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XXXVI Cycle

Emerging technologies for quantum information processing

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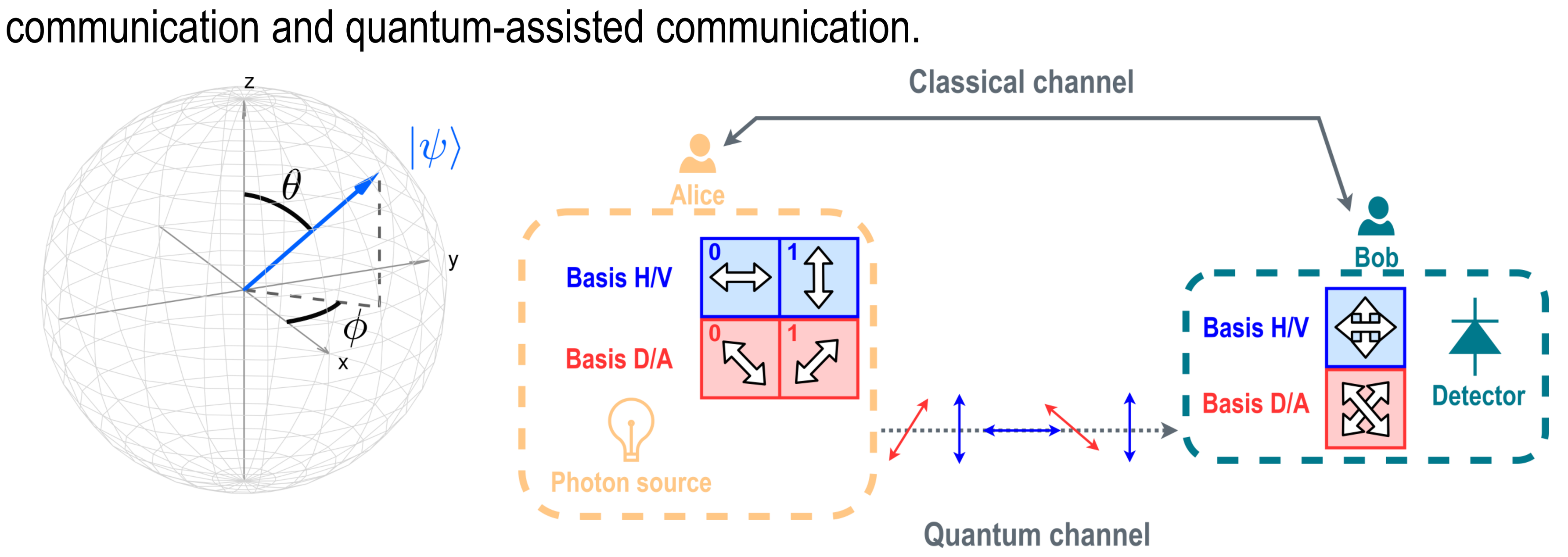
Research context and motivation

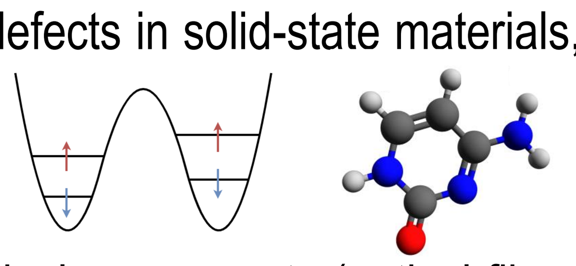
Quantum Information Processing (QIP) represents a change of paradigm: information is encoded on quantum states (qubits). QIP stands for quantum computing, quantum communication and quantum-assisted communication.



- **Quantum Computing (QC)**. The superposition principle: a proper handling of complex probability amplitudes enables QC algorithms to perform better than classical algorithms for specific problems. Several applications: search algorithms (Grover), optimization (Quantum Approximate Optimization Algorithm) algorithms, quantum chemistry (Variational Quantum Eigensolver, Quantum Phase Estimation), medicine.
- **Quantum-assisted Communication (QaC)**. Quantum computers are expected to jeopardize asymmetric classical encryption schemes based on computational security (Shor algorithm). Symmetric cryptography can achieve unconditional security guaranteed by Nature if the distribution of private keys is quantum assisted: Quantum Key Distribution (QKD).

