**Висновки.** Міждисциплінарний підхід в ІТ-технологіях відкриває великі можливості для відновлення та розвитку України. Впровадження інноваційних стратегій та практичних рішень сприятиме швидкому економічному зростанню, ефективному управлінню державними ресурсами та підвищенню рівня життя громадян. Взаємодія науки, технологій та бізнесу дозволить створити стійку екосистему, яка забезпечить країні конкурентоспроможність на світовому рівні.

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DOI https://doi.org/10.36059/978-966-397-491-0-30

## NOVEL IT: WHAT IS Q3C?

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**Motivation: Novel IT in the Mid-Term**

Novel IT in the mid-term means deployment of Q3C: Quantum Computing, Communication and Cryptography. The next few years will be decisive for the establishment of Q3C in both industry and scientific research. Despite existing challenges, numerous research institutions are optimistic that quantum computers will progress significantly in the next 20 years. So, the field Q3C is divided into the following main areas [1-5]:

Quantum Computing/Hardware and Quantum Algorithms/ Programming

Distributed Quantum Communication (connecting quantum computers via conventional channels such as fiber optics and quantum channels)

Quantum Cryptography (with challenges for Post-Quantum Cryptography).

Q3C: what does it mean in other words?

The future QC will be more powerful than the world-wide clusters from Top10 Ranking of Most Powerful Computing Clusters worldwide (based on the status of Nov. 2024 by Top500.org) [2, 6, 7, 8]. Q-computers are computer-technical units that exploit the principles of quantum mechanics (superposition, entanglement, uncertainty, refer to Fig. 1).

Unlike conventional computers, they do not work based on macroscopic states of electronic circuits but based on Q-states of suitable systems. This makes it possible to generate superposition and entanglement states during the calculation, both of which are crucial for information processing in Q-computers (Fig. 1). Still, the technology is in development nowadays. Examples are as follows: [1-5, 9 -11].

**Architectures for Q3C**

Large companies such as D-Waves, Google, IBM, Rigetti, and IonQ as well as leading research institutes worldwide are working intensively [9-11] on the development of physical element bases for quantum computers (refer to Table 1). In 2019, Google demonstrated so-called «quantum supremacy» for the first time. Nanostructured semiconductors provide electrons in quantum dots using established semiconductor technologies. D-Wave Systems is one of the best-known companies that offers quantum annealers commercially.

## Basics

*Q-States* $|0\rangle$ & $|1\rangle$ (1)

Qubit $|A\rangle$ obtains simultaneously the states $|0\rangle$ und $|1\rangle$

Superposition: (4)

$$|\psi\rangle = \sum_{i=0}^{2^n-1} \alpha_i |i\rangle ,$$

$$\alpha_i \in \mathbb{C} : \sum_{i=0}^{2^n-1} |\alpha_i|^2 = 1.$$

Entanglement: (5)

$$|\psi\rangle = |v_0\rangle \otimes |v_1\rangle \otimes \ldots \otimes |v_{n-1}\rangle$$

$$V = V_0 \otimes V_1 \otimes \ldots \otimes V_{n-1}$$

where $|\psi\rangle$ provides Q-states, $|v_i\rangle \subseteq V_i$, and n qubits from a system can be entangled for some spaces V or separated (unentangled) for other such spaces $|v_i\rangle$ (i=0,n-1).

Basic principles:

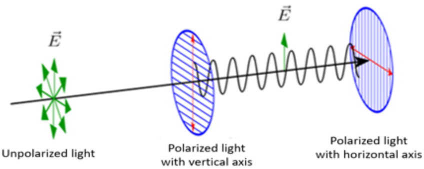
1. Heisenberg's uncertainty
2. Superposition
3. Entanglement
4. Further properties possible

Quanta -> Photons:

*E=1 eV* | $\lambda$ *= 1,240 µm*

$h = 4.136 \cdot 10^{-15}$ eV·s,

$E = h \cdot f = h \cdot c/\lambda$ (2)




Heisenberg's uncertainty:

$\Delta x \cdot \Delta p = h$

$\Delta E \cdot \Delta t \sim h$ (3)

**Fig. 1. Q-physical basics for Q3C**

Another promising approach is the deployment of «anyons» to create qubits in 2D structures, or «thin layers», which provide high robustness to decoherence. However, research in this area is still in its early stages. The most powerful Q-chips are developed in 2019-2025 (Fig. 2): Google Sycamore in 2019; Google Willow in 2024; MS Majorana 1 in 2025.

