Engineering Quantum Computing at Politecnico di Torino

from technological modelling to industrial software applications

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Quantum Computing and High Performance Computing

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The PoliTO team on Quantum Computing



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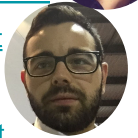


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TECHNOLOGY

APPLICATIONS

Hardware for Quantum Computing

- Many technologies (superconductors, trapped ions, molecules, *etc.*) have been proposed as candidate for the implementation of a quantum computer.
- They can significantly differ in terms of:
  - temperature;
  - magnetostatic fields;
  - bandwidth of EM signals employed for the implementation of quantum gates;
  - non-ideality (*e.g.* decoherence and relaxation) timescales;
  - native gates;
  - fabrication and maintenance costs.
- A system capable of evaluating the quality of a quantum circuit/algorithm on different quantum computers, taking always into account their pros and cons, is required.

TECHNOLOGY

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Methodology for comparing quantum technologies

TECHNOLOGY

Given the same circuit/algorithm, technologies can be compared in terms of:

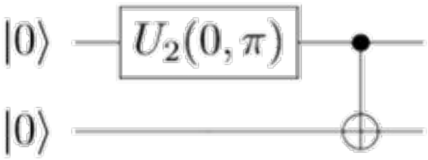
- effects of non-idealities in the execution;
- native quantum gates;
- qubits connectivity;

circuit transpiling

- feasibility of a quantum circuit according to the classical hardware instrumentation required for manipulating qubits (bandwidth, time duration of elementary pulses, amplitude of electromagnetic signals, magnetostatic fields, *etc.*).

Comparison must be simplified by taking into account the main features of each technology

Example: Bell state circuit



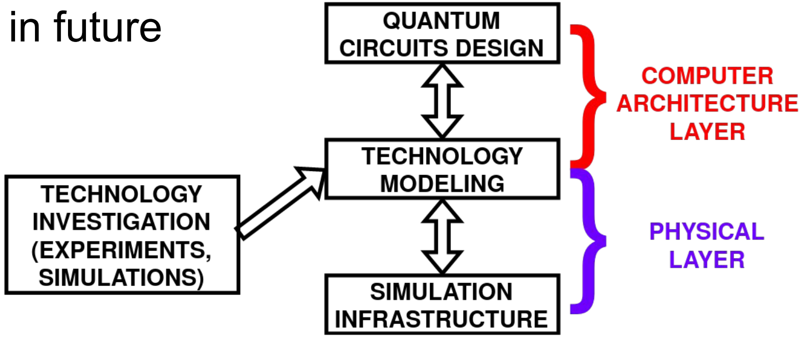
Superconducting qubits

Trapped ions

Methodology for analyzing a QC technology

TECHNOLOGY

- Perspective: development of a software tool for designing and comparing the execution of quantum circuits with different technologies (superconductors, trapped ions, molecules, *etc.*).
- Each technology is described by a simplified model which takes into account its main physical properties, in particular non-idealities, starting from experiments or physical (*e.g. ab-initio*) simulations.
- An optimized simulator for non-ideal quantum circuits is required.
- The integration of this infrastructure into Quantum Computing frameworks as Qiskit is going to be proposed in future



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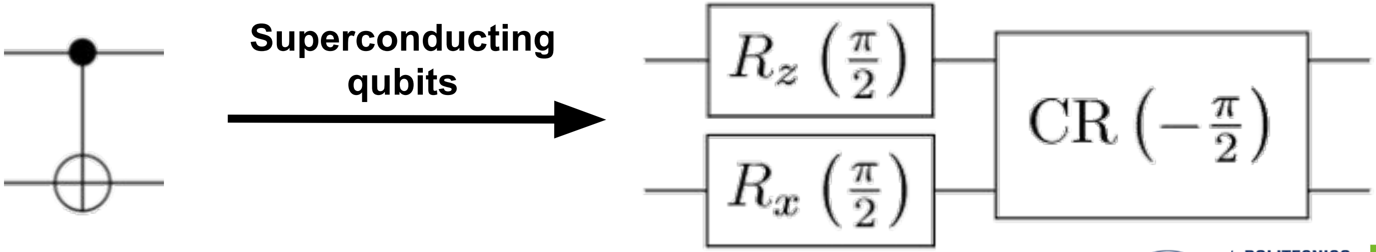
Quantum circuits design

- The simulator is thought for ensuring quantum circuits design with more degrees of freedom:
  - Setting the parameters of each quantum gate according to its physical implementation (core)
  - Using hardware-agnostic gates of a HDL (currently OpenQASM), with automatic derivation of the parameters of *physical gates*
- *Ad-hoc* quantum circuit transpiling strategies according to the exhamined technology can be defined.