Addressed research questions/problems

Quantum computing:
- A quantum computer shall be able to encode the quantum information, execute one and two-qubit quantum gates (addressing *on-demand* one or two qubits in many-qubit quantum systems), preserve the quantum information for a sufficiently long time, initialise the system and measure the outcomes and allow for scalability.
- Several potential technologies may partially fulfil these requirements: superconductive circuits, **quantum dots in semiconductors**, trapped ions, defects in solid-state materials, **nuclear magnetic resonance** and molecular nanomagnets.



Quantum-assisted communication:
- A QKD network requires single-photon sources, passive optical components (optical fibre, Pockels cells, beam splitters) for the handling and transmission of the information, and single photon detectors.
- The non-ideal behaviour of physical components affects the achievable performance, such as Quantum Bit Error Rate (QBER) and secure key rate.

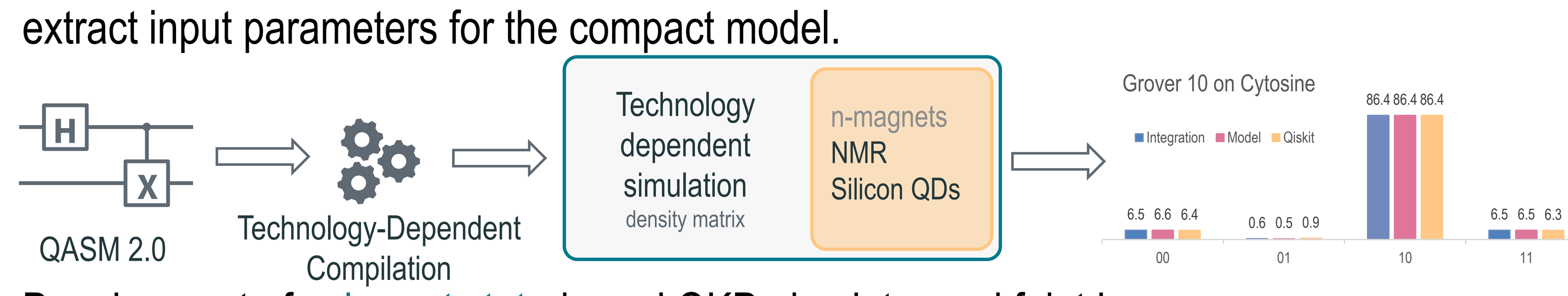
Compact models and toolchains:
- The assessment of the performance of different technologies, setups and components requires simulation tools. Currently available simulators mainly belong to two families: fast high-level simulators developed for handling many-qubit systems that neglect non-ideal phenomena, and CPU and memory-intensive low-level physical simulators based on the direct integration of differential equations.
- Need for low computational complexity yet physically accurate multi-technology compact models that take into account the hardware non-ideal behaviour and its degrees of freedom.
- The development of comprehensive simulation toolchains for some specific technologies that, starting from abstract quantum algorithms and detailed physical characterization of the hardware, can determine the expected outcomes.

Submitted and published works

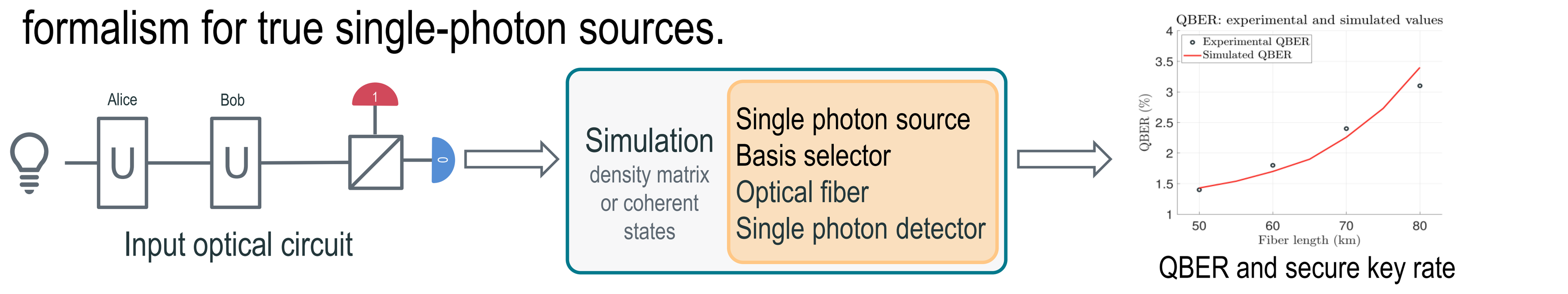
- G. A. Cirillo, G. Turvani, M. Simoni and M. Graziano. *Advances in Molecular Quantum Computing: from Technological Modeling to Circuit Design*, 2020 IEEE Computer Society Annual Symposium on VLSI (ISVLSI), 2020, pp. 132-137, doi: 10.1109/ISVLSI49217.2020.00033.
- M. Simoni, G. A. Cirillo, G. Turvani, M. Graziano, and M. Zamboni. *Towards Compact Modeling of Noisy Quantum Computers: A Molecular-Spin-Qubit Case of Study*. J. Emerg. Technol. Comput. Syst. 18, 1, Article 11, January 2022, 26 pages. DOI: 10.1145/3474223.
- C. Caputo, M. Simoni, G. A. Cirillo, G. Turvani, and M. Zamboni. *A simulator of optical coherent-state evolution in Quantum Key Distribution systems*. Optical and Quantum Electronics 54, 689, September 2022. DOI: 10.1007/s11082-022-04041-8.
- M. Avitabile, G. A. Cirillo, M. Simoni, G. Turvani, and M. Graziano. "*Development of a multi-technology, template-based quantum circuits compilation toolchain*". Accepted for publication on Quantum Information Processing. DOI: 10.1007/s11128-022-03649-9

