Quantum Correlations in Nonlocal BosonSampling

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Determining whether the correlations between two systems are quantum or classical is fundamental to our understanding of the physical world and our ability to use such correlations for technological applications. In quantum information theory, quantification of quantum correlations is mainly based on the notion of quantum entropy [1].

In contrast, in quantum optics it is common to study nonclassical features of bosonic systems in a quantum analogue of the classical phase space. While in a classical statistical theory in phase-space the state of the system is represented by a probability distribution, the quantum phase-space distributions can have negative regions, and hence, fail to be legitimate probability distributions [2]. The negativities are thus considered as nonclassicality signatures. Within multipartite quantum states, the phase-space nonclassicality can be associated with quantum correlations, due to the fact that in a classical description of the joint system no such effects are present [3, 4].

Recently, Ferraro and Paris [5] showed that the two definitions of quantum correlations from quantum information and quantum optics are inequivalent. This means that every quantum state which is classically correlated with respect to the quantum information definition of quantum correlations is necessarily quantum correlated with respect to the quantum optical criteria and vice versa. One can also compare the operational differences between the two approaches. On one hand, the quantum correlations of quantum information have been shown to be necessary for specific nonlocal quantum communication and computation tasks to outperform their classical counterparts. On the other hand, however, quantum correlations in quantum optics lack such a nonlocal operational justification, i.e., there is no particular quantum information protocol which exploits phase-space nonclassicality to outperform a classical counterpart protocol.

In this paper, we introduce nonlocal BosonSampling as an intermediate model of quantum computing which is performed by distant agents (see Fig. 1) and use it to demonstrate the operational interpretation of phase-space nonclassicality in quantum informatics [6]. Specifically, we show that there exists a quantum state, namely a product of fully dephased two-mode squeezed vacuum states,

$$\begin{aligned}\hat{\varrho}_{\mathrm{AB}} &= \hat{\varrho}_i^{\otimes m}\\ &= (1-\epsilon^2)^m \sum_{j_1,\ldots,j_m=0}^{\infty} \epsilon^{2\sum_{k=1}^m j_k} \left(\bigotimes_{k=1}^m |j_k\rangle_{\mathrm{A}}\langle j_k|\right)\\ &\qquad \otimes \left(\bigotimes_{k=1}^m |j_k\rangle_{\mathrm{B}}\langle j_k|\right),\end{aligned} \tag{1}$$

which is strictly classical (CC) with respect to entropic measures of correlations in quantum information allowing for efficient classical simulation of local statistics of two BosonSampler parties, Alice and Bob, in our protocol, which at the same time, prohibits efficient classical simulation of nonlocal correlations between the two. The only known resource present within the state (1), in contrast to the scatter-shot BosonSampling [7], is that of phase-space nonclassicality, as shown in [8]. Hence, we see that, nonlocal BosonSampling takes advantage of phase-space nonclassicality to perform a nonlocal task more efficiently than any classical algorithm.

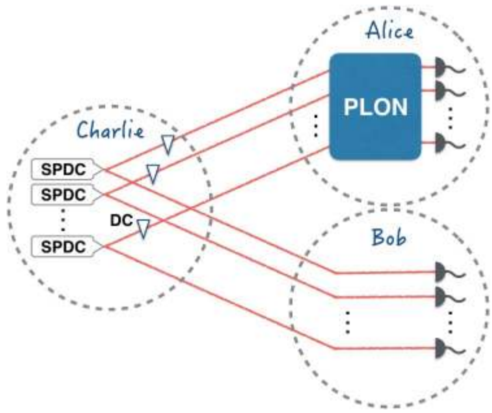

Figure 1: The schematic of a nonlocal BosonSampling protocol with CC input state. Charlie uses m SPDC sources and a series of dephasing channels (DC) to produce fully dephased two-mode squeezed vacuum states (FDTSV), and shares the final state between two spatially separated agents. Alice performs BosonSampling using a passive linear-optical network (PLON) and $\{0,1\}$ Fock basis measurements, while Bob only performs $\{0,1\}$ Fock basis measurements. We show that, Alice and Bob can efficiently simulate their local sample statistics classically. However, they cannot efficiently simulate the correlations between their outcomes using classical computers and any amount of classical communication, although there is no entanglement or discord between agents at any time.

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