Abstract

The inception of Einstein-Podolsky-Rosen (EPR) paradox ensured quantum correlations to take a center stage in the investigations of foundations of quantum theory. The creative discussions in this direction led to the advent of quantum information and computation (QIC)- a computing paradigm based on the fundamental aspects of quantum mechanics. Clearly, the last three decades have been instrumental in establishing quantum correlations as fundamental ingredients to achieve potential applications which are otherwise not possible using classical resources. Nonlocal correlations exhibited by entangled systems have been utilized for several efficient and optimal applications in quantum information and computation. In fact, discord- a measure of quantumness in an underlying state- captures nonlocal correlations even in a separable state. Therefore, classification and quantification of nonlocal correlations in quantum systems not only support the description of foundations of quantum information but also help to identify new and efficient resources. With the increase in number of qubits, description of entanglement and nonlocality, becomes much more difficult even in pure states. For example, the nonlocal properties of two qubit pure states are well established in terms of violation of the Bell inequality but the description of nonlocality for three qubit pure states still requires a better physical interpretation using Bell-type inequalities. Although the Mermin inequality captures nonlocal correlations in a set of three qubit pure entangled states, it fails to distinguish between bipartite and genuine tripartite correlations. Further, the three-qubit Mermin inequality also fails to identify nonlocal correlations in a set of partially entangled three qubit pure states. The Svetlichny inequality, however, confirms the presence of genuine three qubit nonlocal correlations by effectively distinguishing between bipartite and tripartite nonlocality, but fails to characterize nonlocal correlations in a large set of three qubit entangled pure states for a given range of the state parameter. As one further increases number of qubits to the system, the complexity also increases with an increase in number of different entangled classes. The analysis of entanglement and nonlocality becomes much more involved considering real conditions and mechanisms to protect nonlocal correlations for obtaining better efficiencies of entangled resources. Surprisingly, for three-qubit or multiqubit systems, no generic inequality is found to identify nonlocal correlations in all entangled states. Moreover, one can also find two qubit mixed states which may be entangled but would still not violate the Bell inequality. It is probably the characteristic trait of theory- complexity- that makes the discussion much more challenging and interesting. The measures of nonlocality do not agree with the measures of entanglement and if we consider the presence of noise then the situation becomes even more intricate. The role of correlations in quantum information and communication is, therefore, far from well established. A generic approach to classify nonlocal correlations in multiqubit systems would further ascertain the usefulness of such systems for quantum communication and information processing and would certainly lead us to have a better insight into the subtle nature of quantum correlations.

The Thesis is an attempt towards establishing a general description of nonlocal correlations in bipartite and multiqubit pure and mixed states. A simple description that can be obtained analytically or numerically to distinguish the quantum and classical boundary would definitely be of great value. For this, we propose a new measure of nonlocality based on many-body statistical mechanics to map out the behavior of nonlocal correlations in entangled resources. We systematically establish analytical relations between the optimal expectation values of the proposed operators, degree of entanglement, noise and state parameters for bipartite and multiqubit systems considering the inevitable presence of noise. We further extend our analysis to protect and study robustness of nonlocal correlations in presence of noise. Our results show that the proposed and modified operators successfully identify nonlocal correlations in multiqubit pure

states. In fact, our study further demonstrates the presence of nonlocality in mixed and separable states where even the Bell or Bell-type inequalities fail to capture nonlocal correlations. The results successfully address issues of bipartite vs tripartite vs multiqubit nonlocality and further identify all pure multiqubit entangled states for the complete range of state parameters. The discussion is extended to quantify nonlocality in different classes of four and five qubit entangled pure states. Furthermore, the analytical results obtained in this Thesis are in complete agreement with numerical results.

Based on our studies for bipartite and multiqubit systems, we readdress the usefulness of partially entangled multiqubit states for quantum information and computation. For this, we revisit the question of analyzing efficiencies of four different sets of partially entangled states in three qubit classes under real conditions. In the presence of noise, we show that maximum entanglement and nonlocality in the input state do not always guarantee maximum efficiency in a protocol. For example, our analysis suggests that efficiencies of a set of partially entangled states are much more robust to noise than those of maximally entangled states in Greenberger–Horne–Zeilinger (GHZ) class of states. For a set of partially entangled states in presence of noise and weak measurements, efficiencies of communication protocols achieve the optimal value independent of the state and decoherence parameters. We further generalize our study to address efficiencies of $(N+2)$-qubit partially entangled states for the presence of N controllers in a noisy environment from the perspective of controllers' authority and average fidelity. These values are obtained by designing a generalized circuit using single and two-qubit gates and studying different cases of two sets of partially entangled multiqubit states. Our analysis identifies a set of partially entangled states for which the average fidelity is independent of the state parameter and measurements performed by $(N-1)$ controllers thereby facilitating the experimental set-ups to worry about a smaller number of parameters in the protocol when dealing with a multiqubit network. Interestingly, even in the presence of noise and weak measurement operations, we find the efficiency of a set of $(N+2)$-qubit partially entangled states to be independent of the measurements performed by $(N-1)$ controllers. The efficiencies of these states are consistent with the analysis of nonlocal correlations using our modified operators and quantum discord.

…