ZZ coupling simulations of two coupled qubits

Joint Qub-IT PNRR May meeting – 13/05/2024

Marco Gobbo - University of Milano-Bicocca

H. Corti, D. Labranca, R. Moretti, A.S. Piedjou Komnang, S. Tocci, L. Banchi, A. Giachero, C. Gatti

Two qubit gate schemes

Two-qubit gates are logical operations that allow entangling the state of two qubits. In the field of superconducting devices, these types of gates are implemented by applying **RF pulses** and/or **flux pulses** to the qubits.

Several two-qubit gate schemes have been explored and they can be grouped into **three categories**:

Flux tunable

Short gate time (30 – 150 ns)
Exposing the qubits to flux noise

All-microwave control

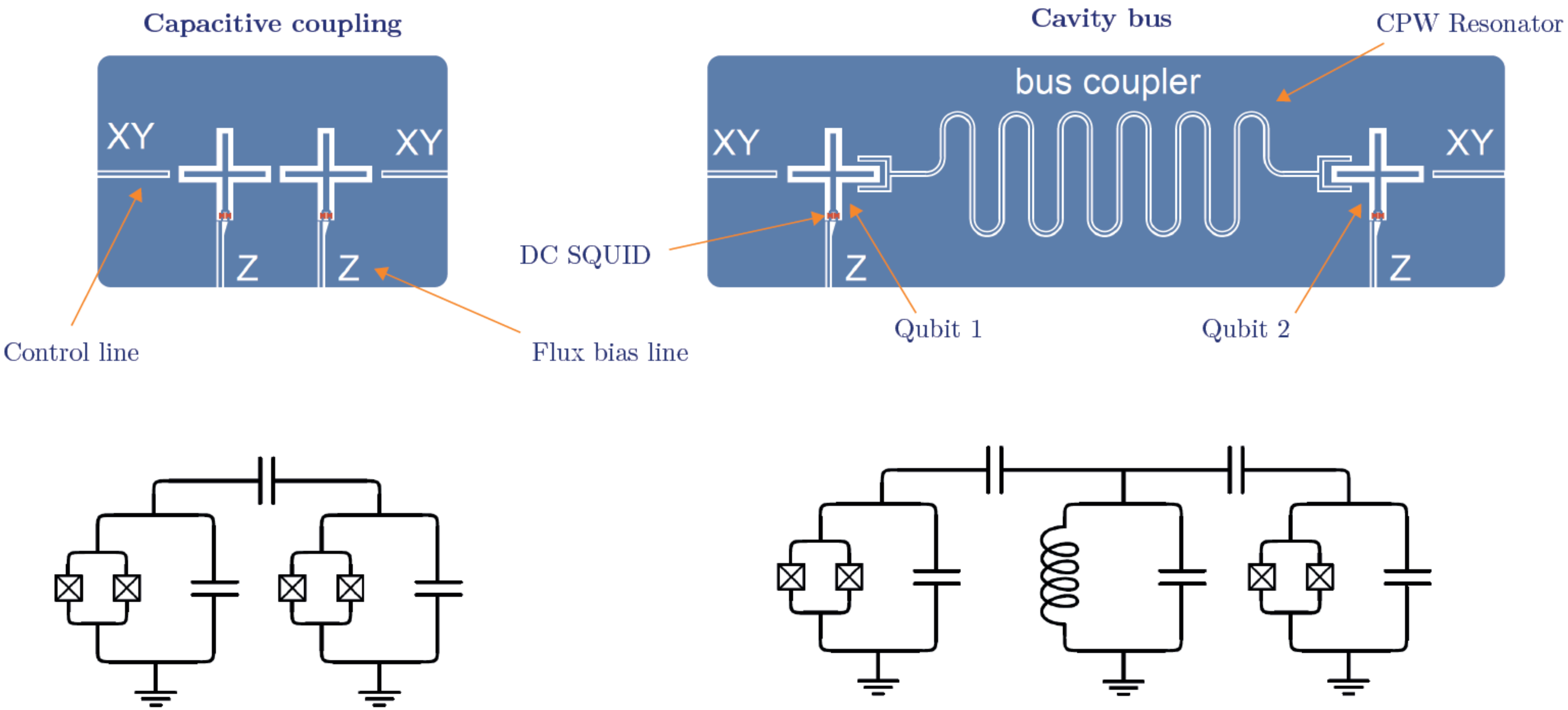
No flux bias lines
No tunable qubits
Long gate time (150 – 300 ns)
Accurate fabrication of JJ
Frequency crowding problem

Tunable couplers

Reduce the gate time
Mitigate the frequency crowding problem
Intensify the ZZ coupling

Two qubit gate schemes

To perform a two-qubit gate between a pair of superconducting qubits, the qubits are coupled together through a **capacitive coupling** or via a **cavity bus**.



