INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2024, VOL. 70, NO. 2, PP. 509–518
Manuscript received May 11, 2024; revised June, 2024. DOI: 10.24425/ijet.2024.149573

Students' view of Quantum Information Technologies, part 3

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***Abstract*—The article is part of a course on Quantum Information Technologies QIT conducted at the Faculty of Electronics and Information Technology of the Warsaw University of Technology. The subject includes a publishing workshop exercised by engineering students. How do ICT engineers see QIT from their point of view? How can they implement quantum technologies in their future work? M.Sc. students usually have strictly declared topics for their master's theses. The implementation of some works is at an advanced stage. The potential areas of application of QIT are defined and narrow if they are to intellectually expand the area of the completed theses. This is the idea of incorporating QIT components or interfaces into classic ICT solutions at the software and hardware level. It is possible to propose a solution in the form of a functional hybrid system. QIT systems should be functionally incorporated into the existing ICT environment, generating measurable added value. Such a task is quite demanding, but practice shows that it interests students. Solutions don't have to be mature or even feasible. They can be dreams of young engineers. The exercise is a publication workshop related to the fast development of QIT. The article is a continuation of publication exercises conducted with previous groups of students participating in QIT lectures.**

***Keywords*—ICT; QIT; biomedical engineering; electronics and communications engineering; sensors; quantum Internet; quantum computing; cybersecurity; quantum networks; quantum metrology; cloud computing**

I. Introduction

QUANTUM Information Technologies are influencing the research work performed by the ICT M.Sc. students. The students are doing their research in engineering - biomedical, software, electronic, communications and cybersecurity. The participants of QIT course participated in a publication workshop. The publishing exercise has already been repeated several times with Ph.D. and M.Sc. students groups creating a wider picture of their views [1]. The workshop result is a paper on potential association of the QIT with particular subjects researched by the students for their M.Sc. engineering diplomas. Students organized common on-line workspace to prepare the paper, using OverLeaf editor. An editorial team was responsible for preparing the final version of the paper and add necessary components like introduction, conclusions, organized references. The structure of the paper is simple. Each student was asked to write a short one-page chapter possibly relating the QIT to the personal work performed for the realized diploma thesis.

The relation between the own research and the QIT subject of free choice was allowed to be loose. The consideration might answer the question, what would have happened if I had added some QIT components to my current work. The requirement was that the applied QIT technology should exist at the technical level. Students were studying a few QIT research papers, only of source character, associated with their interests. Research chapter texts were prepared basing on the source papers. Some common features included in all chapters were extracted during the editorial discussions on the final version of the paper. The worksop initiated a debate how to include the emerging possibilities offered by the QIT to existing functional systems. The branches of considered QIT were sensing and timing, computing, transmission and networking.

The challenge associated with the ICT-QIT publication workshop is related to the facts that the QIT is undergoing very fast development and changes nearly every day. Many QIT components and devices are not yet ready for advanced applications. Some of them offer today better performance than classical solutions. ICT and QIT is expected to cooperate peacefully and efficiently in numerable hybrid solutions. Many QIT components are however quite different from ICT technologies and their requirements. The challenge was to combine efficiently existing different technologies ICT and QIT into a functional system.

II. QIT Application Frontiers

Generally, the QIT research area is divided to quantum time, metrology and sensing, computing and communications. Some of the QIT components from these branches are ready for applications. The application readiness varies between different technologies. Access to quantum computing is provided by several leaders via their quantum cloud facilities. The web based quantum cloud access provides testing of own algorithms. Advanced quantum sensors are available but their prices are acceptable only for big users. Some of quantum

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network services are accessible like the QKD for banks and other big firms. QKD services will be provided via the combined satellite ond optical fiber communications networks.

QIT security develops its applications analogously to the ICT paths. The field embraces extension of classical cyber-security to the quantum and post-quantum fields. Quantum cryptography is maturing due to large research projects like the European Quantum Flagship. It is assumed that the services will be broadly available in a decade.

The area of quantum software and algorithms develops more efficient products for quantum computing. Quantum software engineering was split to several branches. Some of the advances in quantum software have excited new works on modification of classical solutions. QSE develops precise models for quantum computational stack. The models aim at NISQ processors, as well as full quantum error aware computers. One side is the software for operation of NISQ or full size quantum computers FSQC. Other side is functional software for calculations. Large number of existing quantum software environments will be somehow integrated in the future.

The area of quantum hardware embraces technological developments of various types of qubits. Different approaches are used for gate based NISQ processors and quantum simulators and annealers. Several technological paths for qubits are pursued. PIC technology develops its branch of QPIC and quantum photonic computing, using linear and nonlinear coptical integrated components. Transmon qubits are scalable and reach now quite big numbers in the new generation of superconducting quantum processors. Trapped ions are put into tiny integrated cages what facilitates their usage in integrated systems. Quantum dots and nitrogen vacancies NV are used for building more and more reliable quantum processors.

