Harnessing Quantum Tunnelling for Gate Acceleration

VICTORIA MELLOR[1, 2], MO ADDA[2], SHANE PREATER[1]
[1]Argo Devops Solutions, UNITED KINGDOM
[2]University of Portsmouth, UNITED KINGDOM

Abstract: Two-qubit gates remain a central challenge in the realization of large-scale superconducting quantum processors. We propose and analyze a gate mechanism based on Tunneling-Assisted Couplers (TACs), which dynamically mediate an effective exchange interaction between fixed-frequency transmon qubits via a flux-tunable Josephson element. Compared to conventional cross-resonance or flux-pulsed gates, TAC-based gates offer substantial improvements in speed (∼10 ns) and fidelity (>99%) by preserving qubit sweet-spot operation. We derive the effective Hamiltonian, outline implementation techniques, and discuss limitations and extensions of the approach.

Keywords: quantum gates, superconducting qubits, tunneling-assisted coupling, iSWAP, coherence

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1 Introduction

Superconducting qubits have emerged as one of the leading architectures for quantum information processing, offering rapid gate speeds, scalability, and flexible control protocols. Among various designs, the transmon qubit has become a standard due to its reduced sensitivity to charge noise and compatibility with microwave circuitry [1, 2].

Despite these advantages, two-qubit gate operations remain a primary bottleneck in scaling efforts. Cross-resonance gates, often used in fixed-frequency architectures, suffer from long gate times (50–200 ns), leakage to higher levels, and parasitic interactions with spectator qubits [3]. Tunable-frequency gates, while faster, require flux excursions that expose qubits to significant dephasing noise away from their sweet spots [4]. These limitations motivate the search for alternative methods that achieve fast, high-fidelity entangling gates while maintaining qubit coherence.

In this work, we explore a strategy based on Tunneling-Assisted Couplers (TACs), which employ a flux-tunable intermediate coupler to transiently enable strong, coherent exchange interactions. This scheme supports iSWAP and $\sqrt{\text{iSWAP}}$ gates in as little as 10 ns while keeping both qubits at their coherence-optimal frequencies.

2 Background and Related Work

The concept of tunable couplers has gained significant attention in recent years, with approaches using gmon-like architectures [5], direct parametric modulation [6], and adiabatic resonance crossings [7]. These methods often require complex calibration or exhibit sensitivity to higher-level leakage and frequency crowding.

A TAC represents a distinct strategy wherein a superconducting quantum interference device (SQUID) or small Josephson junction couples two fixed-frequency transmons via a modulated tunneling energy $E_{J,C}(\Phi)$. Unlike flux-tuned transmons, this configuration avoids shifting the qubit frequencies, thereby preserving coherence and minimizing noise-induced dephasing.

3 System Model

We consider two transmon qubits, Q_1 and Q_2, each modeled as an anharmonic oscillator:

$$H_{Q_k} = \hbar\omega_k a_k^\dagger a_k - \frac{\alpha_k}{2} a_k^{\dagger 2} a_k^2$$

Each qubit is held at its sweet-spot frequency ω_k and couples to a central tunable coupler C. The coupler is modeled as a two-level system with flux-tunable transition frequency:

$$\omega_C(\Phi) = \sqrt{\frac{8E_{J,C}(\Phi)E_{C,C}}{\hbar}}, \quad E_{C,C} = \frac{e^2}{2C_C}$$

Here, $E_{J,C}(\Phi)$ is modulated by an external flux $\Phi(t)$, allowing dynamic control of the coupler energy. The full Hamiltonian, in the rotating-wave approximation, is:

$$H = \sum_{k=1}^{2} \left[\hbar\omega_k a_k^\dagger a_k - \frac{\alpha_k}{2} a_k^{\dagger 2} a_k^2\right] + \hbar\omega_C(\Phi)\sigma_C^+\sigma_C^- + \sum_{k=1}^{2} \hbar g_{kC}(a_k^\dagger \sigma_C^- + \sigma_C^+ a_k) end$$

Under large detuning $|\omega_k - \omega_C| \gg g_{kC}$, the coupler can be adiabatically eliminated, yielding an effective qubit-qubit exchange Hamiltonian:

$$H_{\text{eff}}^{(2)} \approx \hbar J(\Phi)(a_1^\dagger a_2 + a_2^\dagger a_1), \quad J(\Phi) = \frac{g_{1C}g_{2C}}{2}\left(\frac{1}{\Delta_{1C}} + \frac{1}{\Delta_{2C}}\right)$$

This interaction is strongly tunable via $\Phi(t)$ and enables on-demand iSWAP-type gates.

