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Students review of Innovations in quantum technologies, part 7

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***Abstract*—This paper presents a collection of student-led review studies covering selected topics in modern quantum information technologies. The contributions explore a broad range of theoretical concepts, hardware architectures, and application domains, including quantum computing models, quantum sensing, photonic systems, and optimization techniques.**

The reviewed works examine both gate-based and alternative quantum computing paradigms, as well as hybrid quantum–classical approaches, highlighting their potential advantages and current technological limitations. Particular attention is given to the role of quantum algorithms and physical implementations in addressing computationally challenging problems, such as combinatorial optimization and simulation tasks.

Overall, the paper provides a snapshot of the current landscape of quantum technologies from an interdisciplinary perspective, emphasizing ongoing challenges related to scalability, noise, and practical applicability, while outlining promising directions for future research and development.

***Keywords*—Quantum Computing; Quantum Algorithms; NISQ Devices; Quantum Optimization; Ising Models; QUBO; Photonic Quantum Systems; Hybrid Quantum–Classical Computing; Quantum Annealing**

I. Introduction

QUANTUM information science has emerged as a rapidly evolving interdisciplinary field, combining concepts from quantum physics, computer science, mathematics, and engineering. Advances in quantum technologies promise new computational paradigms, enhanced sensing capabilities, and novel approaches to information processing that extend beyond the limits of classical systems.

In recent years, significant effort has been devoted to the development of quantum hardware platforms, including superconducting qubits, trapped ions, photonic systems, and hybrid quantum–classical architectures. In parallel, quantum algorithms and optimization techniques have been proposed to address problems in simulation, cryptography, machine learning, and combinatorial optimization. Despite this progress, most contemporary quantum devices operate in the noisy intermediate-scale quantum (NISQ) regime, where limited coherence times, noise, and restricted scalability pose major challenges to practical deployment.

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As part of advanced academic education, it is essential for students to engage critically with current research literature in order to understand both the theoretical foundations and practical limitations of emerging technologies. This paper represents a collection of student-led review studies that examine selected topics within modern quantum information technologies. Each contribution focuses on a specific aspect of the field, ranging from quantum computing architectures and algorithms to experimental realizations and application-driven case studies.

Several reviewed works address computational and optimization-related problems, which serve as important benchmarks for evaluating the potential of quantum systems to outperform classical methods. Other contributions emphasize physical implementations, such as photonic and annealing-based platforms, highlighting alternative approaches to quantum computation that differ from the standard gate-based model.

By presenting these diverse perspectives within a single framework, this paper aims to provide an integrated overview of contemporary quantum technologies. The collected reviews highlight the current state of the field, identify common limitations, and outline promising directions for future research, offering readers a coherent snapshot of ongoing developments in quantum information science.

II. Infrastructural Security in Quantum Information Technologies

The development of quantum information technologies also encompasses the sphere of security, both directly and contextually. Security is a broad field comprised of many different components. Quantum security, strictly defined, is related to both the theoretical layer, i.e., the issues of complexity theory, and the practical layer, i.e., the possibilities of implementing security algorithms on quantum computers and in quantum networks. Neither quantum computing nor quantum networks are completely autonomous entities, completely independent of classical ICT systems. The quantum layer will always be surrounded by infrastructure: information, specialized applications, energy, resource distribution, and the security of various layers of infrastructure. Due to the complexity of security issues, its layers are usually considered separately. These security bound layers are, however, interrelated and coupled in a complex way. QIT depends fundamentally on ICT and vice versa. Security of interwoven classical and quantum networks depends on their topologies, infrastructural accessibility and ruggedness.

