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CEN CENELEC Focus Group on Quantum Technologies

TITLE **Functional Description of Control Highway**

PROJECT FGQT Roadmap

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SOURCE Rob F.M. van den Brink (Delft Circuits, The Netherlands), Rob.vandenBrink@Delft-Circuits.com

ABSTRACT

Annex E of the Roadmap document, elaborates on further details about Cryogenic Solid-State based Quantum Computers. The description is subdivided in several modules, and one of these modules is the control highway dealing with all i/o channels between control electronics (at room temperature) and quantum devices (at cryogenic temperatures).

This contribution is to fill section E.6 with content on the Control Highway, by offering a functional description and identifying relevant functional requirements for future dedicated standards. As such it also identifies relevant standardisation needs.

We propose to replace all text in the present annex E, as currently collected in section E.6, by all the text below:

Start of literal text proposal

E.6 Control Highway

The control highway enables the transportation of downstream and upstream signals between control electronics, operating at room temperature, and quantum devices, operating at cryogenic temperatures.

Figure [E.6.1] shows an *example* of a possible control highway dedicated to a *transmon* quantum computer. The I/O channels of *spin-qubit* quantum computers may be different, but this example alone may be sufficient to get basic understanding of various functional requirements for future standardisation.

In this example, the I/O of each qubit is handled via three channels: one for microwave control signals, another one for flux control and a third one for read-out. The response signals of two or more qubits may share a common read-out channel to reduce the overall number of channels. Travelling wave amplifiers may be used for amplifying these response signals, and the need an extra TWPA pump channel for powering. As such, a 50 qubit transmon quantum computer may have 102 or more I/O channels.

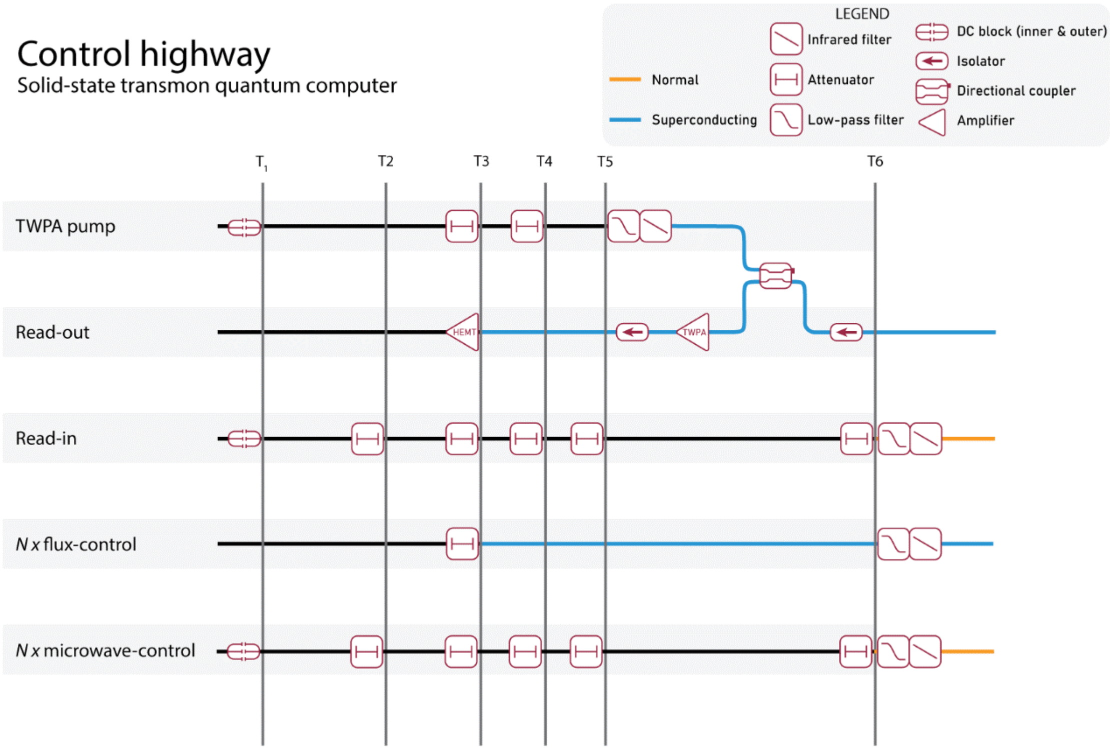

Figure [E.6.1] An example of a control highway applicable to a particular transmon architecture.