Coupling via cavity bus

The coupling of superconducting qubits mediated by a microwave resonator, typically a **half-wave coplanar waveguide resonator** (CPW), is currently the most widespread coupler in large-scale quantum processors. One of the main advantages is the possibility of **coupling non-nearest neighbour qubits**. In the **dispersive regime**, there is no energy exchange between the qubits via the resonator. Nonetheless, the qubit frequency shifts when the neighbor is excited.

By exploiting the **Schrieffer-Wolff transformation** is possible to diagonalize the full system Hamiltonian

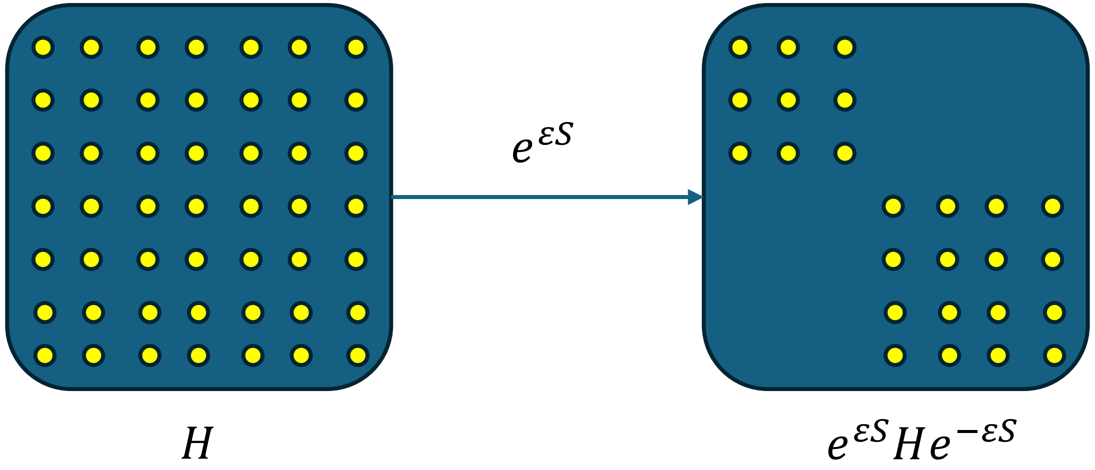
$$H/\hbar = -\frac{\widetilde{\omega}_1}{2}\sigma_z \otimes \mathbb{I} - \frac{\widetilde{\omega}_2}{2}\mathbb{I} \otimes \sigma_z + \frac{\zeta}{4}\sigma_z \otimes \sigma_z$$

where $\widetilde{\omega}_1$and $\widetilde{\omega}_2$ are the *renormalized qubit* frequencies and the **ZZ coupling** is given by

$$\zeta \approx 2g^2\left(\frac{1}{\Delta - \alpha_2} - \frac{1}{\Delta - \alpha_1}\right)$$

The ZZ coupling can be either positive or negative depending on the **qubit frequencies** and **anharmonicities** and if the ZZ coupling is large, this state-dependent frequency shift significantly degrades the performance of simultaneous single-qubit gates.

Schrieffer-Wolff transformation



$$H = H_0 + \varepsilon H_I$$

$$e^{\varepsilon S} H e^{-\varepsilon S}$$

$$e^{\varepsilon S} H e^{-\varepsilon S} = H + \varepsilon[S, H] + \frac{\varepsilon^2}{2}\big[S, [S, H]\big] + O(\varepsilon^2) = H_0 + \varepsilon(H_I + [S, H_0]) + \frac{\varepsilon^2}{2}\big(2[S, H] + \big[S, [S, H_0]\big]\big) + O(\varepsilon^2)$$

