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Simulations of effective Hamiltonians to study the effects of non-computational levels of two coupled qubits via a cavity bus

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<h3>Abstract</h3>

Superconducting quantum circuits stand out as a prominent platform for quantum computers. The most diffused qubit design is the transmon qubit, a type of charge qubit that operates at a significantly different ratio of Josephson energy (E_J) to charging energy (E_C). This unique feature exponentially reduces the sensitivity to $1/f$ charge noise without increasing the sensitivity to other noise sources. Nonetheless, the transmon limit decreases, with a slow power law in E_J/E_C, the anharmonicity that is necessary to prevent qubit operations from exciting non-computational levels.

Although single-qubit operations are well established, two-qubit gates demand greater design, precision, and control. Various architectures have been explored to facilitate these operations: transmon qubits interconnected via capacitive coupling are constrained to local interactions, limiting coupling to nearest-neighbor qubits. A more reliable solution lies in implementing a cavity bus, a distributed circuit element enabling non-local coupling among multiple qubits. However, when qubits are connected, always-on parasitic interactions affect the fidelity of multi-qubit gates. In addition, the small anharmonicity of the transmon regime can cause transitions between computational and non-computational levels to be inevitable. Sometimes, this interaction is wanted and should be strengthened to perform the desired entanglement. Most of the time it is unwanted and sets limits to the error correction algorithms. More precisely, the parasitic interaction accumulates phase error in the computational states and eventually destroys the multi-qubit gates. Therefore, it must be carefully suppressed during the gate operations. Particularly, the parasitic ZZ interaction between a pair of transmon qubits is a limiting factor for two-qubit gates and quantum error correction. Although the ZZ interaction is always one or two orders of magnitude weaker than the coupling strength, it degrades the performance of many quantum gates.

One of the objectives of the Qub-IT project is the development of a chip with two coupled qubits via a cavity bus. To reach this goal, a preliminary study of the case is conducted to identify optimal parameters for the chip design to reduce the known parasitic effects due to the presence of non-computational levels of each transmon. We performed several simulations using QuTiP, an open-source software for simulating the dynamics of open quantum systems, to model the circuit Hamiltonian. These simulations exploit a perturbative method known as the Schrieffer-Wolff transformation, which helps to decouple lower-energy dynamics from higher-energy degrees of freedom through a unitary transformation, resulting in an effective Hamiltonian. Starting from this Hamiltonian, studies of the parameters of interest such as transmon and cavity frequencies, anharmonicities, coupling constants, etc. are performed to minimize these parasitic effects.

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Abstract category

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