Quantum information technologies extend the solvability chances of certain classical problems compared to the used currently ICT methods. Such extensions are being discovered, as are algorithms implementing them, which in itself is not trivial. Classic examples include Shor's, Grover's, and LLH algorithms for factoring numbers, searching data sets, and solving systems of linear equations, among others. Such algorithms have their own constraints on the required resources in the time, space, and energy domains, expressed using the Big O functional notation. These constraints are completely different from classical ones, expressed functionally as a reduction in the necessary resources across domains to achieve a defined goal. The feasibility of such algorithms on a full quantum computer tolerant of quantum faults completely changes the architecture of cybersecurity systems. This change, in a seemingly narrow layer of cybersecurity, has a significant impact on the entire field of infrastructure security. The search for quantum algorithms that significantly improve the computational resource requirements compared to classical algorithms is a topic related to infrastructure security. Methods are being sought for the practical realization of such algorithms. However, this is still not enough; creating a security infrastructure requires many other components. Another fundamental component is the efficient use of standard and non-classical quantum resources and mastery of computational operations on them. Such resources include superposition and long enough coherence time, tunnelling and interference, entanglement and contextuality, and a lot of non-classical quantum emergences. Only in such a system is teleportation, transmission, and distribution of quantum resources possible. Only distribution of quantum resources enables their efficient distillation, improving the quality of qubits, and creation of sets of the most valuable quantum magical states. Only magical states create quantum computing environment which cannot be simulated by classical ICT systems, even the most advanced ones. These, the most valuable resources depend on qubit technology and the topology of quantum systems, i.e., the physical layer. This layer is not agnostic, requiring specialized support. Direct implementation of the algorithms mentioned above is not possible on it. A computational stack with intermediate layers, from physical to the logical layer of quantum algorithm implementation is necessary.

The issue of quantum security and the discovery of low-resource algorithms immediately generated the field of post-quantum security. This is possible because quantum extensions to help solving NP-hard and NP-complete problems do not reach the global limits of solvability of complexity classes. It seems that only with the practical availability of post-NISQ quantum systems and the implementation of real quantum computational tests will we see further, faster progress in this area. The traveling salesman algorithm, which is an NP-hard problem, and other related ones moved by students in this series of papers, demonstrate some of the solvability and security issues raised, yet to be resolved.

III. Review of Quantum Approaches to the Traveling Salesman Problem

The Traveling Salesman Problem (TSP) remains one of the most extensively studied NP-complete problems and continues to serve as a canonical benchmark for evaluating the performance of both classical and quantum optimization techniques. Its relevance stems not only from its theoretical complexity, but also from its wide range of practical applications, including logistics, network design, scheduling, and routing problems.

In this review, two complementary studies are analyzed: *Solving the Traveling Salesman Problem on the D-Wave Quantum Computer* (Jain, 2021) [1] and *Solving the Traveling Salesman Problem via Different Quantum Computing Architectures* (Padmasola et al., 2025) [2]. Together, these works provide a comprehensive overview of the current landscape of quantum optimization applied to the TSP, encompassing gate-based quantum processors, quantum annealers, and emerging photonic computing platforms.

From a classical perspective, the TSP can be solved exactly using brute-force enumeration, which scales factorially with the number of cities. More efficient exact algorithms, such as dynamic programming approaches exemplified by the Held–Karp algorithm with time complexity $O(n^2 2^n)$, significantly reduce the search space but remain infeasible for large problem sizes. Consequently, heuristic and metaheuristic methods, including genetic algorithms, simulated annealing, and ant colony optimization, are commonly employed in practice. While these approaches yield high-quality approximate solutions, the number of possible Hamiltonian cycles,

$$\frac{(n-1)!}{2},$$

grows exponentially, highlighting the intrinsic computational hardness of the problem.

Quantum computing approaches aim to mitigate this combinatorial explosion by leveraging quantum mechanical phenomena such as superposition, interference, and entanglement. In the gate-based quantum computing paradigm, the TSP is typically formulated as a Quadratic Unconstrained Binary Optimization (QUBO) problem, where binary decision variables encode city visitation order and constraints are incorporated via penalty terms. Algorithms such as the Quantum Approximate Optimization Algorithm (QAOA) operate by alternating between the application of a problem-specific cost Hamiltonian and a mixing Hamiltonian. The parameters γ and β governing these unitary evolutions are optimized classically to minimize the expectation value of the cost Hamiltonian.

