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CryogenicSolidState_Draft06

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Description

Dear members,

Please find attached an updated version V06 of the draft "Cryogenic Solid State Quantum Computing" document. It has been extended with contribution N136 about modular spin qubits, as agreed during the Paris meeting.

Kind regards,

CEN/TC XXX

Date: 20YY-XX

prEN XXXXX:20YY

Secretariat: XXX

JTC 22 WG3 Quantum Computing

Cryogenic Solid State Quantum Computing

Functional Requirement

Draft 06, 2025-06-09

CCMC will prepare and attach the official title page.

Contents

Page

European foreword

This document (prEN XXXX:20YY) has been prepared by Technical Committee CEN/TC JTC22/WG3 “Quantum Computing and simulation”, the secretariat of which is held by XXX.

This document is currently submitted to the CEN Enquiry/Formal Vote/Vote on TS/Vote on TR.

This document has been prepared under a Standardization Request given to CEN by the European Commission and the European Free Trade Association, and supports essential requirements of EU Directive(s) / Regulation(s).

[NOTE to the drafter: Add information about related documents or other parts in a series as necessary. A list of all parts in a series can be found on the CEN website: www.cencenelec.eu.]

Introduction

One of the many possible hardware architectures for quantum computing is “Cryogenic Solid State Quantum Computing”. This family of architectures include solutions based on superconducting qubits (like Transmons and Flux Qubits), semiconductor spin-qubits, topological qubits, artificial atoms in solids, etc. They have in common that their quantum devices should operate at very low temperatures in a cryostat, and that their operation is controlled from electronics outside the cryostat.

This Technical Report elaborates on the functional descriptions and functional requirements of these architecture families.

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1 Scope

This document describes the functionalities of modules for use in cryogenic solid-state quantum computers and associated functional requirements. It leaves further details about interfaces and quantification of requirements to other, future, CEN/TRs.

This document does not specify specific values, only functional requirements, and may offer informative examples that have been proven in practice. Functional requirements are mainly an enumeration of characteristics that are considered as relevant for future specification as well as a motivation why they are relevant.

Cryogenic solid-state quantum computers belong to an architecture family of which all members make use of a cryostat. The quantum device(s) within the fridge are usually controlled from outside by room-temperature control electronics, through a (huge) number of I/O channels. Examples of members within this architecture family are solutions based on superconducting transmons, superconducting flux qubits, semiconductor spin qubits, topological qubits and artificial atoms in solids.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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EN XXXX, *Title of document*

EN XXXX-1:20YY, *General title of series — Part X: Title of part*

EN XXXXX (all parts), *General title of series*

[NOTE to the drafter: If a dated reference is impacted by a standalone amendment or corrigendum, list the main standard and include a footnote as follows:

EN XXXX:20YY[1], *General title*]

[1] As impacted by EN XXXX:20YY/A1:20YY.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp/

— IEC Electropedia: available at https://www.electropedia.org/

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Note 1 to entry:

[SOURCE: EN XXXX:20YY, definition XX]

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4 Overview

The description of cryogenic solid state quantum computing comprises the hardware and software layers of the CEN/CENELEC *Layer model for gate-based quantum computers* [*], as shown within the box in figure 4.1. It involves an architecture family of which all members make use of a cryostat. The quantum device(s) within the fridge are controlled from outside by room-temperature control electronics, through a (huge) number of I/O channels. Examples of members within this architecture family are superconducting transmons, superconducting flux qubits, semiconductor spin qubits, topological qubits and artificial atoms in solids.

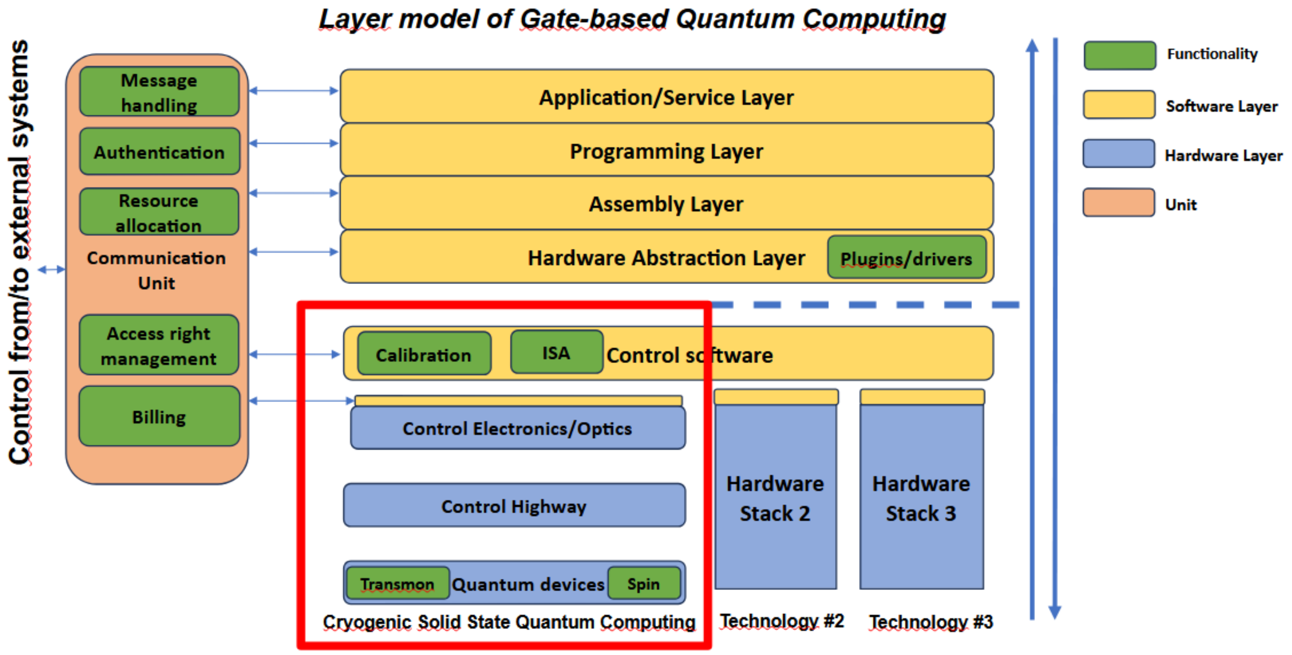

Figure 4.1 *- Overview of the layer model of quantum computing.*
Only the layers within the red box are in the scope of this document.