Table 1

**Cutting-Edge Companies in Q3C (status on 2025, based on [1-5])**

| # | Company and location | Content |
|---|---|---|
| 1. | IBM Quantum (USA) | Leader in the development of superconducting qubits and cloud-based quantum solutions (IBM Q Experience, Qiskit). |
| 2. | Google Quantum AI (USA) | Development of the Sycamore and Willow QPU chips, which first demonstrated quantum supremacy. |
| 3. | Microsoft Quantum (USA) | Focus on topological qubits with potentially higher error resistance. Development of Majorana 1 QPU. |
| 4. | Rigetti Computing (USA) | Specialized in hybrid quantum-classical systems and the Quil programming language. |
| 5. | D-Wave Systems (Canada) | Market leader for quantum annealers, specializing in optimization problems. |
| 6. | IonQ (USA) | Focused on ion trap quantum computers with long coherence times. |
| 7. | Quantinuum (UK/USA) | Fusion of Honeywell Quantum and Cambridge Quantum, with a focus on quantum algorithms. |
| 8. | Pasqal (France) | Leader in neutral atom-based quantum computers. |
| 9. | Xanadu (Canada) | Develops photonic quantum computers with PennyLane as an open-source framework. |

a) Microsoft Q-chip Majorana 1, based on 2D-topological qubits and superconducting circuits

b) Google Q-chip «Sycamore», based on superconducting circuits for «Q-Supremacy» (right)

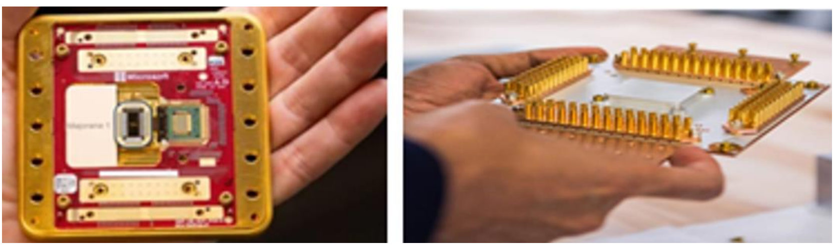


**Fig. 2. Q-chips by Google (2019) and Microsoft (2025) [9-11]**

There are various Q-architectures and implementations (refer to Table 2). Still only a few quantum algorithms are at the heart of Q3C. Therefore, the main challenge is development of Q-algorithms! Notable examples include:

Shor's algorithm (prime numbers factorization of n = pq)

Grover's algorithm (search in a large DB with a primary key)

BB84, E91, and B92 protocols in Q-cryptography.

Further algorithms are concerning to:

Quantum Machine Learning (QML), which integrates machine learning with quantum computing

Several algorithms address specific applications in simulating quantum physics, solving optimization problems, and addressing differential equations.

Table 2

**Various Q-architectures [1-5, 9-11]**

| # | Implementation | Short description |
|---|---|---|
| 1. | Quantum annealers | Quantum annealers let us use multiple qubits |
| 2. | Ion traps | Ions are captured in electromagnetic traps and held in a vacuum. |
| 3. | Superconducting qubits | They use macroscopic circuits made of materials such as niobium or tantalum, which become superconducting at extremely low temperatures. |
| 4. | Electrons in quantum dots | Quasi-zero-dimensional semiconductor structures with discrete electron states. Manufactured using established semiconductor technologies. |
| 5. | Spin qubit computers | Nuclear spins of foreign atoms in silicon or nitrogen-vacancy centers in diamonds are particularly promising under so-called nuclear-magnetic resonance (NMR). |
| 6. | Anyons, or 2D-topological qubits | Anyons are exotic quasiparticles that could also be used as qubits in 2D, which is very useful for industrial production. |
| 7. | Photonic quantum computers | Photonic systems are essential in quantum communication because they enable the secure transmission of quantum information over long distances. |

**Photonic Communication**

**Hybrid Q-Internet in Boston at Harvard University:**

Harvard University demonstrated the first Q-network in Boston. So-called Q-internet is aimed at transmitting data securely and extremely. This hybrid network is based on existing optical fibers. The deployment of such a solution was a significant step forward in the realization of a Q-internet [1, 5].