Experimental demonstrations of QAOA on IBM Q devices show that near-optimal solutions can be obtained for small TSP instances involving approximately 10–12 cities. However, the performance of these gate-based approaches is fundamentally constrained by noise, limited circuit depth, gate infidelities, and the restricted number of available qubits. As a result, scalability remains a major challenge within the noisy intermediate-scale quantum (NISQ) regime.

An alternative paradigm is provided by annealing-based quantum computing, most prominently represented by the D-Wave Advantage 1.1 system. In contrast to gate-based processors, quantum annealers rely on continuous-time adiabatic evolution. The system is initialized in the ground state of a transverse-field Hamiltonian and gradually evolves toward the ground state of an Ising Hamiltonian that encodes the optimization problem,

$$E(x) = \sum_{i} h_i s_i + \sum_{i,j} J_{ij} s_i s_j.$$

In this framework, the optimal TSP solution corresponds to the minimum-energy configuration of the spin variables.

Although the D-Wave hardware features more than 5,000 superconducting qubits operating at cryogenic temperatures of approximately $15\,\mathrm{mK}$, its practical applicability to the TSP is limited. The sparse qubit connectivity necessitates an embedding process, which introduces significant overhead and reduces the effective problem size. Empirical results indicate that reliable solutions are typically limited to TSP instances with fewer than 10 cities, and even then, the solutions are often sub-optimal when compared to advanced classical solvers. These observations suggest that current quantum annealers do not yet exhibit a definitive quantum advantage for combinatorial optimization.

A particularly promising development discussed in the reviewed literature is the emergence of optical and photonic Ising machines, exemplified by the QCi Dirac platform. Unlike superconducting architectures, these systems encode optimization variables in optical degrees of freedom, such as photon number distributions and phase states. The computation proceeds via entropy-driven quantum computing, where dissipative processes suppress high-energy configurations and progressively amplify states corresponding to low-energy solutions of the Hamiltonian.

The QCi platform comprises two primary architectures: Dirac-1, designed for QUBO and Ising formulations, and Dirac-3, which supports integer and mixed-integer linear programming without requiring explicit binary encoding. This capability significantly reduces problem overhead and allows direct formulation of the TSP using standard integer linear programming models, such as the Miller–Tucker–Zemlin or Dantzig–Fulkerson–Johnson formulations. Owing to its inherent all-to-all connectivity and the absence of embedding constraints, QCi Dirac has demonstrated the ability to solve TSP instances with up to 18 nodes, representing the largest problem size reported among current NISQ-era quantum and quantum-inspired systems.

In summary, the reviewed studies collectively indicate that no existing quantum architecture currently delivers a consistent and scalable computational advantage over classical algorithms for solving the Traveling Salesman Problem. The primary obstacles include limited precision, noise, hardware connectivity constraints, and the overhead associated with problem encoding. Nonetheless, photonic architectures and hybrid quantum–classical optimization frameworks exhibit substantial promise. Their natural parallelism, reduced susceptibility to decoherence, and favorable energy efficiency suggest that TSP instances involving 20 nodes or more may become tractable in the near future. These developments underscore the potential of photonic quantum computing as a viable pathway toward practical quantum acceleration in combinatorial optimization.

IV. Quantum sensing of microwave signals

Quantum sensing of signals in the Radio Frequency (RF) range is a recently emerging discipline presented in [3] and [4], which introduces new possibilities for applying quantum techniques. In [3], a Quantum Reservoir Computer (QRC) for machine learning is presented. The QRC consists of a qubit entangled with an input analog RF signal, producing nonlinear response for an input signal, followed by a linear machine-learning layer that processes the output of the quantum system. In [4], a microwave quantum radar is demonstrated, showing a quantum advantage over classical radar. In both works, an analog microwave signal is entangled with a qubit. By measuring quantum state it is possible to extract input analog signal properties. The present section focuses on practical aspects of implementing such processing schemes, which are important when discussing possible applications.