The description of this architecture family is organized as a stack of the following hardware and software layers, that are described in further detail in succeeding chapters :

- Layer 1: Quantum devices
- Layer 2: Control Highway
- Layer 3: Control Electronics
- Layer 4: Control Software

A module is an implementation that may be constructed from (smaller) modules and components. It could offer the functionality of a single layer, of multiple layers, or just of a fragment of a layer. A module may also support different operating modes, such that it complies with the requirements of multiple members and/or multiple architecture families. As such, the functionality of a module may cover multiple layers and/or families and/or members.

5 Layer 1 – Quantum Devices

The quantum devices in hardware layer 1 are modules with qubits that are operating at cryogenic temperatures and may be implemented as chips and connected by PCBs (Printed Circuit Boards). Different solutions have been developed over time on how to implement the qubits in these devices, including transmons, flux qubits, semiconductor spin qubits topological qubits and NV centers in diamonds. Functional descriptions and functional requirements of these devices are described below.

5.1 Functional Description

The following members have been identified within this architecture family:

- Transmons;
- Semiconductor spin qubits;
- Flux qubits;
- CAT qubits
- Topological qubits;
- Artificial atoms in solids.
- Molecular spins

5.1.1 Functional description of Transmons

A transmon is one implementation of the unit of quantum information. A number of transmons on a chip forms a superconducting quantum processor unit (QPU), which is typically controlled using microwave and DC signals. The microwave signals are used to initialize and manipulate the state of the qubit, to perform quantum operations and readout. The DC signals are typically used to change the qubit's working frequency.

A single transmon qubit is a non-linear LC resonator with a narrow frequency in the bandwidth between 4 and 8 GHz. It has several input and output lines:

- A direct drive line that is used for injecting pulses modulated on a microwave carrier. These pulses are used to perform single qubit operations, such as initialize and manipulate the state of the qubit. The frequency of the pulse is at the same frequency of the corresponding qubit, so within the 4-8 GHz bandwidth, while their phase, amplitude and duration govern the amount of X and Y rotation that the qubit will acquire in the Bloch sphere. Typical values for the amplitude and duration of direct drive signals are -110 dBm (at PCB interface) and <30 ns, respectively.
- A flux line that is used to tune the individual qubit frequency to its desired value via a current. This DC current can be static (qubit at fixed frequency) or can be varied over time to move a qubit in or out of resonance with respect to other qubits, for example during 2 qubit gate operations. Moreover, a low frequency modulation can be over imposed to the DC current, to allow for a more accurate control of the trajectory of the qubit in its frequency and phase. The DC component of the flux signals have a maximum of around 2 mA, while the low frequency modulation might have a bandwidth up to 800 MHz and an amplitude of -110 dBm.
- A readout resonator (typically 6-7 GHz) is used to detect the state of the qubit. A readout tone at the frequency of the readout resonator is injected into resonator for a time between 300 ns up to a micro second depending on the desired read out fidelity. The signal reflected from the resonator has a shift in frequency that depends on the state of the qubit.

A QPU, which consists of an array of transmon qubits may have additional input and output lines such as:

- An (optional) control line for tunable coupling, in QPUs where the qubit-qubit interaction is mediated by a controllable element. Similarly to the flux bias lines for qubits, the DC component of the tunable coupler signals have a maximum of around 2 mA, while the low frequency modulation might have a bandwidth up to 800 MHz and an amplitude of -110 dBm.
- The read-out signals at the feedline output are to be amplified first with dedicated ultra-low noise amplifiers operating at cryogenic temperatures. Commonly used solutions are Traveling Wave Power Amplifiers (TWPA). Typical TWPA-pump signals are narrowband tones with a power of around -40 dBm at around 8 GHz.

5.1.2 Functional description of Spin Qubits

A spin qubit defines an implementation of a unit of quantum information. A multitude of connected spin qubits on a chip define a quantum processing unit (QPU). A spin qubit based QPU is typically controlled by a combination of dc, baseband, and microwave signals. The dc signals are used to bias the QPU to the right operating regime. The baseband signals can be used to perform quantum operations, as well as perform qubit initialization and readout. The microwave signals can be used to perform quantum operations, as well as reflectometry for qubit readout.

Different implementations of spin qubits in quantum dots exists, but in general the quantum information is encoded in one or more electron/hole spins confined in one or more semiconductor quantum dots. The simplest example is a single electron/hole in a quantum dot, where spin-up and spin-down states span the qubit Bloch sphere.

Typically, the spin-qubit is operated in a cryostat within the bore of a cryogenic magnet, the latter to provide a static magnetic field. This can either be a single-axis or multi-axis (vector) magnet.

A single spin qubit is typically controlled by electric signals send to the different input terminals of the qubit. Effective control signals can also consist of components on several input lines, for example to offset crosstalk within the QPU. Typical control input lines of the QPU are defined by electrostatic gates which define a very-high impedance load.

Typically control signals control different physical parameters of the spin-qubit system:

- Charge occupation within the quantum dot system. By shifting the potential levels within the quantum dot system, carriers can be moved between quantum dots.
- Coupling between the different quantum dots. By shifting the potential level of the barriers between different quantum dots in the quantum dot system, the interaction between different quantum dots can be controlled.