The involved I/O channels may be build-up from a variety of building blocks, for instance from transmission lines, attenuators, directional couplers, low-pass filters, infra red filters, DC-blocks, superconducting sections, amplifiers, isolators, circulators as well as thermalization means and vacuum feed troughs.

E.6.1 Consideration of relevant requirements

The *transmission requirements* on the control highway are to be defined in detail, and these requirements are highly dependent on the specific architecture and use case. The same applies to various *interconnection* and *footprint requirements.* But there are more issues of relevance that are to be specified, which may be less obvious. Their relevance is explained below.

Heat flow considerations. A cryogenic fridge cools the setup in multiples stages, with temperatures from T1, T2, T3, and so on, down to the lowest temperature; usually down to the milli-Kelvin range. The control highway has to bridge a temperature drop of about 300K, and these channels will leak heat from room temperature into the fridge down to the quantum device. This will challenge the cooling mechanism of the fridge, and may prevent desired temperatures at the quantum device. Most of the heat flows through the metallic parts of the cabling, mainly through the shielding of coaxial cabling or ground planes of stripline cabling. To minimize that heat flow, the cabling should have low thermal conductance, and be thermalized at each temperature stage. Most of the heat flow through the cabling will then flow via the thermalization into the cooling mechanism. The residual heat flow to a next stage in the fridge will then be minimized.
A superconducting transmission line at one of the bottom sections may be used to reduce the heat flow even further. Superconductors tend to combine low thermal conductance with high electrical conductance, which is the opposite behaviour of metals.
Due to the large number of channels, this thermal leakage cannot be ignored and puts limits on the lowest temperatures that can be achieved since the cooling capacity of the fridge is limited. This puts a maximum on the number of channels.
This explains the need of various *thermal requirements* on the control highway as a whole.

Noise considerations. Each I/O channel suffers from adding some noise to the signal. Even passive lines generate at least thermal noise. Without any loss in a channel, and (hypothetical) noise-free control electronics, this noise would be at least the thermal noise of a 50 ohm resistor at room temperature. Therefore, attenuators are placed at different temperature stages, to achieve noise temperatures that are only slightly above the temperature of each stage. Attenuation values between 40 to 80 dB are not uncommon.
The lowest achievable noise level (in absence of any signal) occurs when all attenuation is concentrated in the stage with the lowest temperature. However, under operational conditions, signals will be dissipated in the attenuators, which is the reason why attenuation has to be distributed. The reason is explained below.

- At first, the dissipation of signal in the attenuator results in more heat power that should flow away via the cooling mechanism of the fridge. Since this cooling capacity is limited, with the lowest capacity at the coolest stages, this dissipation can easily overload the cooling. This is one reason why attenuation has to be *distributed*, which also increases the noise at the end of the chain.
- Secondly, the dissipation of signal power in the attenuator will increase the *hot-spot temperature* of the internal resistors. That temperature will raise above the outside temperature of the attenuator, which is usually thermalized at the stage temperature. This raise increases the thermal noise as well, which will be most pronounced by the last attenuator at the lowest temperature. Preventing all dissipation at a single spot by proper distribution of attenuation will reduce this noise. So even with infinite cooling capacity, attenuation has to be distributed because of noise.
- The increase of hot-spot temperature can be reduced by effective *hot-spot cooling*. It requires attenuators with high thermal conductance between internal hot spots and

external thermalization points. Unfortunately, the thermal conductance of many materials is low at cryogenic temperatures, which challenges effective hot-spot cooling.

This may illustrate that effective hot-spot cooling and distribution of attenuation is essential to minimize the noise at the end of the I/O chain. The optimum distribution is use-case dependent, such as available cooling capacity of the fridge and used signal powers.
This explains the need of various *noise requirements* on the control highway as a whole.

Vacuum considerations. A vacuum is needed as heat insulation to reach the low temperatures for cryogenic quantum devices. Once a vacuum pump has achieved the desired vacuum level, leakage from outside will gradually raise this level. It may be obvious that this puts strong vacuum requirements on the feed-throughs between outside and inside the fridge.
In addition, materials inside vacuum, and cavities within constructions, may suffer from *out-gassing.* This will gradually fill the vacuum with unwanted particles. And even when this out-gassing stops after a while, it may occur again after reopening the fridge when materials and cavities act like a sponge.
But outgassing is also strongly temperature dependent. At low temperatures almost all outgassing is stopped since most materials will freeze at cryogenic temperatures. This may suggest that outgassing is mainly a room-temperature issue.
However the main problem with leaks and outgassing is that the gases may condense and freeze at the colder parts of a cryostat which dissipates energy and uses part of the available cooling power. This explains the need of various *vacuum requirements* on the control highway as a whole.