The fundamental premise of utilizing entanglement between an analog RF signal and a quantum state is the elimination of the digital processing stage. In conventional measurement systems, an analog signal is first conditioned by analog circuits, and then converted by an Analog-to-Digital Converter into the digital domain, where digital signal processing takes place. In contrast, direct transfer of an analog RF signal to a quantum state, without transferring the signal through the digital domain, enables potential application of Quantum Signal Processing (QSP) [5] directly on analog microwave signals [3]. QSP can be regarded as an equivalent of classical signal processing in quantum domain and has the potential to offer higher accuracy and higher measurement speed compared to conventional approaches. The development of such techniques opens a new paradigm for measuring and processing analog signals, beyond the limitations of time-domain digitization.

A. Analog input signal

This subsection outlines the key requirements for the analog input signal, which directly determine the range of possible applications of the proposed QSP scheme. Although additional limitations should be taken into consideration in specific implementations, the constrains presented below are the most relevant for general considerations.

1) Power of analog input signal: Analog signals applied to quantum structures must be characterized by very low power levels, primarily due to thermal constraints. Any electromagnetic signal delivers a finite amount of power. This power ultimately is dissipated as heat in the detector. This represent a significant difficulty in the quantum domain, as superconducting quantum circuits, employed in the referenced experiments [3], [4], require operating temperatures below 50 mK. Excessive power dissipation at the receiver would prevent the quantum system from maintaining the required low temperatures.

A second reason for the low signal power requirement is that quantum systems operate at the microscale. Since quantum states correspond to extremely small energy levels, input signal amplitudes are inherently low. Consequently, in report [3], the input analog signal is attenuated by 60 dB before it reaches the quantum system. Such low signal levels impose strict requirements on control electronics in terms of noise so that the input signal is transferred undistorted to the quantum structure. They also enable direct measurements and QSP of weak analog signals [3]. This capability opens new opportunities for measurement applications.

2) Frequency range of analog input signal: Another important requirement is that the input signal which can stimulate qubits must be narrowband around a specific center frequency. This constraint arises from the architecture of the experimental setups described in [3], [4]. In both examples, the input signal is entangled with a qubit through resonators, whose resonance frequency determines the operating frequency of the system. This constraint poses difficulties in analysing low-frequency signals. However, this limitation can be mitigated by upconverting the input signal to frequencies close to the resonant frequency of the oscillator.

The narrowband character of the input signal indicates that quantum sensing is well suited for RF applications. If the center frequency of the RF system is selected to match the available resonator frequencies, additional frequency conversion stages can be avoided, simplifying the system architecture.

3) Number of qubit measurements: Due to the probabilistic nature of quantum measurements, typically a large number of qubit measurements is required to achieve a high confidence level in the obtained results. This behaviour also applies to QRC described in [3]. As a consequence, only slow-changing signals can be measured by this approach. This requirement is a major limitation in practical scenarios, because modern systems increasingly require both high accuracy and high processing speed. While higher accuracy can be obtained using this technology, the achievable speed is limited by the number of measurements required to obtain a required confidence level of results.

B. Possible applications

The constraints discussed above significantly limit the range of possible applications of quantum sensing technology under the current technological conditions. Nevertheless, there are still application areas in which implementing proposed approach may offer many advantages. Two particularly promising applications are precise measurement systems and telecommunication receivers.

1) Precise measurements: Entanglement between an analog RF signal and a qubit enables new possibilities in measurement accuracy and sensitivity. Due to the high sensitivity of the system, it is possible to detect low-power signals with high precision. Additionally, the main advantage of this application is the potential ability to apply QSP directly on the quantum state entangled with the analog signal [3]. This would allow to process analog data in real-time, before converting it to the digital domain.

2) Telecommunication receivers: The constraints described above—namely, the capability to detect low-power signals, operation in the RF frequency range, and the requirement for repeated qubit measurements-indicate that long-distance telecommunication receivers can be a suitable application scenario for this technology. In long-distance RF communication channels, signal attenuation is high, resulting in low signal power at the receiver. In standard communication links, to ensure a stable transfer, data rates are often reduced. Under these operating conditions, a receiver based on entanglement between an analog RF signal and a qubit can benefit from high sensitivity to weak signals while remaining compatible with RF frequency bands. Additionally, low data rates provides sufficient time for the quantum system to perform a sufficient number of qubit measurements to ensure a high probability of correct detection. Example of telecommunication receiver basing on quantum sensing is presented in an article [3].