From a signal perspective, the control signal inputs can typically be categorized as follows:

- DC signals required to bias the spin-qubit into the correct working regime. These can be applied both to the charge occupation and coupling control parameters. Typical amplitudes of these signals are $-2<V_{dc}<2$ V.
- Baseband signals (100 Hz $< f <$ 1 MHz), used to switch between different operation regimes, such as initialization, manipulation, and readout of the qubit. Typically, these signals consist out of extended plateaus where the same voltage is held, connected with ramped transitions. These can be applied both to the charge occupation and coupling control parameters. Typical amplitudes of these signals are 100-500 mV at the QPU.

- Baseband signals (1 MHz < 1 GHz), used to perform qubit operations. Depending on the encoding and/or operation mode of the qubit, these signals are used to either perform single or multi-qubit gate operations.
  - For some qubit encodings where single qubit operations are performed using baseband signals, these typically consist of ramped rectangular pulses on the charge occupation parameters, with durations of 1-100 ns. The selection between an X or Z rotation is done in this case through a separate control parameter controlling the coupling. Changing the voltage applied to the coupling control line, will tilt the axis around which the qubit will rotate during the baseband pulse, thus switching between e.g. X or Z rotations.
  - Two-qubit interactions can also be performed by applying a ramped rectangular pulse with typical durations of 1-100 ns to the correct control parameter.
  - In addition, these pulses can be shaped differently (e.g. Gaussian pulse) for higher performing qubit operations.
  - Typical signal amplitude might be 10-100 mV at the QPU.
- Microwave signals (100 MHz < f < 20 GHz), used to perform qubit operations. Depending on the encoding and/or operation mode of the qubit, these signals are used to either perform single or multi-qubit gate operations.
  - To perform resonant single qubit operations, these signals consist of short bursts of microwave signals, with a frequency matching the qubit frequency. The duration of the burst controls the angle of rotation, while the relative phase between different bursts controls the rotation axis. As an example, phase shifting a microwave burst by pi/2 with respect to a previous burst will produce a Y rotation, as compared to an X rotation for a burst with phase equal to 0.
  - In addition, these pulses can be shaped differently (e.g. Gaussian pulse) for higher performing qubit operations.
  - Typical amplitude of these signals might be -30 dBm at the QPU.
- Readout signals (100 MHz < 8 GHz), used to perform qubit readout through a resonant readout resonator. Depending on the implementation of the readout, such resonator can be connected to an electrostatic gate or ohmic contact. A readout tone is injected into the resonator for a time of 1-10 microseconds. The reflected signal will have a shift in frequency or amplitude, depending on the exact implementation of readout.
  - Typically, the feed signal for the readout resonator is injected through a directional coupler. The readout signals from the resonator output are amplified with a chain of dedicated low-noise amplifiers, both at cryogenic and room temperature.

Control signals in different frequency domains can sometimes be combined into a single input line, making use of bias-tees/diplexer circuits at different cryogenic stages. It is important to ensure the time-integral of the baseband signals equals zeros in this case, to prevent charging and drift of the bias tee circuitry.

5.1.3 Functional description of Molecular spin systems

Molecular spin systems and in particular molecular nanomagnets (MNMs) [3] have not yet reached the degree of development of the technologies described above but offer peculiar features and competitive advantages that make them a promising platform for general purpose quantum computing. Indeed, several MNMs are multi-level quantum systems, thus potentially offering many well characterized and coherent degrees of freedom that could be exploited for quantum information processing (QIP) [4] at cryogenic temperatures. Another crucial difference from established technologies is the possibility of engineering the energy spectrum and eigenvectors of MNMs at the synthetic level.

This molecular design can provide many low-energy levels potentially protected from decoherence, which could be exploited to develop algorithms that go beyond the binary logic, where qubits are replaced by d>2 quantum systems called qudits. The latter approach could significantly simplify algorithms (such as quantum simulation) and thus lead to important advantages in the current NISQ era. Along this line, the first proof-of-concept quantum simulator was recently implemented on a molecular spin qudit manipulated by radiofrequency pulses [5]. Moreover, d>2 quantum systems can host error-protected logical units, where Quantum Error Correction (QEC) is embedded within single objects. Compared to multi-qubit encodings, the possibility of building a quantum processor with individual elementary physical units, the molecules, each encoding an error resilient logical qubit represents a potential important advantage. Indeed, it considerably simplifies the practical implementation of QEC, by eliminating nonlocal operations, and reduces the number of resources needed to carry out any computation.

Recently, the encoding of an error-correctable logical qubit in a nuclear spin qudit was demonstrated experimentally [6]. The description of these architectures and associated low-level layers is to be developed in future.

5.1.4 Functional description of <other qubit flavors>

Editor's Note: Contributions are invited to add more flavors here. For instance, about CAT qubits, Flux qubits, Topological qubits or artificial atoms in solids. Without input, this section will be removed.

5.2 Functional Requirements

5.2.1 Functional requirements of Transmons

The operation of superconducting qubits can easily be deteriorated by external disturbances from outside the device. Examples are disturbing quantities like temperature, static magnetic fields, EM-fields, vibrations, infrared stray photons, background radiation and cosmic activity. But there may be more issues of relevance that are to be specified, which may be less obvious. Their relevance is explained below.

5.2.1.1 Thermal requirements

Superconducting qubits typically operate at very low temperatures, typically a few milliKelvin, which is close to absolute zero. This is necessary to reduce thermal noise and decoherence in the qubits, which can cause errors in quantum computations.

The low temperatures are achieved using a cryogenic cooling system, which typically consists of a dilution refrigerator with a pulse-tube cryocooler. The cooling system cools the qubits and their local control interconnections to very low temperatures (15 - 50mK), while also providing some level of electromagnetic and mechanical isolation.

