Abstract

Title: Study of Various Aspects of Quantum Communications

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Quantum communication, a pivotal subfield of quantum information science, explores how inherently nonclassical features of quantum mechanics can be harnessed to perform communication tasks with enhanced security and efficiency. The central objective of this thesis is to investigate how various quantum correlations, including temporal nonclassicality, Bell nonlocality, and contextuality, can be operationally utilized in different communication protocols and foundational scenarios. To begin with, the thesis explores quantum random access codes (QRACs), a fundamental communication protocol wherein a sender encodes multiple classical bits into a quantum system, allowing the receiver to retrieve any one of them with high success probability. We show that this communication advantage has a direct equivalence with the violation of temporal inequalities derived from noninvasive realist assumptions. Thus, temporal quantum correlations, though less studied than their spatial counterparts, are shown to be both necessary and sufficient to realize quantum enhancements in time-ordered communication scenarios. Moreover, this link provides a method to certify genuine randomness based solely on temporal behavior. In the context of secure quantum communication, the thesis examines device-independent quantum key distribution (DI-QKD), where no assumptions are made about the internal functioning of the devices involved. Here, Bell nonlocality plays a crucial role as a certification tool. We analyze the performance of random two-qubit states, generated Haar-uniformly, and quantify how increasing mixedness (state rank) impacts both nonlocality and secure key rates. The study reveals that while entanglement and Bell violation degrade gradually with rank, the drop in key rate is more severe. Notably, pure and Werner states are identified as extremal cases that bound the achievable key rate for a same amount of entanglement. Contextuality, another powerful nonclassical resource, is investigated through its implications for communication efficiency in restricted scenarios. The thesis constructs a generalized noncontextual polytope that captures both preparation and measurement noncontextuality. It enables scalable derivation of facet inequalities, uncovering new forms of contextuality. These inequalities are then shown to enhance performance in several communication-relevant tasks, including oblivious communication, certification of non-projective measurements, and dimension witnessing, demonstrating contextuality's relevance beyond foundational tests. Finally, the thesis turns to long-distance quantum communication, focusing on hybrid systems that combine continuous-variable and discrete-variable encodings. By employing entanglement swapping on multi-photon coherent states, we show that high-fidelity polarization Bell pairs can be distributed over intercity distances exceeding 200 km. These shared states are then used for quantum

teleportation of unknown polarization qubits, where the achieved fidelity remains above classical thresholds even under realistic transmission losses, highlighting the practicality of hybrid-state architectures for scalable quantum networks. Overall, the thesis provides a unified perspective on how different forms of quantum correlations can be operationalized to achieve and enhance various quantum communication tasks. The results underscore the fundamental interplay between nonclassicality and information transfer, while also pointing toward promising directions for secure and scalable quantum technologies.

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