C. Summary of quantum sensing possibilities

Quantum sensing of RF signals represents a relatively young research area, offering high potential for future development. Due to novelty of this discipline, some limitations described in this work may be mitigated or overcome in the future. However, the conclusions presented here are drawn based on the current state of knowledge.

At present, the main limitations include low allowable input signal power, the requirement for low operating temperatures of the quantum system, narrow allowable input signal bandwidth, and the need for a large number of qubit measurements to achieve satisfactory measurement accuracy. Despite these limitations, this technology shows clear potential in applications such as precise measurements and long-distance telecommunication receivers. In both cases, new possibilities would arise if it was possible to implement QSP on a qubits entangled with an analog signal. Capabilities of such system could go far beyond today's solutions basing on signal processing performed in the digital domain.

V. QUANTUM EFFECTS IN PHOTOSYNTHESIS

Photosynthesis is one of the most important processes on Earth. The efficiency of the light-dependent phase in converting photon's energy into chemical energy is near-perfect (95-99%). Incident light is absorbed by the light-harvesting complex, creating an exciton on a pigment molecule such as chlorophyll. Förster Resonance Energy Transfer (FRET) theory assumes incoherent hopping between molecules in direction of reaction center. Model based on this mechanism predicts lower efficiencies than those observed [6].

The field transformed in 2007 when Engel et al. discovered quantum coherence in the FMO complex at cryogenic temperatures using two-dimensional electronic spectroscopy [7]. They observed long-lived quantum beatings in the electronic spectra, indicating the presence of coherent superpositions of exciton states within the FMO complex. However, the critical question remained: does coherence persist under physiological conditions? Panitchayangkoon et al. (2010) provided the answer, demonstrating quantum coherence lasting 300 fs at 277 K. It is long enough to influence the transfer process [8].

This discovery sparked intense debate about whether quantum mechanics genuinely enhances biological function.

One way to answer this question is through theoretical modeling and numerical simulation of quantum energy transport. Ishizaki and Fleming (2009) developed one of the first fully quantum mechanical descriptions of excitation transfer in photosynthetic complexes using the Hierarchically Coupled Equations of Motion (HEOM) framework. By applying HEOM to the Fenna–Matthews–Olson (FMO) complex, Ishizaki and Fleming [9] showed that moderate coupling to the vibrational environment can actually enhance transport efficiency. Environmental fluctuations were found to suppress destructive quantum interference while preserving constructive coherence between energy pathways. This is mechanism now known as Environment-Assisted Quantum Transport (ENAQT). Their simulations reproduced key experimental observations, including the oscillatory features seen in two-dimensional electronic spectroscopy, and confirmed that models neglecting phonon coupling fail to capture real photosynthetic behavior.

This work marked a turning point in the field. It demonstrated that quantum coherence in photosynthesis is not merely a cryogenic artifact, but a functional phenomenon maintained by the delicate balance between coherence and environmental noise. The most surprising finding is that moderate environmental noise enhances rather than degrades transport. At optimal dephasing rates, noise prevents Anderson localization while preserving wavelike exploration. Too little noise traps the exciton; too much reduces transport to slow hopping.

Quantum effects are real but modest. Electronic coherence contributes little efficiency enhancement but is evolutionarily significant. Photosynthesis is neither pure quantum system nor classical machine, but complex adaptive system leveraging quantum wavelike properties during brief initial periods, transitioning smoothly to classical diffusion at longer times and larger scales. For quantum technologies, photosynthesis offers not a blueprint for room-temperature quantum computers, but proof that quantum coherence can be functionally harnessed in noisy environments when combined with appropriate structural design.