Overall, the low temperature needed to operate superconducting qubits and the proper thermalization of all the components are critical factors that must be carefully managed in order to achieve reliable and accurate quantum computations.

5.2.1.2 Static Magnetic field requirements

Stray magnetic fields can also be a significant source of noise and can cause decoherence in the QPU. Therefore, it is important to minimize the levels of magnetic interference in the cryostat.

One approach to reducing magnetic interference is to use shielding materials to block external magnetic fields from entering the cryostat. This can be achieved by using materials such as mu-metal or conductive foils to create a preferential magnetic path around the experimental volume. Additionally, careful placement of the cryostat and the orientation of the sample can help to minimize the amount of magnetic interference that arrives at the QPU.

Another approach is to use superconducting magnetic shields, based on the Meissner effect, that expels stray magnetic fields from the experimental volume below its superconducting transition temperature.

In general, the choice of non-magnetic materials in proximity of the QPU is to be avoided. Static magnetic fields can be compensated per qubit (by flux bias compensation) but is not a scalable solution and requires fully superconducting wiring to the QPU to avoid local dissipation.

5.2.1.3 EM field requirements

Electromagnetic interference can also be a significant source of noise and can cause decoherence in the QPU. Therefore, it is important to minimize the levels of electromagnetic interference (EMI) in the cryostat.

One approach to reducing EMI is to use shielding materials to block external electromagnetic fields from entering the cryostat. This can be achieved by using materials such as mu-metal or conductive foils to create a Faraday cage around the cryostat. Additionally, careful placement of the cryostat and other equipment can help to minimize the amount of EMI that enters the cryostat.

Another approach is to use filters and other signal conditioning techniques to reduce the impact of EMI on the QPU. This can include using low-pass filters to remove high-frequency noise, or using notch filters to remove specific frequencies that are known to cause interference.

To ensure that the levels of EMI are within the required limits, it is important to measure and monitor the EMI levels in the cryostat using electromagnetic field sensors. This can help to identify any sources of EMI and enable corrective measures to be taken.

5.2.1.4 Vibration requirements

Cryostat vibration can be a significant source of noise and can cause decoherence in the QPU. Therefore, it is important to minimize the vibration levels in the cryostat.

One approach to reducing vibration is to use a mechanical support system that isolates the QPU from external vibrations. This can be achieved by using a combination of passive and active vibration isolation techniques. Passive isolation techniques include using rubber pads or springs to decouple the QPU from the cryostat, while active isolation techniques use sensors and actuators to cancel out vibrations in real-time.

Another approach is to use a cryocooler that operates at a higher frequency than the natural frequency of the cryostat, which can help to reduce vibration levels. Additionally, careful placement of the cryocooler and other equipment in the cryostat can help to minimize vibration.

Vibrations in the cables have been shown to induce triboelectric noise in qubits. To ensure that the vibration levels are within the required limits, it is important to measure and monitor the vibration levels in the cryostat using accelerometers or other sensors. This can help to identify any sources of vibration and enable corrective measures to be taken.

5.2.1.5 Infrared stray photon requirements

Stray photons in the infrared range can also be a significant source of noise and can cause decoherence in the qubits. Therefore, it is important to minimize the levels of infrared radiation that reach the qubits.

One approach to reducing infrared radiation is to use optical filters to block out infrared photons. This can be achieved by using filters that are designed to block out specific frequencies of infrared radiation. Additionally, careful placement of the qubits in light tight enclosure is necessary to minimize the amount of infrared radiation that reaches the qubits.

Another important consideration is that the waveguides used to interconnect the QPU typically also contain dielectrics that are transparent to IR radiation, therefore is essential to use IR filters or waveguides that are transparent to microwave frequencies but opaque to infrared radiation to create a shield around the qubits. This can be achieved by using dielectric materials such as copper or magnetic powders mixed in an epoxy matrix.

Overall, protecting the qubits from infrared stray photons is an important factor in achieving reliable and accurate quantum computations, and requires careful consideration of IR filtering and material selection.

5.2.1.6 Shielding requirements against background radiation and cosmic activity

Background radiation and cosmic activity can also be a significant source of noise and can cause decoherence in the qubits by the creation of phononic and quasiparticle excitations. Therefore, it is important to minimize the levels of background radiation and cosmic activity that reach the qubits.

One approach to reducing background radiation is to use shielding materials to block out radiation from the environment. This can be achieved by using materials such as lead or tungsten to create a radiation shield around the QPU to reduce the gamma ray component. With careful choice of radio pure materials in close proximity to the QPU, one can mitigate the amount of local radioactivity and the generation of induced secondary radioactivity.

Ultimately, to further reduce the impact of cosmic activity in the form of neutrons and muons, it is advisable to locate the cryostat in an underground facility under several tens of meters or more of ground.

5.2.2 Functional requirements of Spin Qubits

The operation of spin qubits can easily be deteriorated by external disturbances from inside or outside the device. Examples are disturbing quantities like temperature, magnetic fields, electric fields, vibrations. But there may be more issues of relevance that are to be specified, which may be less obvious. Their relevance is explained below.

5.2.2.1 Thermal requirements

Quantum dot spin qubits operate at cryogenic temperatures, typically between 20 and 1000 mK. This is necessary to reduce thermal broadening of the electron states to improving the performance of commonly used readout techniques. Furthermore, low operation temperatures can aid in minimizing charge noise originating from defects in the QPU material stack that can negatively impact qubit coherence. The low temperatures are achieved using a cryogenic cooling system, which typically consists of a dilution refrigerator with a pulse-tube cryocooler. The cooling system cools the qubits and their local control interconnections to very low temperatures (phonon temperature of <50 mK), while also providing some level of electromagnetic and mechanical isolation. To also achieve equally low electron temperatures, proper thermalization of all components and filtering of relevant lines should be carefully managed.

