SEVENTH FRAMEWORK PROGRAMME

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This deliverable has been achieved in several ways, and the goal that was to be achieved has had several ramifications. The report on the deliverable is hence summarizing results from several publications within WP3.5. Generally, these works addressed distributed quantum information processing (quantum games, and communication complexity reducing protocols) and the role of entanglement in them [UG, UoB, OEAW, LUH, LMU]. We have studied non-local computation, Leggett-like inequalities, the relation of Bell's theorem with fundamental quantum informational processes, entangled higher dimensional systems, quantification of classical resources required to simulate protocols as considered in quantum communication.

The basic results concerning the usefulness of various entangled states in protocols aiming at a reduction of communication complexity are reported in the following two main papers:

[LPB1-10]: Entanglement and communication reducing properties of noisy N-qubit states. This part of the report considers properties of states of many qubits which arise after sending certain entangled states via various noisy channels (white noise, colored noise, local depolarization, dephasing, and amplitude damping). The structure of the entanglement contained in those states and their ability to violate certain classes of Bell inequalities are reported. States violate them allow for a higher than classically achievable efficiency when solving related distributed computational tasks with constrained communication. This is a direct property of such states not requiring their further modification via stochastic local operations and classical communication, such as entanglement purification or distillation procedures. We report on families of multi-particle states which are entangled but nevertheless allow the local realistic description of specific Bell experiments (that is can be emulated with classical communication processes). For some of them, the gap between the critical values for entanglement and violation of Bell inequality remains finite even in the limit of infinitely many qubits.

[GLZ1-10]: Non-classicality thresholds for multiqubit states - numerical analysis. This part of the report covers cases which cannot be addressed by analytical reasonings. We resort to a very extensive numerical analysis of such instances. Because of the numerical nature of the study, we solely analyze the non-classicality of correlations of some important families of multiquibit entangled states (required in many quantum informational protocols as, for example, in cryptography, secret sharing and the reduction of communication complexity).

One of the principal tasks one faces when analyzing the communication reducing properties of quantum correlations is to estimate what would be the additional classical communication input to simulate the quantum correlations. We report a solution of such problems for specific cases:

[PKP1-10]: Nonlocal setting and outcome information for violation of Bell's inequality. Bell's theorem is a no-go theorem stating that quantum mechanics cannot be reproduced by a physical theory based on realism, freedom to choose experimental settings and two locality conditions: setting (SI) and outcome (OI) independence. We provide a novel analysis of what it takes to violate Bells inequality within the framework in which both realism and freedom of choice are assumed, by showing that it is impossible to model a violation without having information available in one laboratory about both the setting and the outcome at the distant one. While it is possible that outcome information can be revealed from shared hidden variables, the assumed experimenters' freedom to choose the settings ensures that the setting information must be non-locally transferred even when the SI condition is obeyed. The amount of transmitted information about the setting that is sufficient to violate the CHSH inequality up to its quantum mechanical maximum is 0.736 bits.

One of the central problems and applications related to reduction of communication complexity with entanglement are quantum games. In this part of the report have the following entries:

[LLP1-10]: Biased nonlocal quantum games. We report on the question of when quantum entanglement is a useful resource for information processing tasks. This is done for the exemplary case of a class of nonlocal games that are simple, direct, generalizations of the Clauser Horne Shimony Holt game. For some ranges of the parameters that specify the games, quantum mechanics offers an advantage, while, surprisingly, for others quantum mechanics is no more powerful than classical mechanics in performing the nonlocal task. This sheds new light on the difference between classical, quantum and super-quantum correlations.

[MKT1-10]: Static quantum games revisited. The notion of a quantum game has a vague definition in literature. A new conceptual framework of a quantum-game scenario and an implementation of such a game is reported. It is shown that the procedures of quantization of games proposed in the literature lead in fact to several different games which can be defined within the same scenario, but apart from this they may have nothing in common with the original game. Within the framework, a lot of conceptual misunderstandings that have arisen around quantum games can be stated clearly and resolved uniquely. In particular, the proclaimed essential role of entanglement in several static quantum games, and their connection with Bell inequalities, is disproved.

The final element of our study of communication complexity problems, are their ramifications for other parts of quantum information science. We report on an interesting link between such problems, and the questions concerning the reasons for quantum speedup, as well to the question why some entanglement assisted communication complexity problems can be translated in to equivalent involving sequential actions on a single quantum system.

Finally, we have to declare that due to the broadness of ramifications of all these studies, this research is still continued and future significant results are expected. Especially we intend to move towards problems involving higher dimensional systems (some exiting new numerical results were just obtained in node UG), and as the current experimental techniques finally allow one to build out of integrated optical elements circuits involving multi-port beamsplitters, we shall continue our research in this direction. This will have a direct influence on experimental investigations.

References:

[LPB1-10] W. Laskowski, T. Paterek, C. Brukner and M. Zukowski, *Entanglement and communication reducing properties of noisy N-qubit states*, Phys. Rev. A **81** 042101 (2010).

[GLZ1-10] J. Gruca, W. Laskowski, M. Zukowski, N. Kiesel, W. Wieczorek, C. Schmid, and H. Weinfurter, *Non-classicality thresholds for multiqubit states - numerical analysis*, Phys. Rev. A **82** 012118 (2010).

[PKP1-10] M. Pawlowski, J. Kofler, T. Paterek, M. Seevinck, and C. Brukner, *Nonlocal setting and outcome information for violation of Bell's inequality*, New J. Phys. **12** 083051 (2010).

[LLP1-10] T. Lawson, N. Linden, and S. Popescu, *Biased nonlocal quantum games* (2010) **quant-ph/1011.6245**.

[MKT1-10] M. Markiewicz, A. Kosowski, T. Tylec, J. Pykacz, and C. Gavoille, *Static quantum games revisited* (2010) **quant-ph/1001.2257**.