These are two small QPUs made of diamond disks with special defects: so-called silicon vacancy centers. Q-Node A and Q-Node B are placed in these centers and then connected via 35 km of conventional fibers.

These both nodes contain 2 qubits. They use the electron spin for communication, while a longer-lived nuclear spin acts as a storage qubit.

The researchers controlled both spins with microwave pulses. The diamond devices are only a few millimeters in size and housed in cooling units under temperatures by ~10 mK.

**Photonic networks: Q-Teleportation**

In the walls of Oxford University, the photonic networks are developed. They are well suited as a reconfigurable interconnection layer for distributed Q-Computing. Remote entanglement shared between matter qubits across the network enables logical connectivity through quantum gate teleportation [1, 4].

**Challenges, Limitations, and Problems**

The following challenges, limitations and problems are to be mentioned for Q3C (refer to Table 3):

Table 3

**Challenges for Q3C [1-5, 9-11]**

| # | Tasks and measures | Content |
|---|---|---|
| 1. | Improving qubit stability | Developing robust qubit technologies (e.g. topological qubits). |
| 2. | Expanding the quantum internet | Connecting quantum computers via global networks. |
| 3. | Optimizing error correction algorithms | Using surface codes and new correction methods. |
| 4. | Developing hybrid systems | Combination of classical and quantum processors for realistic applications. |
| 5. | Promoting quantum computing education | Establishing academic programs to train skilled workers. |

Further technical problems are as follows:

Decoherence and error correction: A central problem in the construction of quantum computers is decoherence, because quantum objects lose their quantum mechanical properties when they interact with their environment. This causes superpositions and entanglements to collapse, which can massively affect computing performance. To counteract this, a redundant arrangement of physical qubits is necessary to generate stable logical qubits.

Energy consumption: Cooling systems for superconducting quantum computers are extremely energy-intensive for mK-area.

Scalability: Building quantum computers with the required $10^6$ of qubits remains difficult.

Quantum software: Lack of standardization of quantum programming languages and frameworks.

Security risks in convenient IT: Post-quantum cryptography must be developed to replace classical encryption.

**Conclusion and Outlook**

Novel IT is undergoing a major quantum revolution. While its theoretical foundations have been explored for decades, recent advancements in qubit implementation, quantum annealing, photonic teleportation and quantum cryptography are bringing practical applications nearer.

The key strengths of Q3C lie in parallel processing, high-speed transmission enabled by Q-superposition and Q-entanglement, and secure communication. One of the biggest challenges in building quantum computers is decoherence – the loss of quantum mechanical properties when quantum objects interact with their environment. To preserve these properties, quantum computers must operate at extremely low temperatures, often near absolute zero.

Another critical challenge is extreme resource consumption, which must be addressed for future advancements.

The integration of AI and Q3C is becoming increasingly important, unlocking the synergy and great potential in the next 20 years.

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DOI https://doi.org/10.36059/978-966-397-491-0-31

# ДОСЛІДЖЕННЯ ЗАСТОСУВАННЯ ЗАСОБІВ M5STAMP PICO ДЛЯ ПОБУДОВИ МЕРЕЖЕВИХ ПРИСТРОЇВ

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Розвиток технологій Інтернету речей (IoT) набуває дедалі більшого значення в сучасному цифровому світі, де процеси автоматизації та інтелектуалізації техніко-інформаційних систем стають визначальними напрямками науково-технічного прогресу [1, с. 12]. Особливої уваги заслуговують мініатюрні мікроконтролерні платформи, які здатні забезпечувати ефективну комунікацію та управління у складних мережевих архітектурах. Саме тому дослідження можливостей таких компактних апаратних рішень, як M5Stamp Pico, становить значний науковий та практичний інтерес для фахівців у галузі вбудованих систем та Інтернету речей. Проблемне поле дослідження концентрується навколо питань оцінки потенціалу мікроконтролерних модулів для побудови надійних, енергоефективних та високоінтегрованих мережевих пристроїв, здатних функціонувати в різноманітних умовах з мінімальними апаратними витратами.