VI. Quantum Technology in Internet of Things

The fast development of the Internet of Things (IoT) has led to the deployment of billions of interconnected devices responsible for communication and data collection. Although this enables the creation of smart cities, industrial automation, and improvements in everyday life, it simultaneously introduces significant security challenges. Classical cryptographic methods may prove insufficient in the face of rapid technological changes and emerging cyber threats. In this context, quantum technologies offer promising solutions that can fundamentally strengthen IoT architectures.

One of the most important aspects of IoT systems is secure communication. Quantum Key Distribution (QKD) enables secure exchange of cryptographic keys using quantum entanglement methods. QKD is based on the transmission of single photons encoded in specific quantum states. Any attempt to wiretapping inevitably disturbs these states, introducing detectable errors resulting from the uncertainty principle and the no cloning theorem. As a result, it is possible to verify the presence of a wiretapper and establish a shared secret key with provable physical security. This property makes QKD particularly attractive for critical IoT infrastructure.

Closely related to QKD are Quantum Random Number Generators (QRNG), which provide true randomness resulting from atomic motion or atomic decay processes. Unlike classical pseudorandom generators, the outputs of QRNGs cannot be predicted or reproduced, which significantly increases cryptographic resilience. In IoT environments, QRNG devices can be embedded in edge devices or network gateways to strengthen encryption schemes.

Another important contribution of quantum technologies to IoT systems is quantum sensing. Quantum sensors exploit phenomena such as superposition and quantum entanglement to achieve extremely high sensitivity. They are capable of detecting minimal changes in magnetic fields, gravitational variations, or electromagnetic radiation. In IoT applications, quantum sensors enable high-precision navigation without GPS and advanced environmental monitoring. Their integration into IoT networks allows for the acquisition of high quality data and a departure from traditional measurement methods.

To control and manage these elements, a quantum central unit can be created. Such a central unit may use quantum computers to process IoT data on a large scale and perform complex optimization tasks. The parallel nature of quantum computing is better suited for big data processing, which is highly desirable in IoT systems. Hybrid architectures, in which classical IoT networks are connected to quantum processing backends, represent a realistic solution for the near future.

In summary, the integration of quantum cryptography, quantum randomness, quantum sensing, and quantum data processing with IoT systems has the potential to drive dynamic technological development and significantly increase security, reliability, and performance. Although technological and economic barriers still exist, gradual deployment strategies provide a realistic path toward advanced IoT infrastructures in the near future.

VII. Microwaves in Quantum Technologies

Microwaves are an irreplaceable tool in the development of modern quantum information technologies, enabling precise control and readout of the state of qubits, the fundamental units of quantum information. In the article on which this section is based, the authors focus on these three platforms: trapped atomic ion qubits, semiconductor spin qubits, and superconducting qubits.

The physical basis of the light-matter interaction at the quantum level is described by the relation $E = \hbar\omega$, where the energy of the photon E is linked to its angular frequency ω ($\hbar$ is the reduced Planck's constant, $\hbar = h/2\pi$). This relationship allows for the resonant interaction of microwave photons with quantum version of computer bits (qubits). A qubit, a quantum mechanical system with two energy eigenstates, 0 and 1, encodes quantum information as a linear combination of these states, called a superposition [10].

Conceptually, a qubit can be thought of as a nonlinear electromagnetic resonator with a high quality factor, $Q \gg 1$, where the resonant frequency ω_{01} is set by the energy difference $\Delta E = E_1 - E_0$ between the qubit states.

Different physical realizations of qubits use microwaves across various frequency ranges and in different ways:

- Superconducting Qubits (Transmon): This type of qubit is a microscopic circuit composed of a Josephson junction (nonlinear inductance, L_J) and a capacitance, C_Q (operating as a nonlinear LC resonator). It encodes information in the energy states of the entire circuit. In this case, for control and readout are used microwaves with a carrier frequency in the range of 4–8 GHz. Short pulses with a shaped envelope (e.g., using the DRAG technique, which mitigates unwanted energy leakage to higher states) are essential for achieving high-fidelity quantum gates [10].
- Semiconductor Spin Qubits: The quantum information is encoded in the spin of a single electron confined in a nanostructure called a quantum dot. Operation typically requires a strong magnetic field. Carrier frequencies for control span a broad range, typically from 0.1 to 50 GHz [10].
- Trapped Ion Qubits: Here, the information is encoded in the electronic states of the atom, with ions held in a vacuum using electromagnetic fields (Paul trap). They are most often controlled by lasers, but microwave fields can also be used. Carrier frequencies range from 5–20 MHz to 1–12.6 GHz. They are characterized by a very long coherence time [10].