TECHNOLOGY



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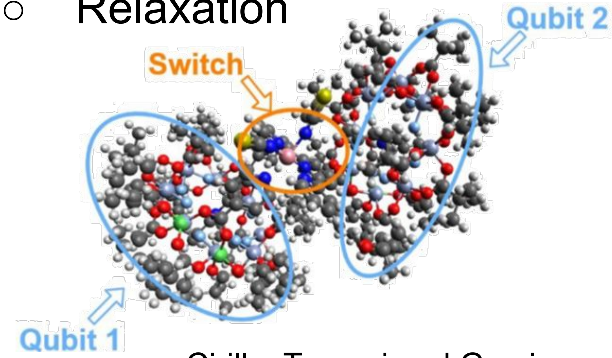
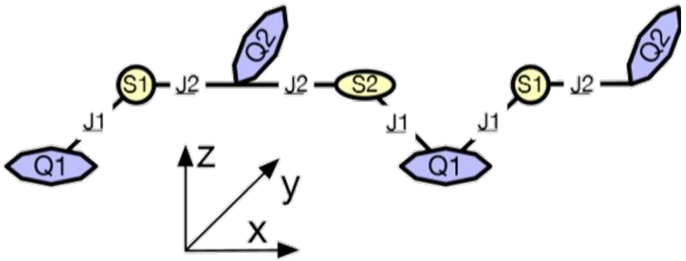
A practical example: Cr_7Ni molecular nanomagnets

Main features:

- Chain of spins exploited for encoding qubits and switches
- Possibility to implement $R_{x,y}(\theta)$ and Controlled-phase gate (universal set of quantum gates)
- Non-idealities:
  - Interaction between adjacent spin qubits
  - Decoherence
  - Relaxation

TECHNOLOGY





Cirillo, Turvani and Graziano, *IEEE Transactions on Nanotechnology*, 18(2019), pp. 1027-1039.

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A practical example: Cr_7Ni molecular nanomagnets

1. Build simplified descriptions of qubit and switch evolutions in presence of external EM fields (with the possibility to regulate pulse shape, duration, amplitude, *etc.*) and non-idealities (qubit-qubit interaction, relaxation, decoherence).
2. Define single-qubit and Controlled-phase gates, which are the micro-instructions of the computer architecture, over the simplified models of the system evolution.
3. Define more complex gates based on microinstructions, eventually optimizing with circuit transpiling and virtual-Z gates.
4. Design a quantum circuit/algorithm with low-level routines or in OpenQASM.
5. **Evaluate the results in presence of non-ideality phenomena**.

TECHNOLOGY

```
function singlequbitevolution(...){
      ...
}
function singleswitchevolution(...){
      ...
}
function switchinteractionqubits(...){
      ...
}
```

→

```
qs.rotate(0,pi/2,-pi/2)
qs.rotate(1,pi/2,-pi/2)
qs.controlledphase(0,1,pi)
qs.rotate(1,pi,-3*pi/2)
qs.measure()
```

→

```
OPENQASM 2.0;
include "qelib1.inc";
qreg q[2];
creg c[2];
h q[0];
cx q[0], q[1];
measure q -> c;
```

Applications

- Optimization of Constraint Satisfaction Problems
  - Graph exploration
- Apply QC to IT problems
  - Internet of Things
    - Air Pollution Monitoring sensor networks
  - Process Scheduling
- Investigation on already available Quantum-Proof DLT
- Integration IoT + DLT
  - Food-Chain use case