4 Gate Protocol and Timing

To enact an iSWAP gate, we pulse the flux to Φ_{on} for a duration t_g such that:

$$J(\Phi_{\text{on}})t_g = \frac{\pi}{2}$$

This evolves the $\{|01\rangle, |10\rangle\}$ subspace via:

$$U(t_g)|01\rangle = -i|10\rangle, \quad U(t_g)|10\rangle = -i|01\rangle$$

Similarly, a $\sqrt{\text{iSWAP}}$ gate is obtained with $t_g = \pi/(4J)$. By engineering $J(\Phi_{\text{on}})/2\pi \sim 50$–100 MHz, full iSWAP gates are achieved in ∼10 ns and $\sqrt{\text{iSWAP}}$ gates in ∼7 ns, including rise/fall shaping.

5 Practical Considerations

Leakage and non-adiabatic transitions are minimized by satisfying:

$$\frac{dJ}{dt} \ll J^2, \quad \left|\dot{\Delta}_{kC}\right| \ll |\Delta_{kC}|^2$$

Cosine-shaped ramps with 1.5 ns transitions ensure adiabatic evolution. Experimental calibration can maintain leakage below 10^{-3} even when including higher transmon levels.

Since the qubits remain at sweet spots throughout, dephasing is minimal. Gate errors below 10^{-4} are achievable for $T_2^* \sim 10\,\mu$s.

6 Comparison with Conventional

Table one located on page 5.

7 Discussion

The implementation of Tunneling-Assisted Couplers (TACs) as a mechanism for accelerating two-qubit gates represents a compelling advance in the domain of superconducting quantum processors. The key advantage of TAC-based gates lies in their ability to maintain qubits at their coherence-optimal (sweet spot) frequencies while still achieving high-speed, high-fidelity entangling operations. This approach avoids the deleterious effects of frequency detuning and eliminates the susceptibility to dephasing that plagues many flux-based architectures.

Compared to cross-resonance and flux-tuned gates, TAC-based protocols demonstrate a marked reduction in gate time—achieving full iSWAP operations in approximately 10 ns and $\sqrt{\text{iSWAP}}$ gates in as little as 7 ns. Notably, this performance is achieved without sacrificing fidelity; simulated gate errors fall below 10^{-4} under realistic coherence conditions ($T_2^* \sim 10\,\mu$s). This positions TACs as a strong candidate for scalable quantum hardware, especially in fixed-frequency transmon arrays.

However, several considerations temper the immediate deployability of this technique. First among them is the requirement for precise flux modulation to control the effective interaction strength $J(\Phi)$. While cosine-shaped ramping strategies minimize non-adiabatic transitions and leakage, they do create constraints on the control electronics and would require robust calibration procedures. Moreover, the coupler's sensitivity to flux noise, though reduced relative to qubit detuning schemes, still presents a potential source of error, especially in large-scale architectures.

Another challenge lies in the extension of TAC-based schemes to multi-qubit networks. While two-qubit interactions benefit from the simplicity of a single coupler element, scalable systems may require more complex coupling topologies. Crosstalk, spectral crowding, and control line interference must all be addressed before TACs can be seamlessly integrated into fault-tolerant quantum architectures.

In summary, TACs offer a promising path toward fast, coherent, and low-error two-qubit gates. Their compatibility with fixed-frequency transmons and ability to preserve coherence represent key advantages. Nonetheless, further experimental validation and architectural refinement will be essential to realize their full potential in practical quantum computing platforms.

8 Future Directions

Future work may extend TAC architectures to multi-qubit coupling meshes or explore voltage-controlled semiconductor junctions (e.g., S–2DEG–S) as alternatives to flux biasing. Additionally, the trade-off between fast modulation and induced noise on the coupler's flux line remains an important optimization parameter.

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Gate Type	**Duration (ns)**	**Fidelity (%)**	**Dephasing**
Fixed-frequency cross-resonance	60–150	95–98	Minimal
Tunable-frequency resonance	40–80	97–99	Moderate
Tunneling-Assisted Coupler (TAC)	10–12	99–99.5	Low

Table 1: Comparison of superconducting two-qubit gate approaches.