The applications of QIT extends to quantum biophotonics, biochemistry, pharmaceutics industry. Quantum simulators help design of new generations of biochemical and biological medicines. Advanced photodynamic therapy optogenetics, and nanomedicine are indicating new paths in medical developments, including cancer fight, quantum level genetic engineering. Quantum communication is mastering such techniques like quantum teleportation, entanglement swapping, entanglement distribution and distillation. Transmission experiments with qudits are opening the possibility to build not only point-to-point quantum transmission but also multipartite.

III. OPM MEG

A major part of applied quantum technologies are quantum sensors, which are being widely used in studying the human brain. Their integration led to significant advancements in the diagnosis of brain injury and disorders such as epilepsy and dementia [2], as well as deeply enlarged our knowledge about the functioning of human brain and its individual components.

In this chapter, the exploration is centered on magnetoencephalography (MEG) - a modality employed for the precise acquisition of magnetic field data originating from cerebral activity. Said activity predominantly involves ion currents flowing through the apical dendrites of neurons, which currents are generated by the presence of excitatory and inhibitory postsynaptic potentials [3].

The MEG examinations are performed with the use of quantum sensors – superconducting quantum interference device magnetometers (SQUIDs) or optically pumped magnetometers (OPMs) that will be discussed in more detail.

In OPM sensors, so called optical pumping method is utilized to prepare alkali metal atoms into an adequate quantum state, making them highly sensitive to magnetic fields [4]. The photons in the beam of light passing through alkali metal vapour (typically cesium or rubidium) interact with the atoms. When the correct frequency and circular polarisation of light is provided, photons are absorbed by the electrons and transitions in the electron orbitals, known as D1 transitions, occur. This process results in an increase in the atoms' angular momentum along the laser axis. Finally, most atoms occupy the same energy level and no more energy is transferred. Significant polarization of the atomic spins can be observed, as they are aligned in a manner that maximizes their sensitivity to external magnetic fields. As mentioned polarization is not a stable state due to various relaxation phenomenon, the necessity appears to minimise them by increasing the vapour density and operating at zero magnetic field [4].

The measuring system can be built as follows: light is delivered to a sealed glass cell containing the alkali metal vapor using a laser or an optical fibre, putting the atoms in an adequate quantum state. Subsequently, the probe laser beam's properties correlating with the magnitude of the magnetic field like polarity or intensity are carefully monitored and analyzed using specialized equipment such as a polarimeter or a photodiode [2]. To improve SNR (signal to noise ratio), modulation with on board coils is used. Measuring system is placed in shielded room or capsule [4].

In comparison with SQUID sensors that have been mostly used for MEG, many promising benefits of OPMs can be seen. First of all, they do not need to be cooled. It lets to have sensors placed closer to the brain, which obviously improves the signal strength and quality. Another issue is that when using SQUID sensors, the measurement must be performed in a magnetically shielded room, which is very costly and requires a lot of space. OPMs on the other hand, can be used in smaller, human-sized capsules [5]. OPM helmets are mobile which makes the approach adequate for people with Parkinson disease. Last but not least, the results of medical examination with the use of SQUIDs are often found unsatisfying when performed on people with permanently implanted dental metal elements [3], which is not the case when using the OPMs [6].

Undoubtedly, quantum sensors with OPMs among them have brought a big value to the neuroimaging, offering non-invasive methods of real-time examinations with excellent sensitivity. The future of OPM MEG might be a multimodal approach combining it with a different methods of functional neuroimaging, like electroencephalography (EEG) and functional near-infrared (fNIRS) [7].

IV. Quantum Artificial Neural Networks in Stock Prediction

Field of Quantum Artificial Neural Networks (QUANNs) has always been considered for the most prominent usage in Quantum Information Technologies. The development, simulation, and experimentation of QUANNs was discussed and compared with Classical Artificial Neural Networks (CLANNs) across various tasks. QUANNs are found to be more efficient and, in some cases, more powerful than CLANNs, especially for larger and more complex domains. The research highlights that not all components of a QUANN architecture need to be quantum to achieve these advantages [8]. It is shown that a partly quantum network may perform as well or better than a fully quantum one, raising questions about the interaction between quantum and classical components in future QUANNs. The aforementioned study includes experiments on the simulation of QUANNs and their application in classification and learning tasks, demonstrating their potential benefits over traditional neural networks.

The constitutive architecture of QUANNs is inspired by the double-slit experiment, representing a novel integration of quantum mechanics into neural computing [8]. Several years later, this concept was extended by introducing a new model [9], proving its capability for universal approximation, and discussing its potential applications, especially in approximating the state of a quantum system driven by a time-dependent Hamiltonian. The construction of QANNs is outlined as systems of interconnected *quantum neurons* that compute quantum states from input quantum states. A key contribution is the proof of a Universal Approximation Theorem (UAT) for QANNs, demonstrating that any continuous mapping transforming n quantum states into a non-normalized quantum state can be uniformly approximated by a QANN. This theorem underscores the potential of QANNs as a powerful tool for handling quantum information.