APPLICATIONS

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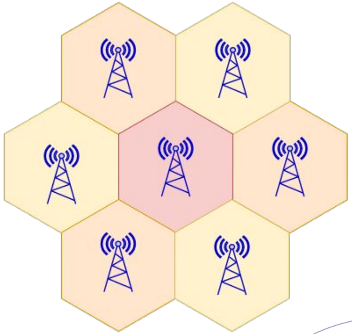
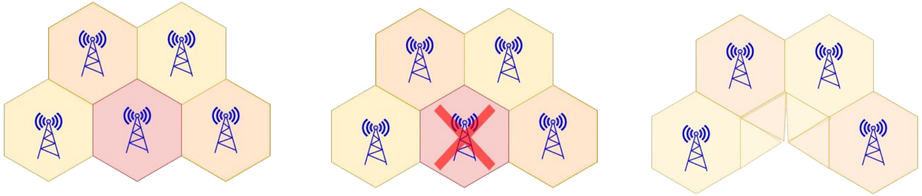
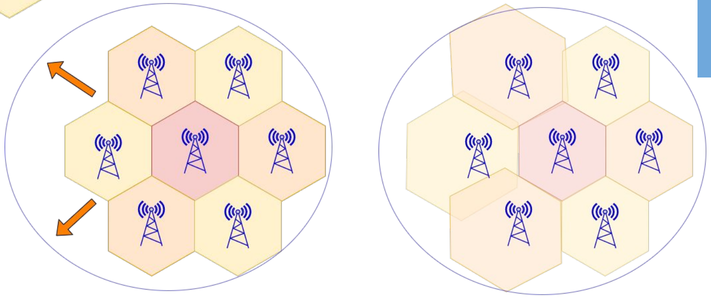
Collaboration with TIM in Telco Industry

- Optimization of LTE network infrastructures
  - Physical Cell Identifier (PCI) Planning
  - Self-organizing Networks (SON)
    - Configuration
    - Optimization
    - Healing







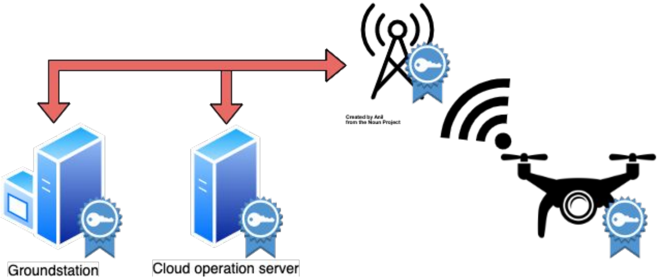
APPLICATIONS

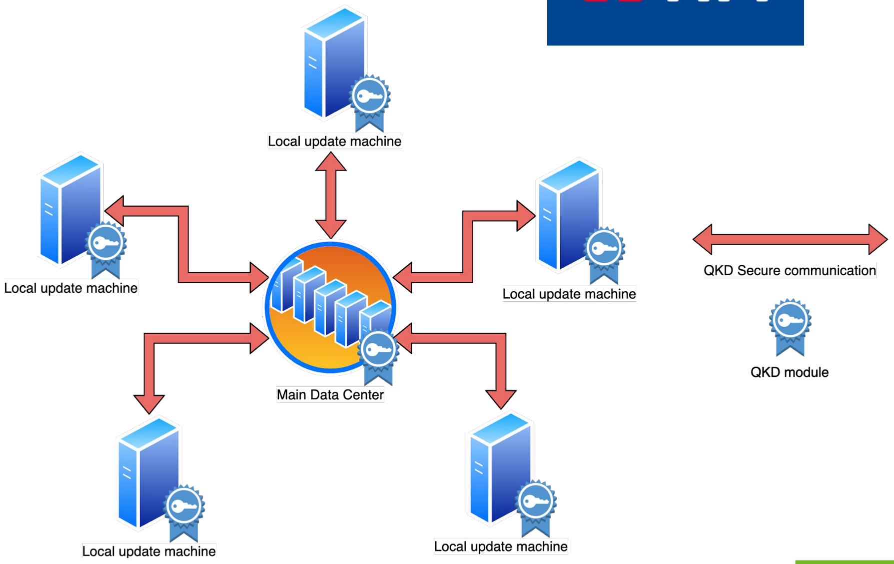
Collaboration with TIM in Telco Industry

- Quantum Key Distribution applications
  - Automotive
  - Drones
  - Computer networks
  - DLT

TIM

APPLICATIONS





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QKD in softwarised networks

- **Quantum key distribution (QKD)**
  - cryptographic method for **random secret keys exchange**
  - based on quantum mechanics effects (e.g. superposition, entanglement)
  - beyond the assumed computational complexity of mathematical problems
  - **quantum-resistant**
  - many protocols have been developed (e.g. **BB84**, E91)
- **QKD applications**
  - key exchange in Network Function Virtualization (NFV) / Software-Defined Network (SDN) scenario
  - using optical networks, optical switches
  - commercial solutions (e.g. ID Quantique ID3100 Clavis)
  - replacing the classic algorithms for key exchange in many protocols:
    - IPsec, IKE (network layer)
    - TLS (transport layer)
    - IEEE 802.1 MACsec (data link layer)
- **QKD standards and helpful frameworks**
  - ETSI GS QKD (https://www.etsi.org/committee/qkd)
  - Qiskit (https://qiskit.org)