The fundamental operation in quantum computation is the single-qubit operation, realized by rotating the state vector on the surface of the Bloch sphere. These operations, called gates, are implemented by applying a resonant microwave field to the qubits. XY Gates (Rotations in the XY plane) are performed using microwave pulses. Resonant excitation of the qubit leads to Rabi oscillations, which are a cyclic change between the 0 and 1. The pulse parameters such as amplitude, duration, and phase, precisely control the rotation angle and axis, which is crucial for achieving the desired transformation. The second type of operations are Z Gates. These solely affect the qubit phase (ϕ), and rotates the Z plane. They can be realized virtually (by applying a phase jump to the RF carrier for subsequent XY gates) or physically (by detuning the qubit frequency by $\delta\omega_{01}$ for a controlled duration τ) [10].

The DRAG technique for modulating control pulses was mentioned earlier during describing transmons. Classical, short pulses, such as rectangular or pure Gaussian, have a broad spectrum in the frequency domain. For this reason, in addition to exciting the resonant transition $0 \leftrightarrow 1$, they can undesirably excite higher energy states of the qubit, such as 2, which leads to loss of coherence. To counteract this phenomenon and obtain high-fidelity gates, the Derivative Removal by Adiabatic Gate (DRAG) technique is used. DRAG is a quadrature modulation (I/Q) pulse modulation technique. It is based on the simultaneous transmission of two signals. In in-phase channel transmits a fundamental, resonant, Gaussian-shaped pulse, responsible for the main rotation of the qubit in the XY plane. Channel Q transmits a quadrature component, which is the time derivative of the Gaussian pulse from Channel I, additionally scaled by a factor proportional to the anharmonicity of the qubit. This additional component corrects undesirable effects resulting from non-zero population annihilation at the end of the pulse, effectively suppressing unwanted transitions to the 2 state. As a result, the DRAG pulse minimizes quantum leakage, allowing gates to be realized with fidelity exceeding 99.9% [11].

A direct measurement of the qubit state would destroy the quantum state. For superconducting and spin qubits, we typically use a technique called Dispersive Readout. This involves coupling the qubit to a microwave resonator in the dispersive regime. In this regime, the qubit's state (0 or 1) causes a slight shift in the resonator's frequency ω_r by an amount 2χ (the dispersive shift). By measuring the reflection coefficient (or transmission) of a probe tone near ω_r, the qubit state can be determined without direct interference [10].

Microwaves in quantum technologies is a rapidly evolving field where progress is mutually driven by the demands of quantum physics and innovations in microwave engineering. The possibilities of using microwaves to perform calculations and read the state of qubital objects are presented above. In the case of transmons, microwaves are an integral part of quantum computing.

VIII. Conclusion

The collection of review studies presented in this paper provides a broad overview of contemporary quantum information technologies, encompassing theoretical models, algorithmic frameworks, and physical implementations. Across the examined topics, a common theme emerges: while quantum systems demonstrate remarkable conceptual potential, their practical performance remains constrained by hardware limitations, noise, and scalability challenges characteristic of the NISQ era.

The reviewed contributions show that, in many application domains, quantum approaches do not yet deliver a consistent advantage over mature classical methods. This is particularly evident in computational and optimization problems, where factors such as problem encoding overhead, precision requirements, and limited qubit connectivity significantly impact performance. As a result, hybrid quantum–classical strategies and heuristic methods continue to play a crucial role in achieving practical results.