Transitioning to stock market predictions, it is necessary to indicate that market analysis is best defined as an attempt to predict the behavior of financial markets. One of its branches is technical analysis. In this variant, the analysis focuses on examining market trends, mainly through the use of charts, aiming to forecast upcoming price movements. In this method, extensive knowledge in economics is not required to make predictions. The skill in chart interpretation suffices [10]. The stock market prediction in a very basic approach is made on the basis of six components that comprise the daily price of a security: *Opening and Closing Price* (the first and the last quotation on a given day); *Highest and Lowest Price* (the highest and the lowest price of a given instrument); *Adjusted Closing Price* (the closing price after distributing dividends) and *Volume* (contracts concluded) [11].

In this context, a quantum artificial neural network has been specifically designed for predicting stock closing prices [12]. The Quantum Elman Neural Network (QENN) model builds on the classical Elman network architecture, incorporating quantum computing principles to enhance sensitivity to dynamic information. It includes input, hidden, context, and output layers, with context neurons that store previous states through self-connections, optimizing the network structure for dynamic system modeling. The learning algorithm of QENN utilizes gradient descent with adaptive learning rates for parameter optimization, leveraging quantum parallelism to achieve all possible states of the network for improved prediction accuracy. To fine-tune learning rates, the Double Chains Quantum Genetic Algorithm (DCQGA) is employed, combining quantum computing's capabilities with genetic algorithm strategies. This approach adjusts learning rates through population initialization, solution space transformation, rotation angle direction and size determination, and a mutation process, aiming to optimize the convergence and performance of the QENN model effectively.

Building on the advancements detailed in the Quantum Artificial Neural Networks (QANNs) for stock market price prediction, further research could explore the integration of quantum-inspired optimization techniques with deep learning models to capture more complex patterns in high-dimensional data. Leveraging the inherent parallelism of quantum computing, these models could analyze vast datasets more efficiently, potentially uncovering subtle market signals overlooked by classical algorithms. Additionally, exploring adaptive hybrid models that dynamically balance quantum and classical computing resources could offer scalability and performance improvements, addressing practical limitations of current quantum hardware. Moreover, considering the data, an attempt could be made to incorporate into the input of QENN not only the closing prices but all dimensions of daily quotations. Finally, the experiment presented with QENN is limited by only examining MSE (Mean Squared Error). Meanwhile, having regard to the fact that the effectiveness of a stock price predictor should be measured not only by the difference between the predicted values and the true data, but also by its usefulness in trading, one should test with a backtesting strategy and calculate metrics such as: volatility, max drawdown, and Sharpe ratio of the returns of the chosen strategy as proposed [13].

V. QML for Drug Discovery

In the field of pharmaceutical research, Quantum Machine Learning (QML) algorithms emerge as powerful tools able to revolutionize traditional approaches. Leveraging the advantages of quantum computing, QML is postulated to accelerate modelling protein folding, predicting protein structure (the amino-acid sequence) [14], and computing proteins' similarity rates [15]. Various QML methods have been proposed, including hybrid quantum-classical convolutional neural networks for protein binding affinity prediction [16], and applying Variational Quantum Eigensolver (VQE) and quantum Ising Hamiltonian for protein structure prediction [14].

In a hybrid QCNN, some of the convolutional layers are substituted with a random quantum circuit. The data is first normalized with Flexible Representation of Quantum Images (FRQI), and mapped into the circuit using data encodings, such as an amplitude encoding. Subsequently, it undergoes transformation through quantum operations, before being aggregated and processed by the following convolutional and pooling layers. In FRQI the number of qubits scales logarithmically with the dimension of the block, while the number of gates scales linearly. A hybrid QCNN can be constructed with the use of quantum reservoirs (QR). Reservoir computing models are recurrent neural networks, which consist of input, reservoir and output nodes. The weighs are adjusted in the output layer and kept fixed in the reservoir, which allows for a relatively short training process [17]. In a QR, the reservoir layer is built of the basis states of coupled quantum systems, with the output layer being measured occupation probabilities [18]. The research shown that hybrid QCNNs can be used to reduce the complexity as well as the training time of classical convolutional neural networks due to the exponential scaling of the Hilbert space, and thus by managing better the multi-dimensional data, present in the drug development research [16].

