Fig. 2 (b)].

Our results show that the dynamics of this system evolves from collective evolution in the Markovian regime to single-qubit evolution for high waveguide-qubit coupling. By modifying either the inter-qubit separation or the waveguide-qubit coupling, we can change from one regime to another, thus controlling the evolution of the qubit states. This control of the degree of entanglement may be useful for circuit QED purposes, and also to study strong light-matter interaction phenomena.

References

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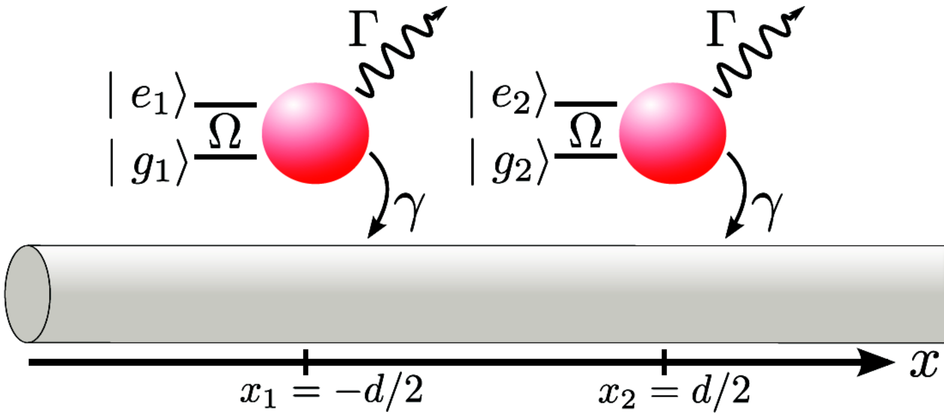

Figure 1. *Sketch of the system under study. Two qubits with frequency Ω are placed near a waveguide, coupled to it through an energy γ, and emitting to free space modes at a rate Γ.*

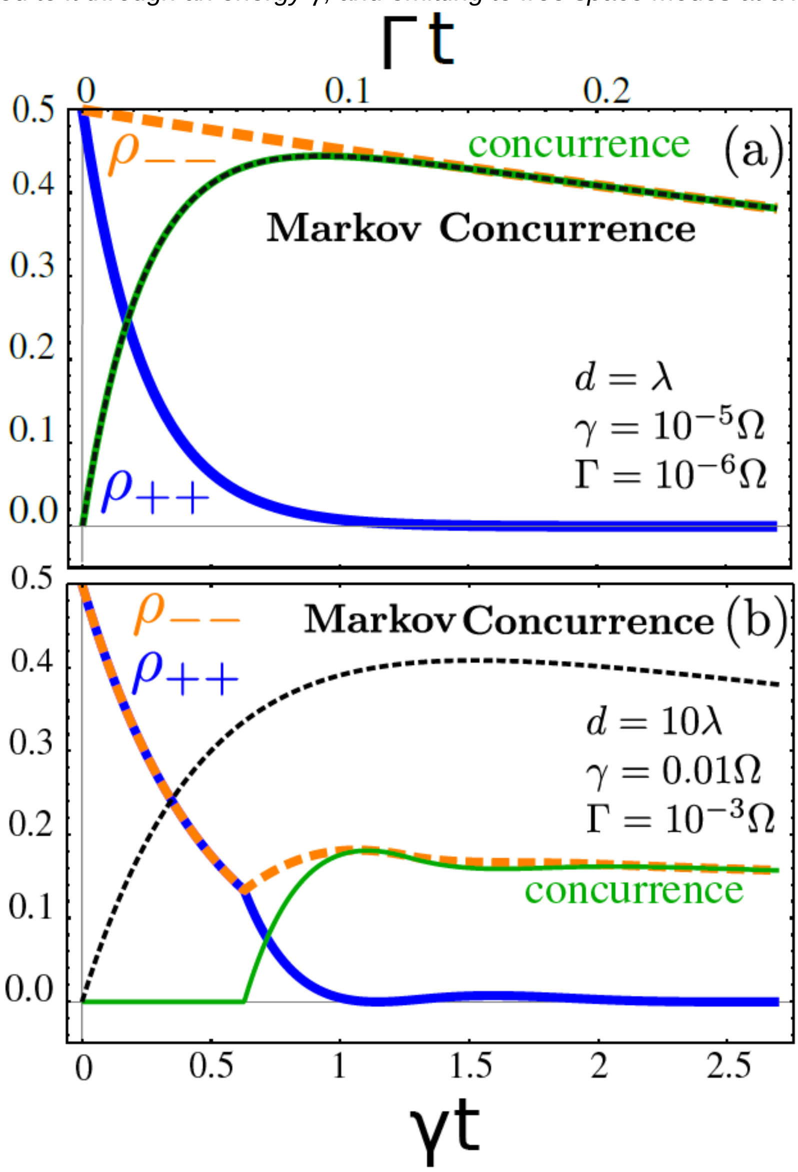

Figure 2. *Time evolution of the populations of the entangled symmetric (+) and antisymmetric (-) states, and the corresponding concurrence. a) Markovian regime. b) Non-Markovian regime.*