5.2.2.2 Magnetic field requirements

Magnetic field fluctuations and/or distortions can be a source or decoherence or operation errors with the QPU. It is therefore important to minimize the levels of magnetic interference in the cryostat. As an example, careful placement of the cryostat in relation to sources of magnetic noise, such as transformers or large-current carrying wires can help to minimize magnetic interference. To minimize the distortion of applied magnetic fields, care should be taken to avoid the use of magnetic materials in the vicinity of the QPU, avoiding magnetization because of the applied magnetic fields.

5.2.2.3 Electric field requirements

Electric field fluctuations can be a source of decoherence or operation errors within the QPU. In particular, for spin-qubit implementations where a coupling between electric and magnetic fields is implemented for rapid qubit control, e.g. through spin-orbit interaction or the presence of micromagnetic structures. In such case, fluctuations of the applied control voltages can directly impact the qubit energy splitting and lead to decoherence. As a result, the qubit coherence can be impacted by noise with a wide range of frequencies, including slow (near dc) fluctuations. Therefore, it is important to minimize the levels of electric interference and noise on the control lines. One approach to reduce electric noise is by filtering and/or attenuating the control lines going into the cryostat. Exact filter bandwidths and attenuation values depend on the requirements of each specific line and should be tailored to the application. Another approach is to use control electronics that have a low output noise, in particular within the required output bandwidth, as this is particularly difficult to filter.

5.2.2.4 EM field requirements

Electromagnetic interference can also be a significant source of noise and can cause decoherence in the QPU. Therefore, it is important to minimize the levels of electromagnetic interference (EMI) in the cryostat. One approach to reducing EMI is to use shielding materials to block external electromagnetic fields from entering the cryostat. This can be achieved by using materials such as conductive foils to create a Faraday cage around the cryostat. Additionally, careful placement of the cryostat and other equipment can help to minimize the amount of EMI that enters the cryostat. Finally, when the bandwidth requirements of certain control lines permit, using twisted pair wiring can aid in reducing EMI pickup in the control highway.

5.2.2.5 Vibration requirements

Cryostat vibration can be a significant source of noise and can cause decoherence in the QPU. While the qubits themselves are not affected by the vibrations, noise can couple into the system through the generation of effective electric of magnetic fields. Vibrations in the cables have been shown to induce triboelectric noise. Vibrations of the qubit with respect to the cryogenic magnet can lead to effective magnetic noise. Therefore, it is important to minimize the vibration levels in the cryostat. One approach to reducing vibration is to use a mechanical support system that isolates the QPU from external vibrations. This can be achieved by using a combination of passive and active vibration isolation techniques. Passive isolation techniques include using rubber pads or springs to decouple the QPU from the cryostat, while active isolation techniques use sensors and actuators to cancel out vibrations in real-time. Another approach is to use a cryocooler that operates at a higher frequency than the natural frequency of the cryostat, which can help to reduce vibration levels. Additionally, careful placement of the cryocooler and other equipment in the cryostat can help to minimize vibration.

5.2.2.6 Signal integrity requirements

Depending on the specific implementation, the accuracy of the quantum operations can be sensitive to the exact pulse shape arriving at the QPU. The usage of various components with different bandwidths and (effective) filter characteristics in the control highway will lead to a deformation (in the time domain) of the input signal at room temperature. One approach to reduce these effects is by measuring the deformation and predistortion of applied signals to correct for the imperfections in the control highway. Another approach is to design the control highway in such a way that within the relevant bandwidth, minimal signal distortion is present.

Secondly, cross talk between different control lines can lead to unwanted quantum operations and/or decoherence. One approach to overcome this is by minimizing crosstalk between different control lines, through careful design and implementation of proper shielding/grounding of the control highway. Another approach to overcome this is by applying correctional operations to the QPU, to undo effects caused by the crosstalk of previous operations. To ensure that levels of crosstalk are within the required limits, it is important to measure and monitor crosstalk between various control lines. This can help to identify any sources of crosstalk and enable corrective measurements to be taken.

5.2.3 Functional requirements of <other Qubit flavors>

Editor's Note: Contributions are invited to add more flavors here. For instance, about CAT qubits, Flux qubits, Topological qubits or artificial atoms in solids. Without input, this section will be removed.

6 Layer 2 – Control Highway

The control highway is a hardware module for connecting qubits in a cryogenic environment with control electronics at room temperature. It includes all I/O channels (input-output) needed for transporting downstream signals to qubits up to microwave frequencies and for returning upstream signals carrying their response.

6.1 Functional Description of the Control Highway

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

Figure 6.1 shows example channels in a possible control highway dedicated to a quantum computer using transmons. 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 downstream 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 upstream read-out channel to reduce the overall number of channels. Travelling wave amplifiers may be used for amplifying these response signals, and may need an extra TWPA pump channel for powering. As such, a 50 qubit transmon quantum computer may have 102 or more I/O channels.

The involved I/O channels may be build-up from a chain 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 throughs.