However computationally fast, current algorithms - AlphaFold2 and RoseTTaFold, struggle with both mutated sequences and intrinsically disordered regions, leading to inconsistencies. An experiment conducted on the test case of a helicase protein coming from the P-loop of Zika-virus [14] and performed with the use of VQE and quantum algorithm's Ising Hamiltonian on IBM Cleveland quantum computer, showed a distinct advantage of those algorithms in predicting protein structure over AlphaFold2. It is worth noting the difference in solved and known protein structures (around 300 million and 200 thousand). Some quantum researchers advocate for further advancing physics-based methods, molecular dynamics and *ab inito* methods. Quantum algorithms are proposed to stimulate these methods and remove their time and scalability constrains to bridge this gap.

While both experiments show an exciting promise on the possible applications of quantum computing in drug research, the technical challenges remain [19]. The current size of the largest quantum computer and one necessary for breaking most secure cryptography (in 8 hours time), is 433 to 20 million qubits. For the quantum computations to be useful, a substantial portion of physical qubits needs to be used for error correction calculations – to mitigate EM and cosmic rays induced noise.

VI. IQT in Swarm Robotics

Rather unintuitive application of the QIT can be found in the terms of robotic swarm. Firstly, let's define the swarm as the system that consists of numerous agents which somehow complete the complex task on the basis on local interactions [20]. The idea behind the swarm robotics is that a large number of relatively simple agents can perform better and more reliable than the single advanced robot. Nevertheless, the design of the swarm is not a trivia. Hence, recently the attention is directed towards quantum as the solution to this task.

One of the proposed solution is to use quantum formalism so as to model the single agent in the system. This approach was given in the paper where the single tennis ball picking robot was modelled [21]. Researchers proved that the entanglement can be used to make a single action on the basis on the robot's perception. Furthermore, they designed a quantum circuit and obtained promising simulation results with the use of IBM quantum computer. Finally, researchers suggested that combining quantum logic with the multi-robot system to model complex behaviors.

The Chella et al. showed in several papers explicitly the use of quantum modeling with the swarm robotics [22] [23] [24]. The local interactions of the robots are modeled with a quantum circuit. To obtain the global behavior from the local interactions there is used a block matrix-based model. In this approach robots' all interactions are entangled, however, each agent has certain autonomy. Started from purely theoretical approach [22] and then tested in the simulations with the search and rescue scenarios [23] [24]the results were promising. In simulations there were used the IBM Quantum Simulator and IBM Quantum Computer to simulate the robots mutual interactions. In spite of promising methodology, it does not allow for accomplishment of the advanced tasks. Hence, there is an interesting field for research. For instance with the quantum formalization of the methodologies oriented on high-level swarm design [25].

Finally, there is defined the idea of a general swarm intelligence [26] where the swarm itself is treated as a single super-intelligence entity. The researcher [26] gives the theoretical description of a swarm system in which all agents constitute to a single deep convolution neural network. Nonetheless, each agent is an autonomous entity. Currently, this is not possible to implement, as the author suggest that there is need for each robot to possess a quantum processor which would consist of hundreds of millions qubits.

The aim of this section was to show how QIT can enhance the field of science which seems to have little in common whereas it is in fact quite opposite. The swarm robotics with the quantum computing might enable this technology to everyday life starting from precision agriculture to precision drug delivery [27]. Finally, the general swarm intelligence could be extremely powerful as shown by the Stanislaw Lem in the novel "The Invincible" [28] where the general swarm intelligence ends the life on the whole planet.

VII. QKD

While quantum computing is mostly considered a threat to security, with regards to potentially breaking prevalent and widely adopted cryptographic standards like SHA-256, it also creates opportunities for creating provably-safe algorithms, like BB84 or E91. Current cryptographic algorithms are based upon operations, like modulo division, which are practically one-way – there is no algorithm which guarantees breaking the encryption is reasonable time. Cryptographic hashing functions, though are not proven to be safe, but base on the fact that computing power required to break the encryption is currently not existing. Specifically, existence of any purely one-way function has not been proven yet and is still regarded as one of the most foremost questions in computer science [29].

Proposed algorithms, based on quantum mechanics could be proven to be safe, because of physical nature of reality, thus security is independent of available computing power.

Most notably, quantum key distribution algorithms are divided into 2 groups: based on quantum entanglement and quantum superposition [30]. Both groups, in general, rely on no-cloning theorem, which states, that given quantum state cannot be replicated, after it has been measured (and therefore destroyed) [31]. This fundamental difference between quantum and classical cryptography allows quantum key distribution to be provably safe, regardless of resources used by the attacker (time, compute, etc.).

Algorithms based on quantum superposition, notably the fact that measuring photon state destroys it, making listening to communication possible, but listening and not-being detected impossible, because photon state would inevitably change. BB84 is an example of such algorithm [32]. In quantum channel sender sends bytes encoded in the following way: after choosing a base from vertical or diagonal for each photon, he encodes it in chosen base and remembers which base has been used. The receiver doesn't know which base has been chosen, so he also decides at random. This results in around 50% of all photons being faithfully readable. Then, by comparing received bytes values and selected bases, sender and receiver are able to check if the communication has been compromised. If so, they don't establish classical channel communication, but negotiate another key, using protocol described above.