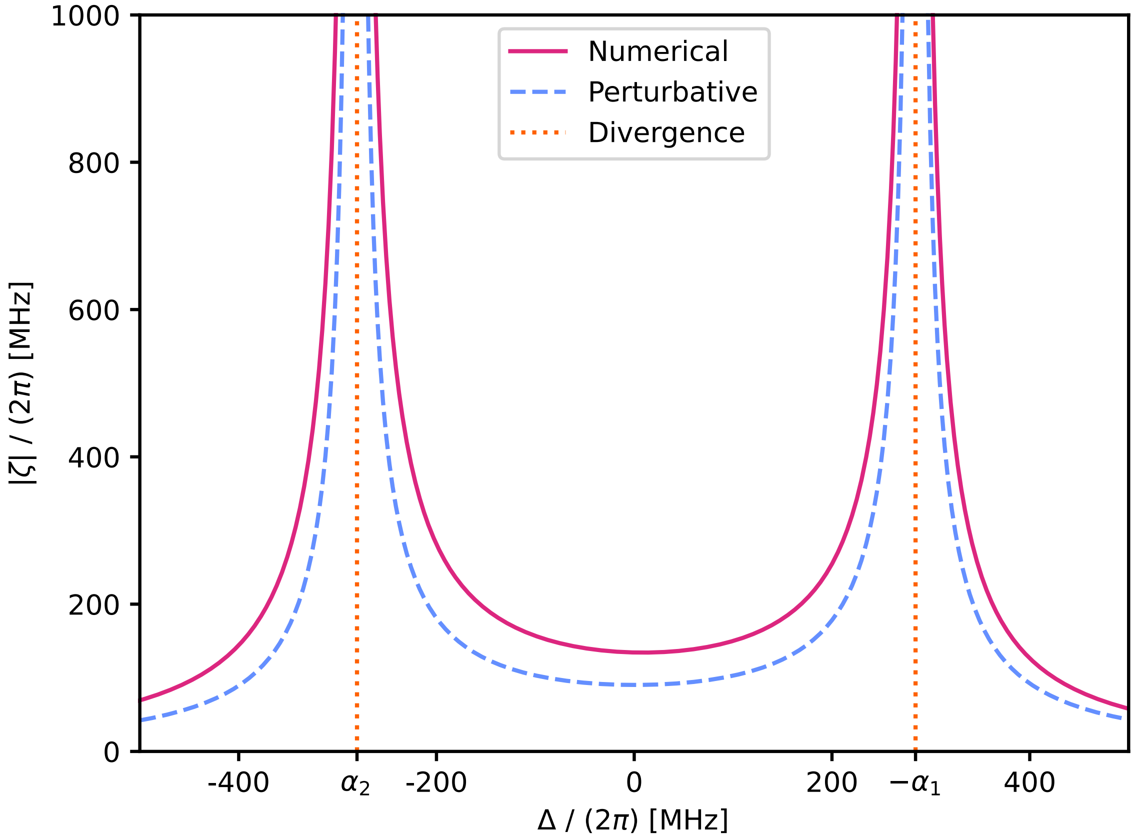
$$H_I + [S, H_0] = 0$$

$$e^{\varepsilon S} H e^{-\varepsilon S} = H_0 + \frac{\varepsilon^2}{2}[S, H_I] + O(\varepsilon^2)$$

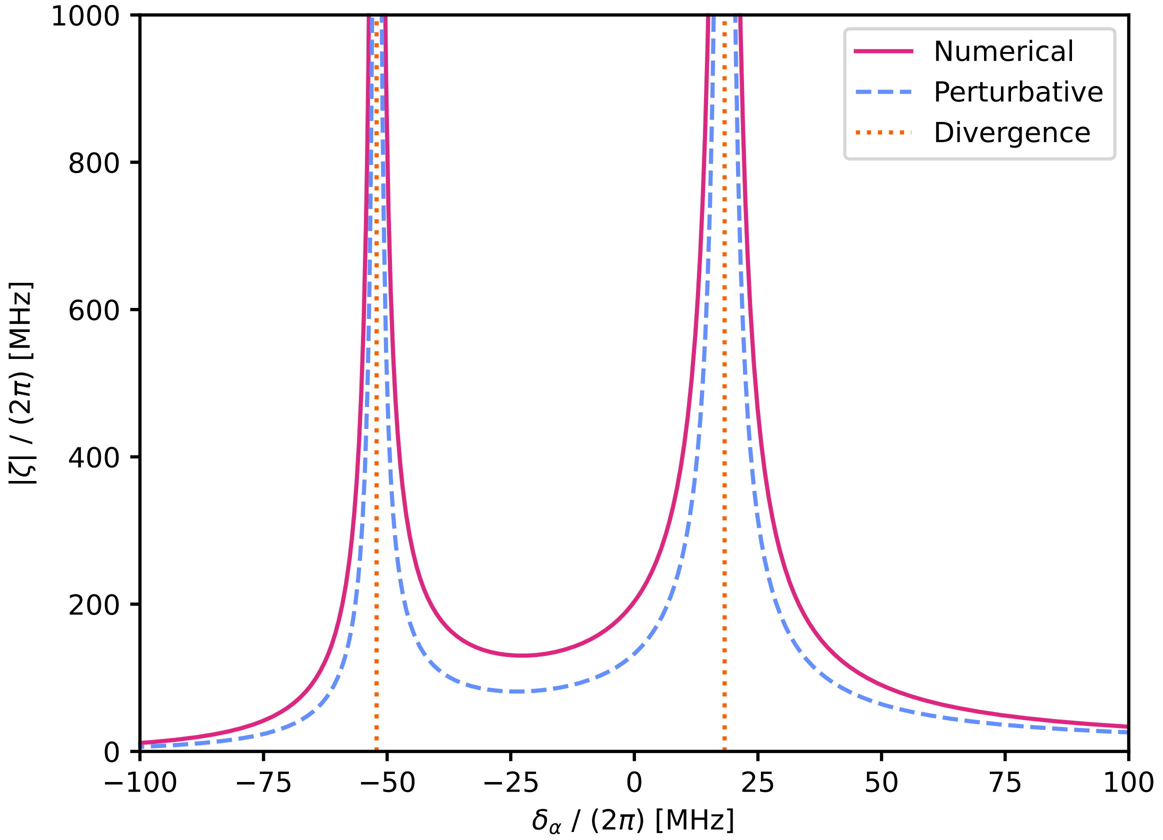
$$H_{eff} = P\left(H_0 + \frac{\varepsilon^2}{2}[S, H_I]\right)P$$

