Peer Review of Group 14 by Group 8

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03.07.2020

1 Summary of the paper

Microwave drivers are key electronic components of the architectures that control experimental quantum processors. As quantum computers scale up to sizes necessary for fault-tolerance, the use of conventional room-temperature controls face new challenges. The paper reviews a recent approach to scaling up control using microwave drivers at cryogenic temperatures. This lowers delay times by bringing control architectures closer to the quantum processor. Further, they discuss the use of frequency-division multiple access control, which allows parallel, multiple access to qubits such that the number of control lines grows slower than the number of qubits. The paper concludes with two state-of-the-art examples of such cryogenic microwave driver technology, developed by Google and Intel.

2 Quality of the content

2.1 Have all points been addressed?

2.1.1 Are microwave drivers required for solid-state qubits? (5/5)

They mention three platforms, trasmon qubits, single electron semiconductor platforms and NV centres in diamond where microwave drivers are the go-to technology to perform single qubit rotations. The authors also mention a key disadvantage of using microwave drivers, which is the inherent trade-off between power consumption and gate speed, which becomes a greater challenge at cryogenic temperatures. However, they also mention a platform based on multiple electron spin qubits that can implement single qubit rotation by means of the Heisenberg exchange operation, raising the possibility that microwave drivers are not essential for qubit control in all hardware platforms.

Given that they give a complete, clear description of the use of microwaves in several platforms, along with advantages and disadvantages, we believe the authors deserve 5 points in this question.

2.1.2 Room temperature vs cryogenic MW drivers: pros and cons. (4/5)

The authors aptly outline the cons associated with room temperature microwave drivers, namely the delay (of up to 10ns) and thermal load caused by long cables running from the drivers to the processor. However, they do not explicitly mention advantages of room temperature drivers, which could be for example their simplicity or, as mentioned in Bardin *et al.*, the fact that power consumption is not an issue at room temperature and one can use well established technology.

Regarding the cryogenic drivers, the authors explain how low temperature drivers can address the main disadvantages associated with room temperature drivers. They also outline the challenges associated with implementing drivers at cryogenic temperatures.

The authors did not specifically address the pros of room temperature drivers, but otherwise adequately explained the trade-offs between room temperature and cryogenic drivers. For this reason, we believe they deserve 4 points for this section.

2.1.3 Advantages and requirements of FDMA. (5/5)

The authors give a good overview of FDMA and explain how it can take advantage of the tunability of qubit frequencies in order to address many qubits through one microwave line, while allowing for parallel operations (in contrast to time-division multiple access approaches).

They also explain that implementing FDMA requires drivers with a larger range of frequencies available to them, as well as more complex readout components. One final cost of FDMA is introducing potential cross-talk between qubits, something that will require more complex electronics to mitigate and control.

Since they address explicitly both advantages and requirements of FDMA and they also give complementary information regarding to the constrains related to FDMA, we believe the authors deserve 5 points.

2.1.4 Implications of cryogenic electronics on MW driver design. (4/5)

The authors discuss how moving to cryogenic temperatures will impact the design of microwave drivers pointing out the need to "balance power consumption, performance, and robust component selection". Power consumption and performance seem to be addressed adequately, using the Google controller and Horse Ridge as examples from the state of the art. However, more details about how robust component selection affects the design choices could have been included.

As a result, we believe the authors deserve 4 points for this section.

2.2 Other important points that have been treated

The authors include a helpful discussion about implementing universal gate sets on the various hardware platforms mentioned in their paper.

They also discuss why scalable electronics are necessary for the implementation of a fully fault-tolerant quantum computer and mention the threat of leakage outside the computational subspace, especially for transmon qubits.

Finally, they include the NV-centres as part of the solid state platforms that make use of microwave drivers. This is not addressed in the starting bibliography but is still relevant to the presented discussion.

2.3 Analysis of state of the art

The main references provided for this paper were by Bardin *et al.* and Patra *et al.* which we employed by the authors several times. The authors provided a clear overview of the results and methods that Bardin *et al.* used to develop their cryogenic driver, discussing the advantages and limitations at length. They also use the paper as a reference for discussing the power consumption limits of cryogenic microwave drivers, specifically mentioning the 250 μW per qubit limit.

The second main reference by Patra *et al.* was employed in the state-of-the-art section to illustrate the types of design choices made when working with microwave drivers at cryogenic temperatures, in this case improving upon the results of Bardin *et al.* by including FDMA capabilities and extending the range of available frequencies to allow for both transmon and spin qubit control. The review was concise and showed clear understanding of the results presented by Patra *et al.*.

There is another paper that has been extensively employed as reference material which is the reference [5] by Jeroen P. G. *et al.* This reference appears several times all over the paper to support valuable data that helps in the understanding of the topic. Examples of that are the 10ns delay due to cable length that is comparable to the gate time. These gate times are most likely obtained from table 1 and the discussion of section 4 of that same reference.

Finally, there are several other references included to support specific statements that show a wide knowledge of the topic and give strength and veracity to the text. "It make the paper look professional."

3 Clarity of the paper

3.1 Structure

The paper was properly structured and followed the order outlined in the introduction, making it very easy to read. One suggestion would be to have made the "Multiplexing Techniques" and "Microwave Drivers at Cryogenic Temperatures" sections into sub-sections under a section head entitled "Proposed Solutions". This would have made the structure clearer and would have coincided better with the paper overview given at the end of the introduction.

3.2 Language

The language was very clear. A writing style of short, declarative sentences broke down larger concepts effectively. The paper was grammatically correct throughout with hardly any typos or other mistakes, the most noticeable one being in section 5 were they say that the phase needs to be kept within a 0.22% tolerance but it should be (Berdin *et al.*) 0.22°. Nevertheless, it was well-written and clearly proof-read several times.

3.3 Formatting

There were no figures and the one equation in the paper was well formatted with well defined symbols. The bibliography is well formatted and complete with helpful links for references throughout the paper and DOI links in the reference list. However the bibliography does not appear in any particular order, contrary to common approaches that organize entries by appearance in the text, or name, or date.

4 Additional remarks

The authors wrote in an engaging way, illustrating the implications of cryogenic temp on driver design using the current state of the art. Accomplished a lot in one section.

In Section 5, the authors write that Bardin *et al.* use 0.01% as a "benchmark" of the total error rate, which rendered the rest of the paragraph unclear. We thought that their use of the word benchmark meant that Bardin *et al.* were using an overall error rate of 0.01% as the standard against which to compare their results. But, after reviewing the paper, we suspect that they mean that Bardin *et al.* provided specifications corresponding to an overall rate of 0.01%. This point could have been communicated more clearly.

There were sections of the paper where a figure could have added greatly to explanations. We understand that the authors likely chose not to include any figures due to the page limit, but we would argue that figures can be a better and more efficient way of explaining a concept or experimental setup than words alone.

Overall, the paper was clearly written, well-researched and showed good understanding of the concepts and challenges in the development of cryogenic microwave drivers.