Algorithms based on quantum entanglement leverage the phenomenon where the states of particles become correlated, regardless of the distance between them. This property enables the creation of secure communication protocols. One notable example is the E91 protocol, which utilizes the entanglement of photon pairs to establish a shared secret key between two parties. By measuring certain properties of these entangled photons, users can detect any eavesdropping attempts, ensuring the security of their communication [33]. The sender, as well as receiver, and even the eavesdropper could serve as entangled photons source. Because entangled photons have 100% correlation, with regard to polarization communicating parties could faithfully check if the communication is secure.

Algorithms discussed above as well as brief underlying theory may be found to be very useful in the future applications of quantum cryptography. This shows that quantum physics is not only a threat to cryptography (for example, due to the potential compromise of RSA and Trusted Platform Modules), but also an opportunity, allowing us to think about fully trusted and secure communication in the future.

VIII. QPIC

Integrated photonics is increasingly present in our daily lives, in both commercial and scientific applications. Thanks to tremendous miniaturisation, we have moved from large optical tables to small chips that can perform multiple functions. Traditional integrated circuits are mainly used to transmit and process large amounts of data at high speeds, for example through optical fibres. Quantum photonic integrated circuits, on the other hand, are designed to perform quantum operations on single photons. Quantum photonic integrated circuits are growing and have the potential to replace traditional integrated circuits. The introduction of quantum PICs would make it possible to harness the computational power of single photons and contribute to the development of quantum solutions in various fields such as communications, quantum computing and information security.

The basic phenomena used in quantum integrated photonics are entanglement, superposition and quantum tunneling. All phenomena have a wide range of applications in various technical applications such as computer science, communication and sensors. Entanglement allows for the creation of strong correlations between distant points. However, superposition allows the manipulation of photon states possible only in quantum optics, which allows the creation of more advanced quantum states. The last phenomenon, quantum tunneling, can be explained as follows, as a phenomenon that allows the manipulation of photons on a microscopic scale. It is a suitable phenomenon for creating advanced quantum circuits on photonic chips. In addition to the above-mentioned phenomena, the basis also includes tools such as logic gates for single photons and quantum interferometry. Thanks to them, accurate measurements and advanced quantum tasks are possible.

The basic material used in QPIC is silicon, but an interesting new material has appeared which, contrary to appearances, is not completely new, and we are talking about diamond, which is known to everyone. Diamond has so-called NV centers that can emit light in a controlled manner. NV centers are stable quantum optical centers, which allows them to be manipulated and used as individual qubits. This material is extremely durable and therefore resistant to degradation. An important feature of diamonds is their high sensitivity to detecting single photons, which is used for precise quantum measurements. This material will certainly be subjected to detailed research in the coming years, because it has high potential to become an ideal material used in QPIC, due to its unique properties such as the ability to control and store quantum information in individual atoms.

One interesting application of QPIC is photonic quidits on chip. Qudits are distinguished from qbits in that they are d-level versions of qbits. It is possible that qdits may be better than qbits due to the larger state space for storing and processing quantum information. They also show high resistance to changes in the distribution of entanglement. Qudits on a chip allow quantum systems to scale. Taking into account the degrees of freedom, quidits on chip are very advanced. Despite extensive work on this issue, many inaccuracies remain and more work needs to be done on this issue to achieve, for example, precise control of systems.

Secure communication is something that is important in the rapidly advancing technological development. QPICs are used as a platform on which quantum cryptography is implemented. QPIC enables the transport of information in a quantum way. Qunatum key destribution is the most popular application of QPIC in quantum cryptography. Another popular application is encrypting and storing information on photonic chips. It is used in the financial, military and scientific sectors.

Machine learning finds patterns and learns them at lightning speed. This has found wide application in photonics and other fields. The development of machine learning will enable the development of quantum algorithms. Machine learning will allow for schematic creation of layouts when designing QPIC. In quantum photonics, machine learning techniques are used to solve Schrödinger equations, enabling efficient tasks such as quantum state tomography.

Quantum Integrated Photonics is a promising field that combines quantum technologies with photonics on integrated circuits. Key applications include quantum computing, quantum communication and quantum sensing. Examples of technologies include waveguide QED, photonic quantum transistors and quantum dot microcavities. Potential for revolutionary changes in information and sensing technologies.

IX. Quantum teleportation in biological systems

The problem of applying quantum information technologies in biophotonics is treated with no less attention. Below, the topic of quantum teleportation in biological systems will be discussed. The motivation for these considerations includes phenomena such as the transmission of electrical signals by bacteria, as well as their exchange of electromagnetic waves with the environment, the phenomenon of magnetotactic bacteria, and the biophotonic aspects of chloroplast functioning, particularly during photosynthesis [34].