APPLICATIONS

Activities on QKD

- **QKD and Virtual Network Security Functions (VNSFs)**
  - are distributed virtual security appliances
  - shall communicate over long distances on distributed infrastructures
  - typically leverage on SDN and VPN protocols
  - orchestration platforms are in place for their management (e.g. OpenStack)
  - QKD support for secure key exchange

- **Analysis of criticalities regarding QKD**
  - BB84 protocol vulnerabilities
    - classical channel required
    - authentication of the parties
  - QKD attacks
    - Time-shift attack (TSA)
    - MITM attack

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Quantum pattern matching for genomic sequencing

- Modern genomic sequencing requires huge computational resources ⇒ test potential of QC speed-up ($\sqrt{N}$ speed from Grover's algorithm)
- Several QC algorithms have been proposed for this task. Among others 2 top performer (all based on Grover's algorithm):
  - ***Quantum Associative Memory*** (D. Ventura, T. Martinez,Information Sciences 124 (2000) 273-296)
  - ***Quantum pattern recognition*** (Konstantinos Prousalis & Nikos Konofaos, *Scientific Reports*, volume 9, Article number: 7226 (2019)
- Algorithm written with Qiskit, validated against original Quantum Assembly implementation and run on simulator with limited number of qubits (small sequence of reference encoded genome from HIV virus)

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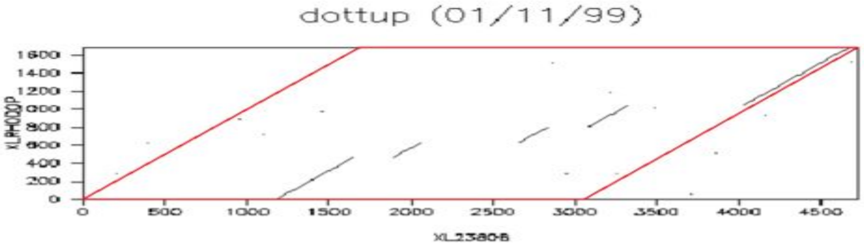
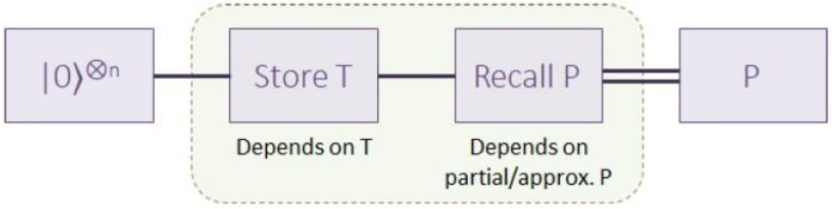
Quantum Pattern Recognition



- Recurrence dot matrix between two genomic sequences (having 1 where the corresponding characters matches and 0 otherwise).
- The algorithm initializes the quantum register as a superposition between all the diagonals from the recurrence dot matrix together with their corresponding indices.
- After initialization, we can search for binary search patterns (that we can interpret as “matching bit maps”) inside this quantum database.

Quantum Associative Memory



- Its goal is to find and complete a search pattern containing wildcard characters (i.e. *?*) inside a reference genome.
- The quantum register will be initialized as a superposition of all the possible sub-sequences from reference genome of length *m* (where *m* is the size of the chosen search pattern), together with their indices.