Capacitance coupling

$\Delta = \omega_1 - \omega_2$

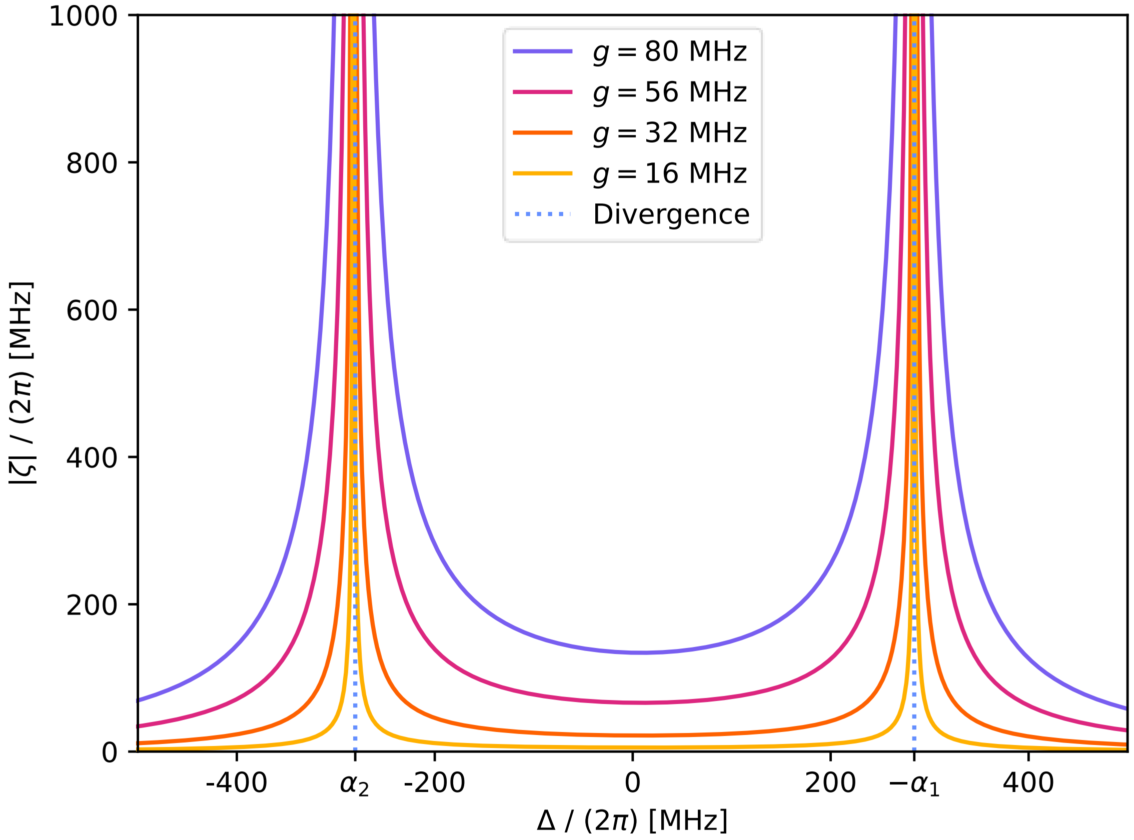


$\delta_\alpha = |\alpha_2| - |\alpha_1|$



Capacitance coupling

$\Delta = \omega_1 - \omega_2$



$\delta_\alpha = |\alpha_2| - |\alpha_1|$