Drawing an outline of the field, the last efforts in quantum optomechanics and electromechanics, leading to the realization of quantum superposition states in larger systems, are noteworthy. This review [35] has shown how quantum coherence may be integral to biological processes such as photosynthesis and avian magnetoreception, suggesting that biological systems might exploit quantum mechanical phenomena for efficiency or functional advantages. Moreover, proposals to realize quantum superposition in living organisms, extending quantum mechanics into the field of microbiology, mark a intersection of physics and biology that could deepen our understanding of both fields. Furthermore, quantum entanglement between a living bacterium witnessed by Rabi splitting is explored [36]. This achievement not only demonstrates the strong entanglement between bacteria and quantized light but also solidifies the role of quantum coherence in biological entities. The analysis uses the Dicke model to confirm the presence of entanglement, evidenced by the lower polariton branch resulting from vacuum Rabi splitting.

Attention has also been given to probing quantum features of photosynthetic organisms by investigating the possible quantum correlations in systems involving living bacteria and light [37]. The experimental approaches and theoretical models reveal that photosynthetic bacteria, when strongly entangled with light in a controlled quantum environment, exhibit non-classical behaviors such as quantum discord and entanglement. This evidence supports the idea that even living systems at the macroscopic level can participate in quantum phenomena, fundamentally challenging traditional views of quantum mechanics' applicability. The implications of these findings suggest potential new techniques in both the study and manipulation of biological systems through quantum information science.

Moreover, the experiments explore several innovative methods for quantum information teleportation using biological systems [34]. One significant finding is the demonstration of biological wires formed by micro-bubbles and microbes near plant cells, which facilitate information transfer between cells without direct contact. These biological wires utilize quantum particles like electrons and protons, allowing for long-distance electron transport as seen in bacteria wire. Additionally, the experiments suggest that chloroplasts and bacteria can exchange quantum information through electromagnetic waves, potentially impacting plant defense mechanisms. Another experimental observation is the emergence of gravitational micro-bio-holes, which appear to play a role in directing the movement of microbes and micro-bubbles towards dense cell clusters, possibly aiding in cellular communication and material transport. Lastly, the use of holographic micro-bio-systems is investigated, showing potential in creating virtual biological interactions that could be leveraged for diagnosing or treating diseases. These findings underscore the complex interplay of quantum mechanics and biological processes, offering novel insights into the control and manipulation of microbial systems.

Based on this, one practical application could be the development of advanced biosensor systems for environmental monitoring. Specifically, the mechanisms of quantum teleportation and the use of gravitational micro-bio-holes and holographic micro-biological systems could open up possibilities for biological sensors capable of detecting and responding to very subtle environmental changes at the quantum level. For instance, utilizing microorganisms capable of transmitting quantum information through biological ”wires” might enable the creation of living detectors that react to chemical or physical changes in soil or water, transmitting information in a non-invasive and energy-independent manner. Such biosensors could be employed in precision agriculture to monitor crop conditions or detect early stages of plant infections. Additionally, the use of holographic micro-biological systems to create virtual images of microbes could lead to new diagnostic medical techniques, where virtual images of pathogens are used to train the body's immune system to recognize and combat actual pathogens without exposing the patient to real infection risks. These novel technologies, leveraging advanced quantum phenomena in biological systems, could significantly contribute to medicine, ecology, and environmental technologies, offering methods more integrated with natural biological processes, crucial for sustainable development and environmental protection.

X. Quantum metrology

Quantum metrology is a rapidly growing field of science, it is characterised by much greater measurement capabilities than classical metrology and its accuracy allows the measurement of signals whose level was the magnitude of the measurement noise [38]. Exploiting entangled states and superposition, quantum metrology opens up new possibilities in the field of precise measurements of time, frequency and also in the detection of very weak forces and fields. The most important discovery is considered to be the invention of atomic clocks which surpass the classical approach by several orders of magnitude. Nowadays, we are seeing a great deal of interest in quantum metrology, which will help us to better understand the world around us.

By using the ideas of quantum mechanics, quantum metrology is able to measure physical parameters with extreme precision. It takes advantage of special quantum phenomena that classical approaches are unable to reproduce, such as entanglement and squeezing. Estimating the parameters of unitary dynamics, which entails knowing a system's starting point and how it changes over time as determined by its Hamiltonian, is a crucial problem. Known as linear interferometers, measurements are usually performed on systems with many particles, where the Hamiltonian is a sum of single-particle components, suggesting no particle interaction. The quantum Cramér-Rao limit [39] sets a limit on the precision of these measurements based on the quantum Fisher information and the number of measurements. The objective is to approach the Heisenberg limit, which provides better precision with fewer particles, and to overcome the classical limit, also referred to as shot noise. However, precise scaling may be constrained by local noise, especially when dealing with a high number of particles. Quantum metrology encompasses various applications such as the exact phase measurement of NOON states in Mach–Zehnder interferometers [40], and its possible use in gravitational wave detection projects like LIGO [41].