At the same time, several alternative architectures and physical realizations discussed in this paper point toward promising future directions. Photonic systems, annealing-based machines, and entropy-driven or dissipative computing models offer complementary pathways that may mitigate some of the limitations of gate-based quantum computing. These approaches emphasize architectural innovation, parallelism, and energy efficiency, suggesting that future progress may rely on diversified hardware strategies rather than a single dominant paradigm.

In conclusion, while large-scale, fault-tolerant quantum advantage remains an open challenge, the rapid development of quantum technologies and the diversity of explored approaches indicate strong potential for future breakthroughs. Continued research at the intersection of physics, algorithms, and engineering will be essential for translating theoretical promise into practical quantum applications.

REFERENCES

[1] S. Jain, "Solving the traveling salesman problem on the d-wave quantum computer," *Frontiers in Physics*, vol. 9, p. 760783, 2021. [Online]. Available: https://www.frontiersin.org/journals/physics/articles/10.3389/fphy.2021.760783/full

[2] V. Padmasola, Z. Li, R. Chatterjee, and W. Dyk, "Solving the traveling salesman problem via different quantum computing architectures," *CoRR*, vol. abs/2502.17725, 2025. [Online]. Available: https://arxiv.org/abs/2502.17725

[3] A. Senanian, S. Prabhu, V. Kremenetski, S. Roy, Y. Cao, J. Kline, T. Onodera, L. G. Wright, X. Wu, V. Fatemi, and P. L. McMahon, "Microwave signal processing using an analog quantum reservoir computer," *Nature Communications*, vol. 15, p. 7490, 2024. [Online]. Available: https://doi.org/10.1038/s41467-024-51161-8

[4] R. Assouly, R. Dassonneville, T. Peronnin, A. Bienfait, and B. Huard, "Quantum advantage in microwave quantum radar," *Nature Physics*, vol. 19, pp. 1418–1422, 2023. [Online]. Available: https://doi.org/10.1038/s41567-023-02113-4

[5] Y. Eldar and A. Oppenheim, "Quantum signal processing," *IEEE Signal Processing Magazine*, vol. 19, no. 6, pp. 12–32, 2002. [Online]. Available: https://doi.org/10.1109/MSP.2002.1043298

[6] R. M. Clegg, M. Şener, and Govindjee, "From Förster resonance energy transfer to coherent resonance energy transfer and back," in *Optical Biopsy VII*, ser. Proc. SPIE, vol. 7561. SPIE, 2010, p. 75610C. [Online]. Available: https://www.ks.uiuc.edu/~melih/Clegg2010.pdf

[7] G. S. Engel, T. R. Calhoun, E. L. Read, T.-K. Ahn, T. Mančal, Y.-C. Cheng, R. E. Blankenship, and G. R. Fleming, "Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems," *Nature*, vol. 446, no. 7137, pp. 782–786, 2007. [Online]. Available: https://doi.org/10.1038/nature05678

[8] G. Panitchayangkoon, D. Hayes, K. A. Fransted, J. R. Caram, E. Harel, J. Wen, R. E. Blankenship, and G. S. Engel, "Long-lived quantum coherence in photosynthetic complexes at physiological temperature," *Proceedings of the National Academy of Sciences*, vol. 107, no. 29, pp. 12 766–12 770, 2010. [Online]. Available: https://arxiv.org/abs/1001.5108

[9] A. Ishizaki and G. R. Fleming, "Theoretical examination of quantum coherence in a photosynthetic system at physiological temperature," *Proceedings of the National Academy of Sciences*, vol. 106, no. 41, pp. 17 255–17 260, 2009. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2762676/

[10] J. C. Bardin, D. H. Slichter, and D. J. Reilly, "Microwaves in quantum computing," *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 403–427, Jan 2021. [Online]. Available: https://doi.org/10.1109/JMW.2020.3034071

[11] F. Motzoi, J. M. Gambetta, P. Rebentrost, and F. K. Wilhelm, "Simple pulses for elimination of leakage in weakly nonlinear qubits," 2009. [Online]. Available: https://doi.org/10.48550/arXiv.0901.0534