E.6.2 Functional description

These requirements could involve:

- Functional description of all I/O chains, including length of each temperature stage, position of thermalization and desired components in each chain. It could highlight typical differences between solutions for transmons, spin-qubit and others.
- Description of additional means to simplify characterization, inspection and/or calibration of the overall setup.
- Description of signal levels, shapes and frequency bands for both downstream and upstream I/O channels.

E.6.3 Transmission requirements

These requirements could involve:

- Requirements on step and/or impulse *response* of the full chain, when the chain is terminated by a realistic impedance. This could involve rise-time, overshoot, and ringing. Note that when the impedance of a quantum device is quite different from 50 ohm, it may not be useful to specify response under 50 ohm conditions.
- Design values (target) as well as masks for upper and lower limits of the *transmission* in the desired pass-band of interest when the chain is terminated by a realistic impedance. This could be offered for the full chain, as well for each stage and/or segment/component. Note that requirements on *reflection* can be made superfluous by setting meaningful transmission and response requirements on the full chain
- Masks for upper limits on low-pass filtering for *out-of-band* frequencies. These masks may be specified up to one or two decades above the highest pass-band frequencies, to reduce out-of-band noise (IR-filtering). If pulses are to be modulated on 8 GHz, these masks may even be specified up to 100GHz or more.
- Requirements on DC/low-frequency characteristics, for instance to separate bias currents from signals. When the pass-band has a lowest break frequency, then the

design of that separation can be simplified if that break frequency can be set as high as possible. This could involve DC-resistance as well, if a particular channel should operate from DC.

- Requirements on EL-FEXT (Equal-Level Far End Crosstalk) between I/O channels. This is the ratio between signal level and crosstalk level (from another channel), as observed at the end of an individual I/O channel. EL-FEXT is indicative for the expected signal-to-noise ratio in each channel, which requires the cumulation of crosstalk from all other channels.
- Requirement on NEXT (Near End Crosstalk) from a downstream I/O channel to an upstream I/O channel. Note that requirements on NEXT between two downstream channels can be made superfluous when meaningful EL-FEXT requirements are set.

E.6.4 Thermal requirements

These requirements could involve:

- Maximum passive heat flow through an I/O channel.
- Requirements on superconducting sections, for reducing the heat flow.
- Maximum signal dissipation in each stage (attenuators), at given signal power, to prevent that the resulting active heat flow overloads the cooling capacity per stage.
- Transversal thermal conductivity of an I/O channel near thermalization clamps.
- Transversal thermal conductivity of attenuators to minimize raise of hot-spot temperatures.

E.6.5. Noise requirements

These requirements could involve:

- Requirements on maximum thermal noise temperatures at the end of downstream I/O channels, under passive conditions (in absence of any signal).
- Requirements on hot-spot cooling and distribution of attenuators to restrict the raise of noise temperatures. These raises occur when signals are heating-up attenuators and therefore produce higher thermal noise levels. Such raise may be too high when the locations of the attenuators are sub-optimal and/or the cooling of hot-spots inside attenuators is inadequate.
- Requirements on noise generated within cryogenic amplifiers.

E.6.6. Vacuum requirements

These requirements could involve:

- Leakage requirements on the vacuum feed-through.
- Out-gassing requirements of the used materials and constructions.

E.6.7. Shielding and magnetic requirements

These requirements could involve:

- Non-magnetic requirements of dedicated connectors and other devices.
- Shielding around (groups) of I/O channels and components.
- Residual magnetic fields allowed in shielded environment.
- Maximum external magnetic fields to avoid saturation of shields.

E.6.8. Interconnection requirements

These requirements could involve:

- Interconnection between I/O chains and quantum devices. This may be performed by specifying preferred connectors or by specifying geometries to make a more permanent interconnection between cabling and these devices.
- Interconnection between I/O chains and control electronics. This may be performed by specifying preferred (bus) connectors.
- Means for organizing a massive number of wiring between fridge and control electronics. It could be by specifying lengths of cabling outside the fridge or preferred intermediate (bus) connectors at some patch panel outside the fridge.

E.6.9. Footprint requirements

These requirements could involve:

- Mechanical/dimensional requirements on thermalization clamps around cabling.
- Mechanical/dimensional requirements on vacuum feed-throughs.
- Mechanical/dimensional requirements on holes in the plates on each stage.
- Ways to organize thousands of channels for controlling > 1000 qubits in a single fridge.

End of literal text proposal