Novel contributions

- Development of density matrix-based noise-aware compact models for NMR and (preliminary) quantum-dots in solid state systems.
- Development of multi-technology compilation, placement and routing toolchain.
- Preliminary analysis of a potential physical level simulation toolchain for quantum dots to extract input parameters for the compact model.

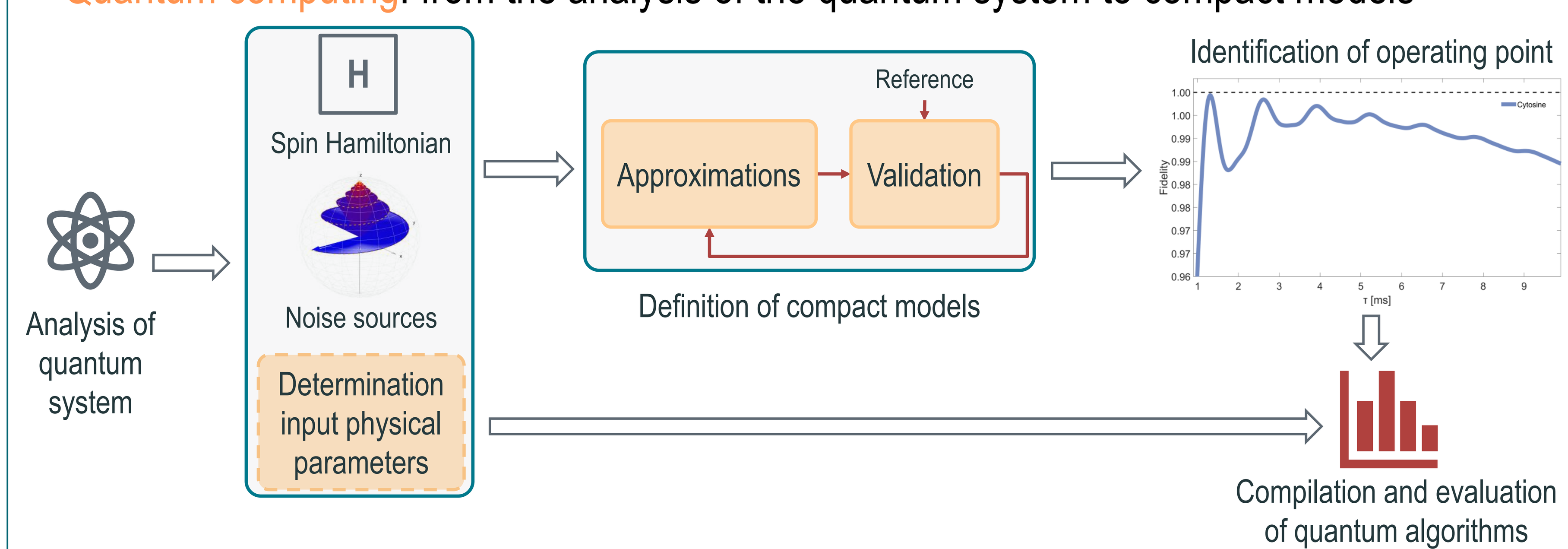


- Development of coherent state-based QKD simulator and faint laser sources.
- Development of preliminary density matrix-based QKD simulator with Schrödinger formalism for true single-photon sources.