According to [42], the Weston's firewall, which only permitted the realization of a single voltage value, has been replaced by the quantum DC voltage standard, which has enhanced work at the GUM. The building had to be rebuilt in order to meet the standard operating requirements, hence the article details the modernization process. In terms of metrological criteria, Poland now holds the title of having the best DC voltage standard worldwide. It is important to remember that standards of this kind still have a low part availability and a material life of just roughly ten years.

To sum up Quantum sensors are beginning to gain popularity, mainly for purely scientific applications, but when their availability improves and the appropriate methods are perfected, classical metrology will be replaced by quantum metrology. The new era of quantum measurements, which are limited only to the fundamental principles of our world, shows incredible efficiency and precision that we cannot achieve with classical measurements. These are new possibilities for better performance in production and quality control and will open up new research insights, for example for the prediction of atmospheric phenomena.

XI. Shor's algorithm

In 1994 [43], Peter Shor proposed an algorithm capable of polynomial-time factorization of prime numbers. This algorithm relies on the utilization of a quantum computer with a small probability of error. In his seminal paper, Shor also demonstrated the efficient resolution of discrete logarithm problems. The underlying assumption is that the precision of quantum computers increases polynomially with input size. The algorithm exhibits a space complexity of O(log(N)) and a time complexity of O(log(N)3), representing a significant advancement compared to classical algorithms.

At the time of its conception, the best classical algorithm, the Number Field Sieve, had an exponential time complexity. Even today, with enhancements to the General Number Field Sieve, the complexity remains exponential. This underscores the potential paradigm shift that Shor's algorithm could bring to the prime factorization problem, given sufficient hardware capabilities.

Main idea in this algorithm is to replace the problem of prime numbers factorization to a problem of finding period of function. This approach allows to utilize quantum superposition to find a solution more efficiently. Final information is being extracted by applying inverse Quantum Fourier Transform. These quantum operations combined with classical computation allows to factor prime number in polynomial-time [43]. However, nowadays implementation only allows factorization of small numbers like 21 and 15.

Estimating the resources required for Shor's algorithm is important for assessing the vulnerability of some of today's public key cryptosystems to future quantum threats. With the fastest quantum hardware operations proposed to date, factoring a 2048-bit integer using Shor's algorithm could be done in minutes with an array of twenty five thousand perfect, noiseless qubits. However, qubits are noisy and requires error correction in order to allow long computations, so amount of physical qubits needed raises to ten of millions and time of executing this computation extends to a day [44].

Currently, the RSA algorithm stands as the predominant encryption method, relying on the difficulty of factorizing large numbers. However, successful implementation of Shor's algorithm would necessitate the development of new cryptographic systems. With polynomial computational complexity, reconstructing a private key from a widely available public key would no longer pose a challenge. Moreover, in general public key cryptosystems rely on 3 mathematically hard problems: big prime numbers factorization, discrete logarithm and elliptic-curve discrete logarithm. Each of them can be efficiently solved with Shor's algorithm executed on suitable quantum computer. This being the case, considerable research is being done in the field of post-quantum cryptography, in an effort to develop cryptosystems that are resistant to both classical and quantum attacks. Other branch of cryptography resistant to Shor's algorithm which is being researched is quantum cryptography. Main difference between them is that post-quantum cryptography does not use quantum effects and relies only on classical algorithms.

XII. Quantum Computers

A quantum computer is an example of a new generation computing machine. It uses quantum mechanics in a signally different way than traditional computers, which use classical mechanics. Systems performing calculations must be isolated from the environment. Moreover, the system is cooled to low temperatures thanks to a cryostat. Qubits are located on small boards that are manufactured in a similar way to classic processors. In addition to the mentioned qubits , there are contacts and microwave wires on the boards. Qubits can be built from elementary (single) particles such as electrons, atoms or loops from superconductors where current flows constantly. The state of qubits can be changed. We can do this using pulses of microwave radiation.

Considering a computational unit, traditional computers use bits in states 0 or 1. Quantum computers, however, use qubits,, which can exist in states 0 and 1 simultaneously, as described by Dirac notation . This is possible using the principle of quantum superposition. What makes quantum computers much more efficient than classical computers is the increased computing power. This allows one to solve problems requiring the study of very large data sets, simulations of quantum phenomena or quantum cryptography.

We can also find differences in the way data is processed. Classical computers perform calculations serially. When faced with the task of adding two numbers, the bits are sequentially processed using an arithmetic logic unit (ALU). However, in quantum computers, calculations are carried out in parallel. The principles of superposition and entanglement are used. The former allows qubits to represent many combinations of states at once. The latter allows the state of one qubit to influence another, where the physical distance between them does not matter. Both phenomena open up new possibilities in the fields of security, industry and medicine, and inspire scientists to conduct quantum scientific experiments.