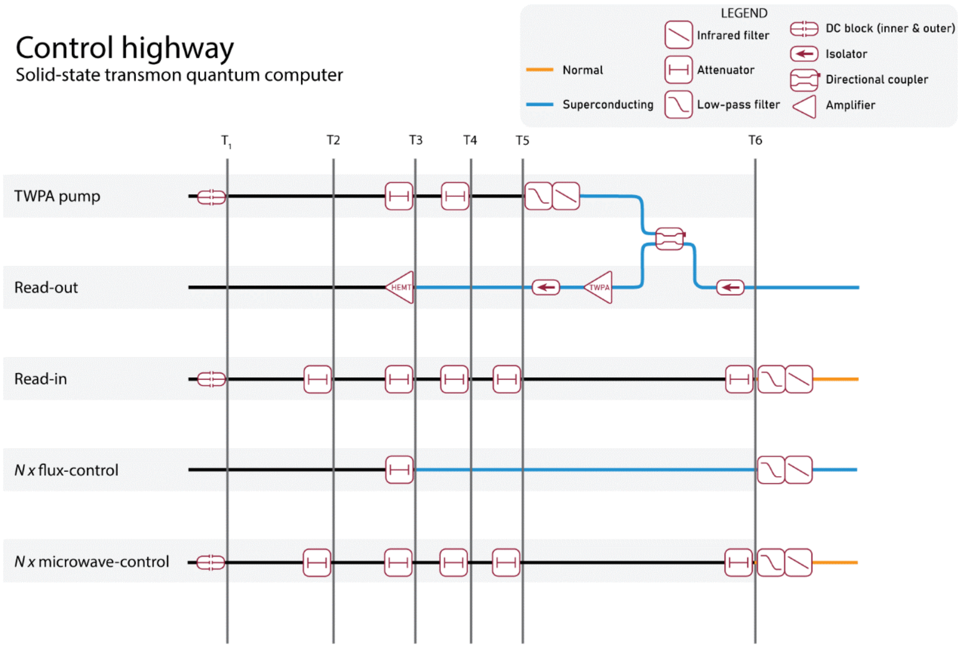

Figure 6.1 An example functional diagram of a control highway applicable to a particular transmon architecture.

A design of a typical implementation usually starts with a functional diagram, including the length of each temperature stage, and position of desired components in each chain. Furthermore, realistic values for those functional requirements that are relevant for the application.

6.2 Functional Requirements of the control Highway

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.

6.2.1 Transmission requirements

Primary requirements on the transmission may include:

Masks for pass-band frequencies. These are 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 specified impedance. This could be offered for the full chain, as well for each stage and/or segment/component.

Masks for out-of-band frequencies These are 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.

An effective reducing of out-of-band noise up to even infra-red frequencies might be of importance for qubits that are sensitive for it. For instance, if pulses are to be modulated on an 8 GHz carrier, these masks might be specified up to 100GHz or beyond. It is not obvious to achieve that with a low-pass microwave filter. This is because of the distributed nature of filters with transmission lines that have the fundamental limitation of passing signals above the break frequency. For instance, a 7th-order stripline filter up to 10 GHz, can have an out-of-band passband between 30 and 60 GHz.

Therefore the use of a microwave filter with an additional “IR-filter” may be essential to be compliant with out-of-band specifications. Such IR-filters are usually based on transmission lines with very lossy dielectric materials (like metal-powder filters), which can offer an extra slope (expressed in dB/GHz) up to 100GHz or more.

DC/low-frequency characteristics. These are requirements for DC-currents and low-frequency characteristics, for instance to separate bias currents from signals. When applicable, the maximum DC currents that may flow should be specified.

This requirement may become extra relevant when the current has to flow through a super conducting section in the chain. Such section will loose its super conductivity when that DC current a critical current.

Another reason to specify a maximum current is dissipation in lossy elements (cabling, attenuators, etc). Dissipation may heat-up the channel and exceeds the cooling capacity of the cryostat.

Step and/or impulse response These are 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 line is terminated with an impedance of a quantum device that is quite different from 50 ohm, it may not be useful to specify response under 50 ohm conditions.

6.2.2 Reflection requirements

Reflections, due to mismatched elements, can cause rippling in transfer functions and distortion of pulses at the end of the chain. But this does not mean that the existence of reflections will always harm. Reflections against filters will always occur for stop-band frequencies, and the same applies for mismatched components. However, reflected pulses will quickly fade-away in lossy lines and will be fully absorbed in matched attenuators.

These lossy conditions are quite common in cryogenic chains. Therefore reflection requirements for *individual* components in the chain should not be over-specified if the impact of these reflections are hardly visible in the transmission properties of the *full*-chain.

What really matters is specifying limits to rippling in the transfer function and deformation of pulse and step responses of the full chain under realistic termination conditions. What occurs internally is hardly of any relevance.

6.2.3 Crosstalk requirements

Crosstalk between channels will cause that a pulse intended for one qubit, will also appear (in weakened form) at other qubits. One should distinct between two different measures of crosstalk: NEXT and EL-FEXT.

- NEXT, or Near End Crosstalk, between two channels is measured by injecting a signal into one side of a channel and observing the crosstalk at the same side in another channel. NEXT will then be the ratio between crosstalk and injected signal levels.
- EL-FEXT, or Equal-Level Far End Crosstalk, is measured by injecting a signal into one side of a channel and observing at the other side what signal level will arrive and what crosstalk will arrive in another channel. EL-FEXT will then be the ratio between arriving crosstalk and arriving signal.

EL-FEXT to the cold side of I/O channels is of primary relevance, due to the typical signal levels that occur in these I/O channels. If a pulse is injected to control a particular qubit, then the EL-FEXT may disturb the quantum state of other qubits. It also may result in a false response signal from qubits in general.

NEXT at the warm side of upstream channels is also if primary relevance for the same reason. The amplified response of a qubit in an upstream channel may still be very weak and can easily be disturbed by pulses injected in downstream channels.

Again, one should not over specify crosstalk requirements. Crosstalk can also occur in the transmission lines within the quantum device. These are often shaped as a microstrip structure, and crosstalk between microstrips is usually much higher than crosstalk between stripline or coaxial structures. Crosstalk between channels in a quantum device put an upper limit to what crosstalk limits are reasonable within a control highway as a whole.

6.2.4 Heat flow requirements.

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 should be thermalized at each temperature stage. Most of the heat flow through the cabling will then flow via the thermal anchors 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.