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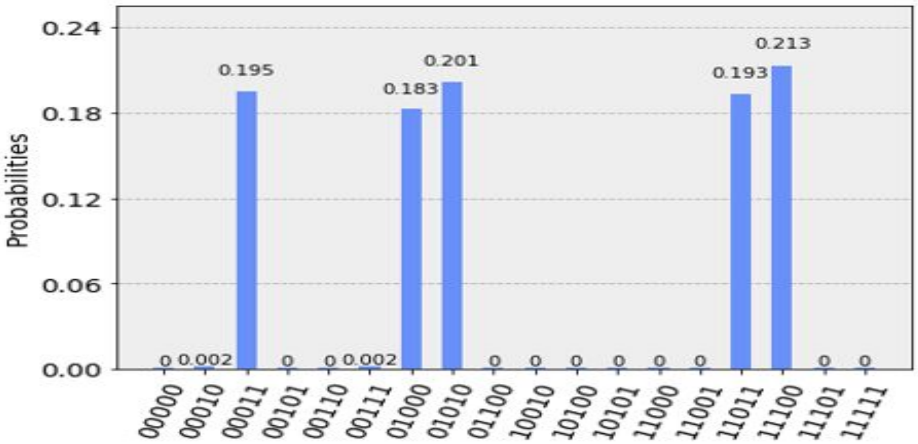
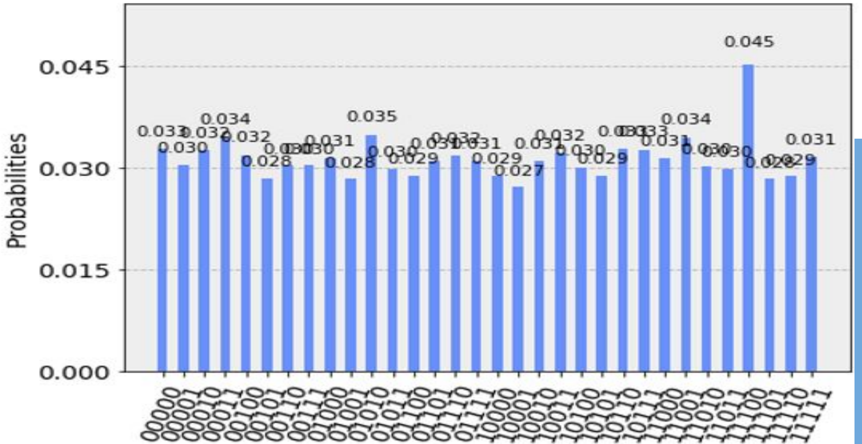
Quantum Pattern Recognition



Reference: TGGAAGGGCTAATTCACTCCCAAAGAAGACAA
Search patterns: *111*, *110*, *011*, *101*.

- Total qubits=18, circuit depth=164673
- Very accurate results but too large circuit depth for practical application on present QC

Quantum Associative Memory



Reference: 32200222130033101311100020020100
Search patterns: *203*

- Total qubits=19, circuit depth=7049
- It works, it is relatively “light” but is not robust against real-world QC with noise

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Education: courses on QC at PoliTO

- *Nano & Quantum Computing* (Graduate course)
  - Held by Prof. Mariagrazia Graziano since 2018-2019 A.Y.
    - Quantum hardware
- *Quantum Computing* (Graduate course)
  - Held by Proff. Bartolomeo Montrucchio and Anna Filomena Carbone since 2018-2019 A.Y.
    - Quantum algorithms
- *Introduction to Quantum Information and Quantum Computation* (undergrad.)
  - Held by Proff. Anna Filomena Carbone and Bartolomeo Montrucchio since 2019-2020 A.Y.
    - Overview of quantum information and computation, hints about hardware

EDUCATION

Laboratory sessions coherent with the contents of each course:

- Qiskit
- D-Wave

Education, Dissemination and Advocating

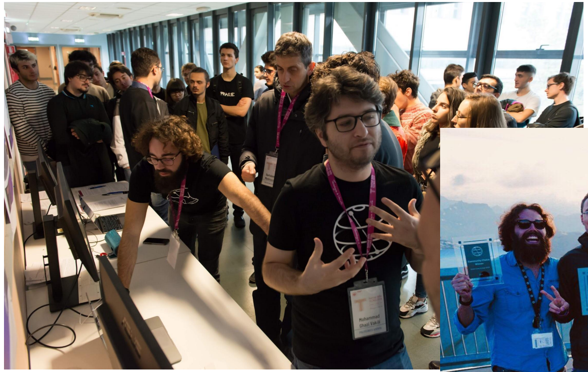
EDUCATION

DET

- 1 Ph.D. Thesis under development, 6 M.Sc. theses on various topics (technology and circuits)

DAUIN + LINKS

- 1 M.Sc. thesis on quantum algorithms



Festival della Tecnologia
PoliTo 2019

Qiskit Camp Europe 2019
Community Choice Award

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Thank you for your attention

Backup

Education: M.Sc. theses

DET (Prof. Mariagrazia Graziano)

- G.A. Cirillo, “A quantum computation model for molecular nanomagnets”, April 2018
- M. Simoni, thesis on molecular QC with expected completion in March 2020
- Four theses on quantum annealing, modeling of technologies different from molecular ones and quantum circuits design, under development

DAUIN (Prof. Bartolomeo Montrucchio) + LINKS

- R. Palmieri: “Implementation and testing of current quantum pattern matching algorithms applied to genomic sequencing”

EDUCATION