Quantum computers differ significantly from traditional computers in terms of speed and processing power. The physical limitations of processors in classical computers affect their computational speed. Additionally, clock frequency, architecture efficiency and the ability to effectively cool also influence the limitations. Quantum computers have much greater capabilities thanks to quantum mechanics. Thanks to the principle of superposition and entanglement, tasks are carried out efficiently because it can process huge numbers of combinations of states simultaneously. Examples include factoring numbers by Shor's algorithm or searching unstructured databases by Grover's algorithm.

Currently, access to quantum computers is limited. This is influenced by, among others, technological complexity, construction costs and appropriate conditions in which it must be stored. Effective use of a quantum computer requires specific scientific knowledge. All this contributes to the fact that access is currently mostly reserved for large corporations or scientists. Large corporations, for example IBM and Google, make their quantum processors available in the cloud. This enables remote sharing for a wide range of users. Investments in quantum technologies currently amount to billions of dollars, which indicates promising prospects for the future of this field.

XIII. Software Engineering Advancements in Quantum Computing

Quantum computing (QC) has seen significant progress through the intersection of software engineering, quantum physics, and cloud architectures. The development of shared framework for quantum software engineering is crucial for developing quantum software, which is essential for achieving the raw computational power of quantum hardware. Here's a comprehensive look at recent advancements in the field, emphasizing the influence of cloud architectures.

Quantum software engineering (QSE) supports the scalable and reliable development of software that operates on quantum algorithms. Essential to this are the quantum software stacks which include quantum operating systems, compilers, and programming languages such as Q#, Qiskit, and Silq [45]. These tools allow to exploit quantum hardware potential, by execution of quantum algorithms. The coding process consists of unique challenges compared to classical software development, emphasizing the need for specialized knowledge in quantum mechanics and software engineering principles.

Current quantum applications are designed as hybrid combination, integrating classical computing infrastructure and quantum computing capabilities. The access to quantum computing is available through cloud-based platforms like IBM Quantum, AWS Braket and Azure Quantum. All these platforms provide essential APIs and SDKs for running quantum software from remote location [46]. This integration is essential because current quantum computers (Noisy Intermediate-Scale Quantum, or NISQ) have limitations such as error rates and stability issues, making them unsuitable for standalone use for all computing tasks [47]. As a consequence, definition of right architecture of such application is crucial.

One of the primary issues is determining the quantum-classical split — deciding which parts of an application should run on quantum versus classical processors [48]. Current pattern in designing architecture for such application is using classical computing for more routine processing and data handling tasks and leveraging quantum computing for computationally complex problem-solving tasks. Additionally, the unstable nature of quantum states in current NISQ devices and the probabilistic nature of their outputs require novel approaches to error mitigation techniques and probabilistic testing frameworks.

Current cloud architecture depends on virtualization technologies. Data security in multi-tenant environment relies on standards, delivered by processors manufacturers, known as TEE - Trusted Execution Environments [46]. Thus it is essential not only for the future of access to quantum computing, but also to cloud computing in general, to develop quantum resistant networking solutions [49]. To target security, while using quantum computer cloud services, delegated quantum computing (DQC) and blind quantum computing (BQC) ideas were proposed, along with hardware solution - Quantum Computer Trusted Execution Environment (QC-TEE) [50], [51].

Ongoing research in field of quantum software engineering emphasize the need for creating shared framework, paradigms, principles and patterns, to improve scalability and reliability of quantum based programming projects. There are lots of proposals on how to enhance security of remote computation in quantum era. This advancement can enable shift in focus, from building ground to one's project, towards resolving computationally complex problems, by utilizing quantum compute power, while keeping the data secure.

XIV. Conclusion

In summary, our collaborative exploration within the Quantum Information Technologies course has led us to discover the vast potential of integrating QIT into the fabric of Information and Communication Technology.

In many areas, QIT applications push limitations, imposed by computation power of classical computers, forward allowing for much deeper insight to our surrounding reality. This workshop has encouraged us to think beyond conventional boundaries and to dream about future technologies that, while currently speculative, could soon emerge as industry standards.

However advancements made in some of them can have double-edged sword effect, in example of quantum-based cryptography, on one hand bringing much bigger cryptographic capabilities, on the other, can be disruptive factor for current data security infrastructure.

Conducting a thorough research concluded with student's own perspective on subject, can be very beneficial. As in any other field, giving a fresh perspective, which does not necessarily have to be in line with current assumptions can lead to a new field of exploration.

This perspective on what effects technological advancements can have, is a great ground for comprehensive reflection on reality of being an engineer.

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