Another source of heat is dissipation of signals in attenuators. They will heat up, and if all attenuation is concentrated at the lowest temperature stage, it may challenge the cooling capacity of the fridge as well as increasing the thermal noise generated within these attenuators. A good solution for restricting the hot spot temperature at the resistors of the attenuator is by mounting these attenuators close to a thermal anchor. An even better way of cooling is to integrate the attenuator in a flat transmission line (like strip lines) and to drain the heat away by mounting directly between the plates of a thermal anchor.

Therefore heat flow 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 that are installed for draining away unwanted heat flow into the cooling system.
- Transversal thermal conductivity of attenuators to minimize raise of hot-spot temperatures. This increase of hot-spot temperature in the resistors of the attenuator will increase the thermal noise generated by these resistors.

6.2.5 Noise requirements

Each I/O channel suffers from adding extra noise to the signal. Even passive lines generate thermal noise, because the introduce loss.

Without any loss in a channel, and (hypothetical) noise-free control electronics, this noise level would be at least the thermal noise of a 50 ohm resistor at room temperature. Therefore, attenuators are to be 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 distributed over the chain 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.

Under operational conditions, however, signals will be dissipated in the attenuators, which is the reason why attenuation has to be distributed. This can be explained as follows.

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, a measure that 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.

Therefore noise requirements on the control highway as a whole 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.
- Requirements on noise generated within cryogenic amplifiers.

When specifying noise requirements, one should also account for the noise floor of the control electronics.

6.2.6 Vacuum requirements

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.

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.

Therefore vacuum requirements on the control highway as a whole could involve:

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

6.2.7 Interconnection requirements

The more qubits that are to be controlled the more challenging it will become to connect them all to room-temperature electronics. Therefore interconnection requirements on the control highway 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. This becomes even more important when connection are to be made directly to the quantum chips.
- 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.

6.2.8 Footprint requirements

Different cryostat implementations are commercially available, and each of them may have different dimensions. Vacuum feed-throughs should fit on holes in the fridge, space near these holes outside a fridge is limited which may trouble access to connectors, cabling modules should fit inside these fridges, and the number of modules that can be mounted in a fridge is limited.

Therefore footprint requirements on the control highway as a whole could involve:

- Mechanical/dimensional requirements on vacuum feed-throughs.
- Mechanical/dimensional requirements on thermalization clamps around cabling.
- 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.

6.2.9 Vibration requirements

A cryostat may use a powerful pump which may induce mechanical vibrations in the setup as a whole. This energy might disturb the control of qubits.

One possibility is that the wiring itself is sensitive for these vibrations and may convert this mechanical energy into (weak) signals inside the cabling. Another possibility is that these vibration changes the transmission properties and modulate the signals flowing into the channels. Bending a cable may make it a bit longer and will then increase the delay through that channel.

Therefore vibration requirements could involve:

- limits to induced signals as can be observed at the end of the channels
- limits to induced variations of transmission properties

6.2.10 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.

Editor's Note: Contributions are invited to add functional requirements on active elements (like TWPA, HEMT), and fiber optic solutions.

7 Layer 3 – Control Electronics

Hardware layer 3 covers all electronics for generating, receiving, and processing microwave, RF and DC signals. Some implementations make use of routing/switching and/or multiplexing of control signals at room temperatures. It may have some firmware on board to guide the signal generation and signal processing.

As shown in Figure 4.1, this layer includes a small software layer in order to translate a unified way to instruct the control hardware into implementation-specific (proprietary) commands tailored to the electronics. An example is the translation of wave pulse shapes, defined as an array of samples, into proprietary commands for storing them into the memory of an AWG (Arbitrary Waveform Generator).

7.1 Functional Descriptions

7.2 Functional Requirements

8 Layer 4 – Control Software

The control software refers to the software systems and tools designed to manage, coordinate and optimize operations dictated by higher level languages. Thus, the software plays a crucial role in translating higher-level quantum assembly instructions into executable instructions that can be processed by quantum processors.

This layer may include an instruction set architecture (ISA), error correction means and calibration functionalities (as seen in Figure 8.1).

- **ISA** (Instruction set architecture) refers to a lower-level method of defining operations on a quantum computer. Instead of defining specific gates, this layer defines gates (or other instructions) as operations, using pulses pulsed for a certain time, on specific qubits. An example of an instruction set architecture is pulse level programming where a user can specify wave pulses on qubits instead of gates. This requires knowledge of the system's control equipment as well as the topology and qubit nature.
- **Error correction** refers to all low-level techniques to enable error-robust physical operations. Error correction as a whole is a functionality distributed over various (higher) layers. The control software handles only low-level techniques, such as detection or simple corrections, partly autonomously and partly controlled from higher layers.
- **Calibration** refers to low-level methods to stabilize the hardware by continuous monitoring of hardware performance to maintain optimal operation.

8.1 Functional Descriptions

8.1.1 Instruction Set Architecture

The aim of an instruction set architecture (ISA) is to convert a sequence of machine-specific instructions from higher layers into commands for the control electronics, to control individual qubits. As such the ISA has full awareness of the underlying quantum hardware and its topology.

Due to the ISA's knowledge on the quantum hardware, it also has the responsibility of handling the execution timings and scheduling of individual instructions, such that higher layers should only know their sequence.

On input, the ISA may receive for instance instructions from higher layers to change the quantum state of qubits (gate-instructions, read-out qubits (measurement instructions)) or any other instructions to interact with all available qubits. These instructions can be fed to the ISA as for instance (binary) machine instructions, as (ascii) human readable instructions, or as function calls. Instructions intended for controlling one or two qubits may be fed one by one to the ISA, but it is more efficient if an ISA can handle many of them in parallel as a "vector" of instructions to interact with an ensemble of qubits simultaneously.

Higher layers may push these instructions into a buffer within the ISA each time the ISA signals to be ready for it. Alternatively, an ISA may also poll these instructions out from a buffer within higher layers each time the execution of a previous group of instruction has completed. This includes the polling of requests and instructions given by many users. In all cases, it requires a well-defined interface (API) with the above layer(s), as well as a well-defined instruction set language (such as OpenPulse [1] or Pulser [2]).

