

Evaluating State Dynamics of Multi-Qubit Superconducting Circuit Quantum Devices through Maxwell-Schrödinger Modeling

Ghazi Khan⁽¹⁾ and Thomas E. Roth^{(1),(2)}

⁽¹⁾ Elmore Family School of Electrical and Computer Engineering, Purdue University, Indiana 47906, USA

⁽²⁾ Purdue Quantum Science and Engineering Institute, Purdue University, Indiana 47907, USA

Quantum computers are a revolutionary technology that promises to utilize quantum effects in order to achieve an unprecedented level of performance boost over traditional computers. While this technology has made great strides in achieving the so-called “quantum advantage” there are significant engineering challenges that must be resolved before these systems can be used for practical applications. Chief among these challenges is the need to develop efficient modeling strategies for simulating quantum circuit initialization, control, and readout. Existing approaches often fall short due to their inefficient use of full-wave computational electromagnetics tools or reliance on labor-intensive curve-fitting methods—both unsuitable for the extensive scaling required to model useful quantum devices. In this work, we extend previous Maxwell-Schrödinger modeling techniques (T. E. Roth and S. T. Elkin, “Maxwell-Schrödinger Modeling of a Superconducting Qubit Coupled to a Transmission Line Network,” *IEEE Journal on Multiscale and Multiphysics Computational Techniques*, vol. 9, Jan. 2024) to simulate coupled superconducting transmon qubits embedded in transmission line networks. Coupled qubits are critical components of quantum devices, enabling multi-qubit gates that generate entanglement—a fundamental requirement for practical quantum algorithms. Our method specifically addresses transmon qubits operating in the dispersive regime, where the resonator frequency is far detuned from the qubits’ transition frequencies. Starting from the self-consistent equations of motion presented in the original work, we extend the framework by incorporating the multi-qubit exchange coupling rate. This parameter, which characterizes quantum effects necessary for intentional multi-qubit gates and the assessment of unintentional quantum crosstalk, can be efficiently calculated using our prior formulation (G. Khan and T. E. Roth, “Field-Based Formalism for Calculating Multiqubit Exchange Coupling Rates for Transmon Qubits,” *Phys. Rev. Applied*, vol. 22, 064084, Dec. 2024). This formula depends on the impedance response of the superconducting quantum circuit, which is particularly advantageous because impedance responses are straightforward to calculate using classical electromagnetic tools. We apply this methodology to simulate realistic quantum circuit topologies commonly found in the literature, showcasing fundamental operations such as the cross-resonance (CR) gate (C. Rigetti and M. Devoret, “Fully Microwave-Tunable Universal Gates in Superconducting Qubits with Linear Couplings and Fixed Transition Frequencies,” *Physical Review B*, vol. 81, 134507, Apr. 2010). By employing this approach, we demonstrate the capability to model complex multi-qubit interactions, while also highlighting the critical role of self-consistent interactions in the Maxwell-Schrödinger framework. These interactions can significantly impact the state dynamics of the qubits and therefore are essential for achieving precise control and robust gate fidelity, which are necessary for practical quantum computation.