Dynamics of Open Quantum Systems Revisited: From Non-Markovianity to Efficient Many-body Simulations

Meng Xu, Jürgen T Stockburger, and Joachim Ankerhold

Institute for Complex Quantum Systems, Ulm University, Albert-Einstein-Allee 11, 89069 Ulm, Germany

Recent advances in quantum technologies have triggered the need for highly accurate, versatile, and computationally efficient simulation techniques for the dynamics of open quantum systems. Long-lived system-reservoir correlation effects and the necessity for high precision beyond the Born-Markov approximation form particular challenges. Approaches to meet these challenges have been introduced, originating from different fields, such as hierarchical equations of motion, Lindblad-pseudomode formulas, chain-mapping approaches, quantum Brownian motion master equations, stochastic unravelings, and refined quantum master equations.

This diversity, while indicative of the field's relevance, has inadvertently led to a fragmentation that hinders cohesive advances and their effective cross-community application to current problems for complex systems. How are different approaches related to each other? What are their strengths and limitations? Here we give a systematic overview and concise discussion addressing these questions. We make use of a unified framework [1] which very conveniently allows to link different schemes and, this way, may also catalyze further progress. In line with the state of the art, this framework is formulated not in a fully reduced space of the system but in an extended state space which in a minimal fashion includes effective reservoir modes. This in turn offers on the one hand a comprehensive understanding of an entire class of existing methods and on the other hand a very efficient and versatile platform for many-body simulations with long-time stability [2-5].

[1] Meng Xu, V. Vadimov, J. T. Stockburger, and J. Ankerhold, Rev. Mod. Phys., Colloquium, in press, doi.org/10.1103/w3nw-hbjc

[2] Meng Xu, Yaming Yan, Qiang Shi, J. Ankerhold, J. T. Stockburger, Phys. Rev. Lett. 129, 230601 (2022)

[3] Meng Xu, J. T. Stockburger, and J. Ankerhold, J. Chem. Phys. 161, 124105 (2024)

[4] K. Nakamura and J. Ankerhold, Phys. Rev. Res. 6, 033215 (2024)

[5] K. Nakamura and J. Ankerhold, Phys. Rev. Res., in press, arXiv:2510.05872v1