Enhancing performance and operational regimes of quantum Otto refrigerator with heat bath algorithmic cooling

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Extended Abstract

Motivation. The interplay between quantum thermodynamics (QT) and quantum information processing (QIP) has attracted increasing attention in recent years. Within QT, quantum thermal machines, such as engines and refrigerators, serve as prototypical platforms for testing thermodynamic principles at the nanoscale. In parallel, QIP seeks to exploit quantum-mechanical laws to achieve computational advantages and enable new technological capabilities. It is therefore natural to ask whether techniques developed in QIP can also improve the operation of quantum thermal machines. Recent work [1] incorporated heat bath algorithmic cooling (HBAC) into a quantum Otto cycle to enhance its performance, but the corresponding thermodynamic analysis was not fully consistent. Motivated by this observation, the present work investigates whether HBAC can improve the performance of quantum Otto refrigerators under a consistent thermodynamic framework and yield additional advantages.

Approach and Methodology. This work investigates an algorithmic quantum Otto refrigerator (AQOR), in which the conventional isochoric cooling stroke is replaced by an HBAC stage. Specifically, we consider two distinct HBAC protocols, each incorporated into the Otto cycle as an alternative cooling stroke. In contrast to the standard isochoric cooling stroke, the HBAC stage employs entropy compression together with selective reset operations to reduce the entropy of the working qubit more effectively before the subsequent stroke of the cycle [2]. In this way, the cooling process is no longer determined solely by direct thermalization with the cold bath, but is assisted by algorithmic cooling operations inspired by quantum information processing.

To evaluate the thermodynamic behavior of the AQOR, we compare it systematically with the conventional quantum Otto refrigerator under the same conditions and parameters. The analysis focuses on the heat extracted from the baths, the total work input, and the coefficient of performance (COP), while explicitly accounting for the thermodynamic cost associated with the HBAC process. We further vary relevant external control parameters, including the reset-qubit frequency and the adiabatic ratio, in order to determine how the two HBAC protocols modify the cooling capability and extend the operational regime over a wider range of bath temperature differences.

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Results. By numerically simulating the model as a function of the frequency ratio between the reset qubit C and the working qubit A, we find that the AQOR can achieve a higher COP than the conventional QOR within a certain parameter range. Another notable advantage is that the AQOR remains operational over a larger temperature difference between the hot and cold baths (see Fig. 1). However, although both Protocols I and II exhibit an extended refrigeration regime as the bath temperature difference increases, the corresponding COP values in this region are relatively small. The AQOR therefore exhibits a trade-off between achieving higher performance in specific parameter regimes and maintaining a broader operating range.

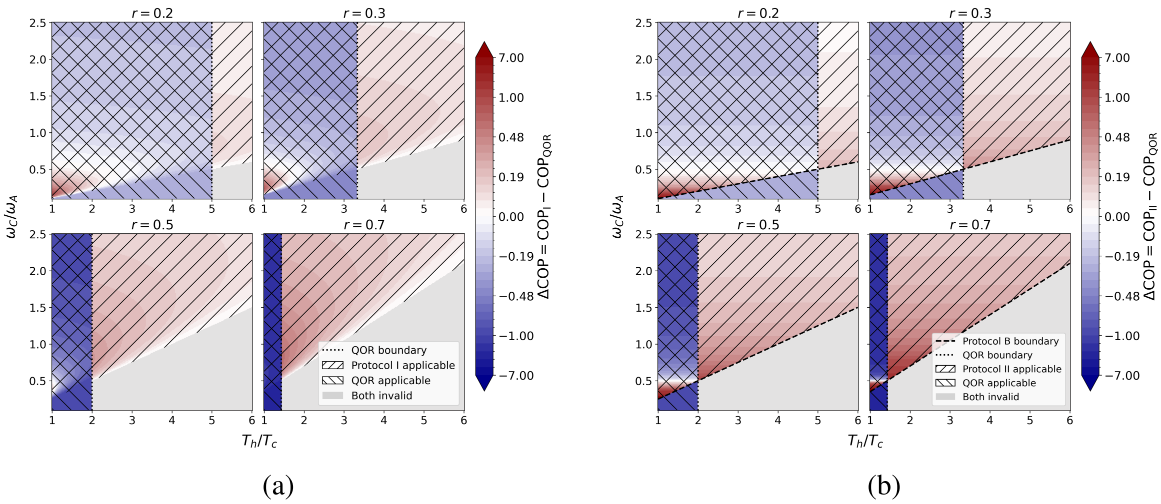

Figure 1: Comparison of (a) Protocol I and (b) Protocol II with the conventional QOR in terms of the ΔCOP, shown as heatmaps for several values of the adiabatic ratio r.

Conclusions and Outlook. In this work, we show that HBAC is not only useful for qubit initialization, but can also play an important role in quantum thermodynamic cycles. These results highlight the broader potential of quantum information processing in the design and enhancement of quantum thermal machines. Looking ahead, we will further investigate the roles of other possible quantum resources in thermal machines, including informational resources and quantum correlations.

References

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