An ISA may handle gate-level instruction as well as pulse-level instructions. Both may be mixed in a single compilation pass for bypassing specific gate instructions, which can be parsed in the SDK by the user. Gate level instructions are considered to be any set of operations that can be parsed onto universal gate based quantum computers regardless of the hardware while pulse level instructions are operations that are heavily dependent on the system's physical architecture. The ISA will thus support instructions to specify the exact waveform of a pulse to be fired to a specific qubit, as well as an ensemble of pulses where each pulse has its own waveform and relative delay.

The common way of sending instructions to the ISA are via higher level layers such as the asembler or programming layer. Alternatively a user may be allowed by the communication module to access the control software layer directly or via the hardware abstraction layer, and supply ISA readable instructions directly.

On output, the ISA sends commands to the control hardware, to fire for instance pulses to qubits or to read-out their response via a measurement. This requires that the ISA is fully responsible of the timing of all these commands.

If a pulse is to be applied to a qubit, the ISA may calculate its characteristics on the fly, such as waveform / pulse-shape and magnitude. But it may also read predefined characteristics from a library created by other software units, stored somewhere in the control software layer or in the control electronics layer.

In all cases, it requires a well-defined interface (API) with the control electronics(s) as well as a well-defined command-set.

Figure 8.1 illustrates from an example work-flow of how an ISA contextually may interact with other functionalities in the stack. When multiple users access the quantum computer, the communication module verifies at which layers they may access the full stack.

- If a (production) user may only access the stack from the top of the assembly layer (or higher layers), the assembler compiler/interpreter will then convert assembly instructions into hardware-abstracted ones for the hardware abstraction layer. These instructions are then compiled into machine-specific code by the control software layer, where the instruction set architecture optimally schedules the user's program. It also determines the program's placement in relation to other users' tasks, ensuring efficient execution across the system.

- If a more dedicated user/designer may also access the stack from the top of the control software layer, he should be fully aware of the hardware-specific aspects of the quantum computer and generate machine-specific instructions for the ISA himself.

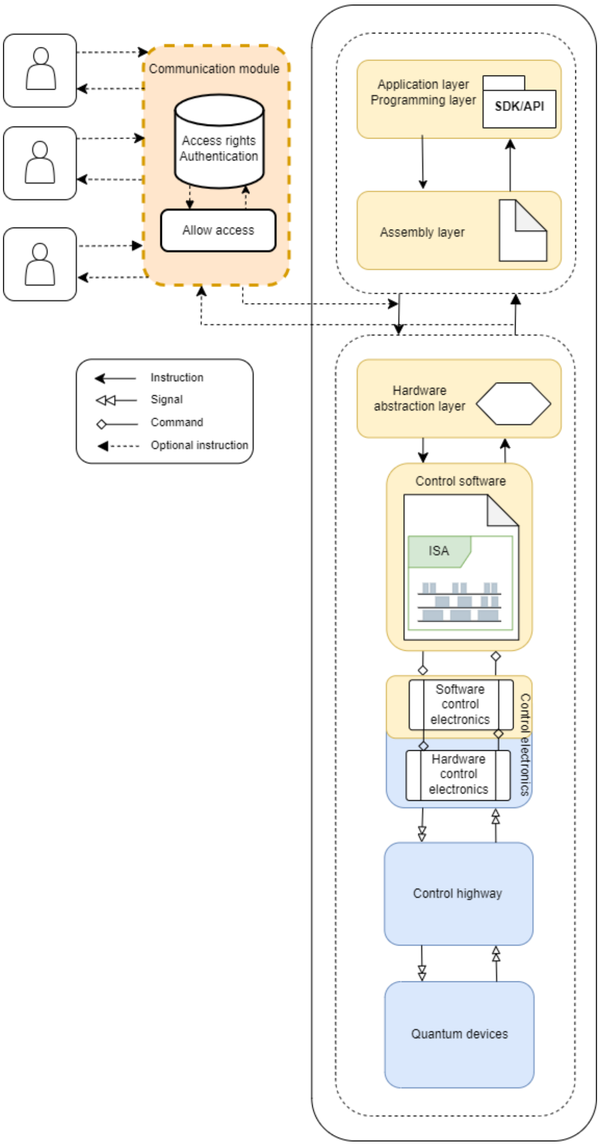

***Figure 8.1** Workflow of instruction set architecture functionality. The colored boxes denote the layer (with a corresponding title) and the arrows show the different information type exchanged.*

Editor's Note/questions:
- Should ISA be responsible for knowing priority of users for program scheduling?
- Hardware abstraction layer local or non-local?
- Instruction, signal and commands correct?
- Assembly layer obfuscates many specific commands that may be relevant to the ISA (compiling/decompiling), how do we deal with this?

8.1.2 Calibration

Editor's Note:
Contributions are invited to fill-in this section

8.1.3 Error Correction

Editor's Note:
Contributions are invited to fill-in this section

8.2 Functional Requirements

8.2.1 Instruction Set Architecture

Editor's Note:
Contributions are invited to fill-in this section.
Topics for considerations are functional requirements related to an ISA, including:

- *Hardware characteristics and ways to inform the control software and higher layers about it*
  - *Topology of the backend*
  - *Time parameters of pulses*
  - *Possible waveforms/pulse shapes*
  - *Accessible qubits (global vs local pulses)*
  - *Qubit dead times*
- *Feedback from communication module between device backend and API*
- *Pre-compilation error handling supplied to user*
- *Compilation of quantum assembly code to instruction set architecture*

9 Benchmarking (Low level)

Editor's Note: Contributions are invited to add text on benchmarking and functionality to enable benchmarking. Without input, this section will be remoived.

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