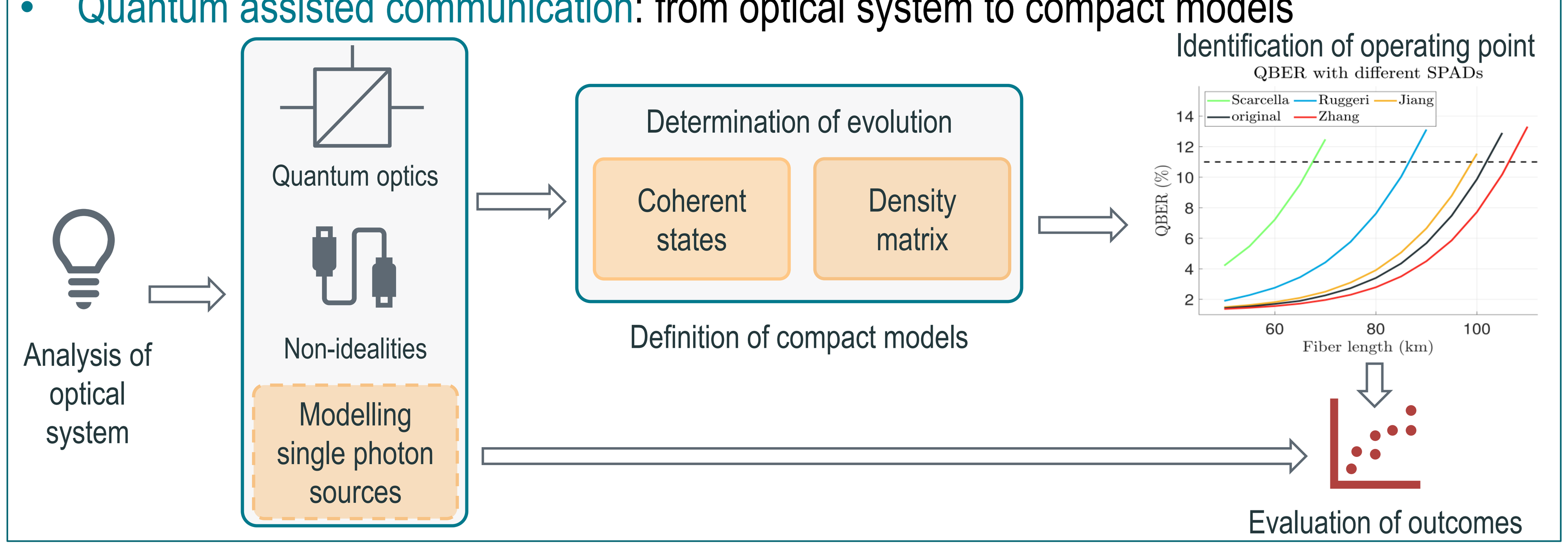


Adopted methodologies

- Quantum computing: from the analysis of the quantum system to compact models



- Quantum assisted communication: from optical system to compact models



Future work

- Improvement of compact model for quantum dots (many qubit-systems, other non-ideal phenomena, ...)
- Improvement of density-matrix based simulation for QKD setups (optical losses in passive optical components, ...).
- Development of a physical level simulation toolchain for quantum dots in semiconductors that, starting from materials and geometry, can provide the compact model inputs.

List of attended classes

- CHI0056 – Chimica computazionale – UniTo (21/01/2021, 6 CFU, 30 hours)
- 01SOKOQ – Integrazione di sistemi embedded (05/02/2021, 6 CFU, 60 hours)
- XXXXX16 – Experimental implementation of quantum devices – UniTo (15/02/2021, 2 CFU, 8 hours)
- 02SFURV – Programmazione scientifica avanzata in Matlab (27/04/2021, 6 CFU, 30 hours)
- XXXXX15 – Quantum communication – UniTo (24/05/2021, 5 CFU, 24 hours)
- 01UNRRV – Entrepreneurship and start-up creation (31/05/2021, 8 CFU, 40 hours)
- XXXXXXX – Introduction to quantum technologies – Università degli studi dell'Insubria (08/06/2021, 24 hours)
- 01TCPRV – Nano and molecular electronics (15/09/2021, 8 CFU, 40 hours)
- 01SHORV – Nano and quantum computing (16/12/2021, 8 CFU, 40 hours)

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