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Reviewer's report of the PhD thesis
"Probabilistic quantum error correction codes for general noise channels"
by Ryszard Kukulski

The theme of Ryszard Kukulski's thesis is the development of probabilistic quantum error correcting codes for general noise channels. Quantum error correction (QEC) addresses a fundamental challenge inherent to quantum systems, namely their extreme sensitivity to errors caused by various sources of noise, such as environmental interactions and imperfections in hardware. The primary role of QEC is to counteract these errors and preserve the quantum information throughout quantum computations, the ultimate goal being to enable the development of reliable and fault-tolerant quantum computers. This topic is very timely, and the candidate explores a very interesting angle of this: Traditionally, the primary focus of research into quantum error correction codes has been on achieving perfect QEC codes. There has been much less attention on probabilistic quantum error correction (pQEC), and the results of this thesis enhances the body of knowledge on pQEC considerably. In particular the main scientific problem the author addresses is whether the usage of probabilistic quantum error correction codes can be beneficial for improving the quality of quantum systems disturbed by different noise channels. The candidate answers this affirmatively, showing that the pQEC codes, in comparison to the QEC codes, can correct noise channels from a broader class of quantum channels.

The thesis is divided into six chapters. The opening chapter gives an introductory overview of the theory of quantum error correction. Chapter 2 establishes the necessary mathematical framework for the subsequent chapters. Chapters 3, 4 and 5 are built upon the original research of the candidate, with Chapter 3 providing new results concerning the sampling of random subchannels, super-channels and instruments. Chapter 4 contains theoretical results about pQEC, and showcases the advantages of the utilization. Chapter 5 leverages the introduced pQEC codes to develop an efficient methodology for constructing approximate quantum error correction codes. To validate the potential of this approach, it is rigorously tested on randomly generated quantum channels. Finally, Chapter 6 serves as a concluding chapter, summarizing the research findings and presenting overall conclusions drawn from the work conducted throughout the dissertation.

The structure of the thesis is good, the used concepts are built up in a logical manner, and the presentation is clean. The author solves the problem he posed by demonstrating the advantages that pQEC codes can have. In particular, the work extends the Knill-Laflamme theorem and establishes criteria for determining the probabilistic correctability of noise channels. It demonstrates that pQEC codes outperform QEC codes in correcting a broader range of noise channels, highlighting a trade-off between error correction probability and code quality. The numerical investigation of pQEC codes was made possible by advancements in generating random quantum channels. In particular, the work demonstrates the equivalence of various sampling techniques based on different representations of quantum channels, and the Kraus representation is found to be particularly suitable for numerical simulations due to its simplicity and the diversity of sampled channels it offers. All these results are original contributions which demonstrates that the author has has a detailed knowledge in this research field and used it creatively. The achieved results clearly represent important contributions the to area of quantum error correction. Furthermore, I believe that these results may be also of practical importance, e.g., in possible future experimental implementations of pQEC code. The only two negative things I could point out is that some of the results, in particular the ones presented in Chapter 5, are not yet published, and perhaps in some cases the previous studies and the literature could have been discussed a bit more. However, this does not matter too much, and I believe that the presented results significantly enhances the relevant research field.

Conclusion:
The thesis of Ryszard Kukulski is well structured and contains many important results about the theory of probabilistic quantum error correction. It meets the statutory requirements for doctoral theses in the field of engineering and technology in the discipline information and communication technology. Thus, I am happy to suggest the acceptance of the thesis and recommend the best possible mark.

Sincerely Yours,

Zoltán Zimborás

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