Exhaustive analysis on the role of quantumness in quantum reservoir computing

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The potential for future quantum technologies is fuelled by quantum resources which are the quantum coherence and the triad of many-body non-classical correlations: entanglement, Einstein-Podolsky-Rosen (EPR) steering and the Bell nonlocality.

One of the most promising avenues in utilizing quantumness for computational tasks is the concept of a Quantum Reservoing Computing (QRC) [1, 2] which offers a promising method for tackling machine learning problems using quantum systems. Noteworthy for its minimal training requirements [3], QRC stands out as a novel paradigm in quantum machine learning (QML), providing an alternative to traditional approaches where trainability issues may undermine the effectiveness of quantum strategies [4]. By leveraging the extensive degrees of freedom in quantum many-body systems, QRC is expected to outperform classical methods [5]. Consequently, it has emerged as a strong candidate for developing practical QML algorithms that can be implemented with current quantum devices[6]. However, attributing the efficacy of QRC solely to the vast dimensionality of the space it addresses is insufficient. The performance of QRC is likely influenced by a variety of intrinsic quantum properties inherent to quantum many-body systems. In particular, the impact of the dynamical regime of the quantum many-body system on QRC performance has been studied[7] as well as the input-output nonlinearities present for different encoding strategies[8, 9]. Recent developments have also explored the roles of entanglement and phase space dimension in QRC performance[10], different particle statistics[11], and the use of an engineered dissipation to increase the QRC capabilities[12].

In this work, we consider two previously unexplored features within this framework. First, we build upon previous analyses by incorporating a more realistic scenario that includes the a priori *unwanted* quantum effect of backaction, namely, the direct influence on the state of a system when it is measured. Second, we take initial steps to understand the role of Bell correlations within this framework. By addressing these intrinsically quantum features, we aim to provide a deeper understanding of the factors influencing QRC performance.

Previous works have primarily focused on what can be considered positive quantum properties. For instance, in [7], the authors demonstrated that QRC achieves maximal performance near the transition between localized and ergodic dynamical regimes. They examined various realizations of these regimes by adjusting local disorder and the transverse field in the transverse field Ising Hamiltonian. This can be understood as follows: in a highly localized regime, each spin behaves independently, preventing information spread due to the existence of local conserved quantities, while in a highly ergodic regime, the system has delocalized global properties. Therefore, the optimal quantum properties, characterized by the richness of degrees of freedom and the ability to spread information, are found near the transition between these two regimes in the more quantum regime. Another interpretation, presented in [10], focused on a smaller portion of the parameter space. This study linked performance to both the entanglement within the system and the explored phase space dimension ratio. Extending this interpretation to the full parameter space supports the conclusion that optimal QRC performance is associated with maximal display of these quantum properties. However, the assumption that *more quantum is better* is challenged when negative quantum effects are introduced. In [13], a practical online protocol for implementing QRC using weak measurements was proposed. In this framework, each time-step measurement introduces a backaction effect on the system, dependent on a coupling factor g, between the system and the measurement apparatus. These indirect measurements have already been implemented by using ancillary qubits [6].

On one hand, our analysis focus on studying the unseen impact of combined quantum effects that were separately considered as positive or negative for increasing the performance of QRC. To illustrate this, we consider the spin network modelled by a transverse-field Ising model studied in [13] to explore the whole possible regimes that could arise when both the Hamiltonian parameters and the measurement strength are tunable. For instance, in the color plots of Fig. 1 we depict the forecasting capacity of our QRC spin system depending on these two parameters. Unexpectedly in the left panel, we show that there is a wide region between $h_0 = 10^{-1}$ and $h_0 = 10$ where changing the measurement strength is not detrimental neither affecting the performance of the system, even for large g values corresponding to projective measurements. However, in practical scenarios, with a finite number of measurement repetitions, depicted in the right panel of Fig. 1, the associated noise hinders the capacity to make good predictions in that regime of parameters.

On the other hand, we want to provide a general analysis of QRC besides the specfic model and task described above. In particular, we aim to characterize the role of many-body entanglement, and many-body Bell correlations in the overall QRC framework. Our work is motivated by the recent boost in systematic generation of massively correlated many-body quantum states in analog quantum simualtors, including optical lattices, Rydberg tweezer arrays or ions trap [14, 15]. We focus on characterizing the amount of quantum resources, including depth of many-body entanglement, needed to see advantage over single-particle based QRC. To this aim, we are currently developing a more general framework based on the calculation of quantum Bell correlations, which can be applied to QRC based on different quantum technologies.

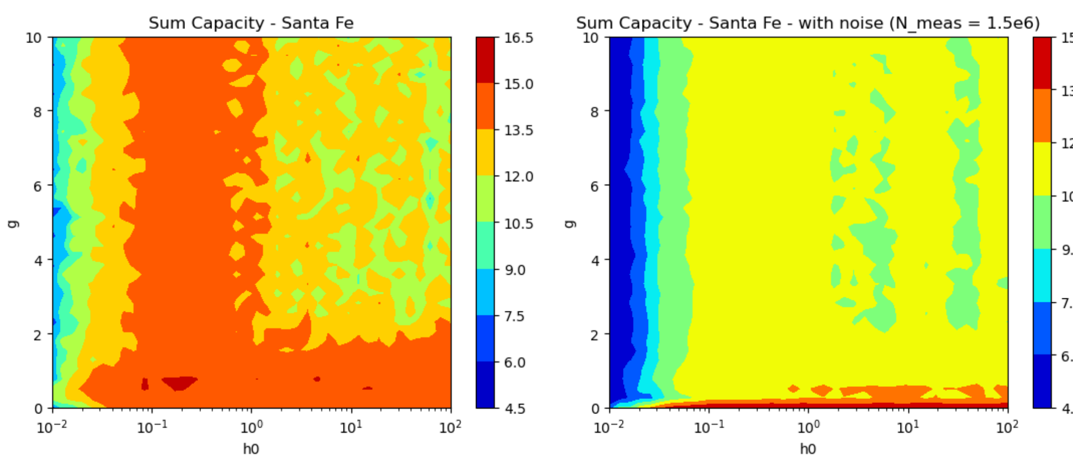

Figure 1: Forecasting capacity of a QRC consisting of a spin network for the Santa-Fe stochastic time series depending on the measurement strength, g, and the magnetic field, h_0, for a transversfield Ising model (see Ref.[13] for details on the definitions). In the left panel, we show the ideal capacity without shot noise, whereas on the right the case with shot noise corresponding to 1.5 million shots per time step is depicted.

References

[1] Keisuke Fujii and Kohei Nakajima. Harnessing disordered-ensemble quantum dynamics for machine learning. *Phys. Rev. Applied*, 8:024030, Aug 2017.

[2] Pere Mujal, Rodrigo Martínez-Peña, Johannes Nokkala, Jorge García-Beni, Gian Luca Giorgi, Miguel C Soriano, and Roberta Zambrini. Opportunities in quantum reservoir computing and extreme learning machines. *Advanced Quantum Technologies*, page 2100027, 2021.

[3] Gouhei Tanaka, Toshiyuki Yamane, Jean Benoit Héroux, Ryosho Nakane, Naoki Kanazawa, Seiji Takeda, Hidetoshi Numata, Daiju Nakano, and Akira Hirose. Recent advances in physical reservoir computing: A review. *Neural Networks*, 115:100–123, 2019.

[4] Han Qi, Lei Wang, Hongsheng Zhu, Abdullah Gani, and Changqing Gong. The barren plateaus of quantum neural networks: review, taxonomy and trends. *Quantum Information Processing*, 22(12):435, Dec 2023.

[5] W. D. Kalfus, G. J. Ribeill, G. E. Rowlands, H. K. Krovi, T. A. Ohki, and L. C. G. Govia. Hilbert space as a computational resource in reservoir computing. *Phys. Rev. Res.*, 4:033007, Jul 2022.

[6] Toshiki Yasuda, Yudai Suzuki, Tomoyuki Kubota, Kohei Nakajima, Qi Gao, Wenlong Zhang, Satoshi Shimono, Hendra I. Nurdin, and Naoki Yamamoto. Quantum reservoir computing with repeated measurements on superconducting devices, 2023.

[7] Rodrigo Martínez-Peña, Gian Luca Giorgi, Johannes Nokkala, Miguel C. Soriano, and Roberta Zambrini. Dynamical phase transitions in quantum reservoir computing. *Phys. Rev. Lett.*, 127:100502, Aug 2021.

[8] L C G Govia, G J Ribeill, G E Rowlands, and T A Ohki. Nonlinear input transformations are ubiquitous in quantum reservoir computing. *Neuromorphic Computing and Engineering*, 2(1):014008, feb 2022.

[9] Pere Mujal, Johannes Nokkala, Rodrigo Martínez-Peña, Gian Luca Giorgi, Miguel C Soriano, and Roberta Zambrini. Analytical evidence of nonlinearity in qubits and continuous-variable quantum reservoir computing. *Journal of Physics: Complexity*, 2(4):045008, nov 2021.

[10] Niclas Götting, Frederik Lohof, and Christopher Gies. Exploring quantumness in quantum reservoir computing. *Phys. Rev. A*, 108:052427, Nov 2023.

[11] Guillem Llodrà, Christos Charalambous, Gian Luca Giorgi, and Roberta Zambrini. Benchmarking the role of particle statistics in quantum reservoir computing. *Advanced Quantum Technologies*, 6(1):2200100, 2023.

[12] Antonio Sannia, Rodrigo Martínez-Peña, Miguel C. Soriano, Gian Luca Giorgi, and Roberta Zambrini. Dissipation as a resource for Quantum Reservoir Computing. *Quantum*, 8:1291, March 2024.

[13] Pere Mujal, Rodrigo Martínez-Peña, Gian Luca Giorgi, Miguel C. Soriano, and Roberta Zambrini. Time-series quantum reservoir computing with weak and projective measurements. *npj Quantum Information*, 9(1):16, Feb 2023.

[14] Marcin Płodzień, Maciej Lewenstein, Emilia Witkowska, and Jan Chwedeńczuk. One-axis twisting as a method of generating many-body bell correlations. *Phys. Rev. Lett.*, 129:250402, Dec 2022.

[15] Marcin Płodzień, Tomasz Wasak, Emilia Witkowska, Maciej Lewenstein, and Jan Chwedeńczuk. Generation of scalable many-body bell correlations in spin chains with short-range two-body interactions. *Phys. Rev. Res.*, 6:023050, Apr 2024.