www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

jet INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2023, VOL. 69, NO. 2, PP. 391-398
Manuscript received April 5, 2023; revised April, 2023. DOI: 10.24425/ijet.2023.144375

Quantum Europe, Quantum Poland

Ryszard S. Romaniuk

***Abstract*—QIT–Quantum Information Technologies promises are very serious, greatly exceeding only technical and market levels. Development of QIT in Europe, treated as building a new infrastructural civilization level, requires a broader view of coordination, funding and priority-setting policy. Simple measures used in the case of the development of new technologies, but not creating a significant ecosystem, are insufficient in this case. Quantum technologies are poised to create a new information layer of knowledge-based society. In this essay, the author subjectively addresses some of the issues such as: what we already know and what we don't know, and what efforts are being made in Europe. Polish version of this paper was published in Przegl.Telekom.2.23.**

***Keywords*—quantum information technologies; computing; teleinformatics; metrology; European Quantum Flagship**

I. Introduction

IF we want to discuss the quantization of Europe and Poland, we need to shift our considerations from the laser and transistor Quantum-1 era of bandgap engineering, to the Quantum-2 era, the second quantum revolution. Quantum-2 is about the functional use of single quantum systems. Moving from the level of quantum physics to technical functionality, such objects are qubits or kudits, two-level or multi-level quantum systems. We organize qubits into registers. We use them to build logic gates and increasingly complex quantum circuits and devices. We optimize logic gates transforming qubits into kudits and vice versa. We build processors and quantum network nodes from gated quantum systems.

We functionalize both single qubits and their one-, two- and three-dimensional registers. In Hilbert space we can also have quantum multidimensional systems. We are talking about the depth of quantum circuits, which is a measure of their complexity and a measure of the possibility of performing more complex quantum operations. We functionalize mutual transformations of quantum states between stationary and flying qubits. We learn to manage valuable quantum resources such as coherence, entanglement and contextuality. These resources have many subtle properties. Most of them remain unchecked. Even so, we operate quite effectively on just a few known and basic properties.

II. Transformation from Quantum-I to Quantum-II

The resources of Quantum-I are energy, current, voltage, transmission rate, etc. The resources in Quantum-II are quantum coherence, entanglement, contextuality, quantum indistinguishability or discernibility, orthonormal quantum states of freedom of the system, etc. A potential resource can be irreducible difference between the thermodynamic domain and the decoherently and selectively coupled quantum domain. We do not know all of these differences. Differences are due to energy constraints, speed of light, Heisenberg's uncertainty principle, inherent non-locality of the Universe, informational and energetic properties of Black Hole singularity and its event horizons, quantum no-go laws, Kochen-Specker, no-hiding, no-deletion, no-cloning, no-teleportation, no-broadcast, no-communication.

This complex space of confinements has to be mastered at technical level. An excellent example of taming the technical quantum domain is effective functional operation at the very edge of the Heisenberg uncertainty principle, which we cannot bypass. And yet it is possible to operate below the state of quantum confinement for one of the components of non-commutative states by squeezing. Squeezed non-classical, sub-Poisson light, not existing in nature, enabled the realization of the LIGO interferometric gravitational wave detector. Such and similar techniques, e.g. quantum teleportations, entanglement switching and distribution, as well as telepathy and other methods of circumventing quantum limitations, enable the technical implementation of quantum teleinformatics, but in this most important layer, i.e. the magic one, which is not realized in a classical way.

An effective, not only European way to implement QIT requires coordination of research and development, as well as a much more thorough understanding and experimental knowledge of the processes of transformation of the quantum world into the classical one. The fuzzy border between these worlds is filled with decoherence processes. The study of new concepts and technical solutions, where quantum technologies are beneficial, leads to the progress of research and applications in biology and medicine, chemistry, energy, but also in the established canonical areas of QIT. The development must take place through the practical demonstration of new quantum technologies and their transfer to existing areas of application or by opening up new areas of research and innovation. The long-term goal of the development policy is to expand the search front and open up new opportunities for QIT applications in the economy and civilization infrastructure.

III. SatCom plus QIT

The combination of the SatCom satellite telecommunications sector with QIT opens up a significant area of new research opportunities that can be almost directly translated into innovations, business applications and the offer of new services. SatCom plus QIT is a perfect marriage of convenience. To shorten the description of the development directions of these areas, it can be said that SatCom is photonized and reaches terabits, and in photonic QIT a single SatCom photon can act as a quaquart and a qutrit, and not only as a qubit. The SatCom+QIT sector must interact directly with the network of optical tubes on Earth.

A single photon prefers outer space, where it is practically not attenuated, than an optical fiber, where it is attenuated exponentially in a material medium, and additionally it travels

Ryszard Romaniuk is with Warsaw University of Technology, Poland (e-mail: r.romaniuk@ise.pw.edu.pl).

© The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0, https://creativecommons.org/licenses/by/4.0/), which permits use, distribution, and reproduction in any medium, provided that the Article is properly cited.

at a slower speed equal to about 2/3 of the speed of light in a vacuum. A photon and a vacuum, such a pair, are also tried to be realized in photonic optical fibers with a photonic band gap replacing the classical refractive propagation. In other words, the photonically generated band gap replaces the small refractively generated potential well. Therefore, ultra-low-dispersion telecommunication optical fibers are called weakly propagating. Any significant increase in the potential well increases the dispersion beyond the allowable telecom limit. These phenomena do not exist in the outer space. However, optical fiber does not support yet the Quantum-2 system, although it could easily. This is still the epoch of Quantum-1, a precisely modulated TDM/DWDM laser beam. We will fully talk about Quantum-2 if we have the technique of single non-clustered photons in the optical fiber, even if it is a beam. It seems that the technique of single photons can completely change QIT.

Implementation of quantum teleportation between satellites distant by a million km is much easier than teleportation in optical fiber over a distance exceeding 300 km, where a quantum repeater should be used. So far, we do not have such a repeater in an effective operational version. We teleport the quantum states of photons in optical fiber over short distances. The essence of telecommunications is not only the massive transmission of information between two points, but above all secure network distribution. A qudit is much more efficient at such a quantum distribution at a network node than a basic qubit. The qudit register, in the distribution and regeneration node of the heterogeneous quantum network, should be supported by a quantum memory. We do not have such a memory in an effective operational version. Effective management of the qudit register is now unavailable, neither in a quantum computer nor in a quantum network node.

We do not have many components to build an effective quantum network and a quantum computer. Searching for quantum solutions and innovations are necessary. Major coordinated research programs are needed, concentration of efforts on priorities, and the implementation of numerous research and innovation projects at the global European and national levels. It is necessary to quantize Europe and Poland. We have a massive quantum flagship research program in Europe, tailored for the decade [1]. We have an optional ESA ARTES 4.0 program with quantum components [2]. We have company projects [3] and a number of national projects, including Poland. From technical literature one can get the impression that we are already quite well quantized, but still not so well that we are not afraid of the lack of quantum cybersecurity.

What do we have truly quantum? We have a lot of components enabling the current fast develepoments. The NISQ era is based on theoretical advances in QIT, on the discovery of quantum algorithms, and on technological advances on qubit technologies, such as transmons. Advances in transmons enabled IBM to open the quantum cloud to a wider range of users [4]. Advances in SatCom on optical quantum systems enabled the launch of the first entanglement-assisted satellite network cryptographic system [5] as early as 2017. Micius [6] is still the only satellite entirely dedicated to orbital quantum experiments. Europe is organizing towards the quantum SatCom sector to catch up with several years of experimental delay against the lone leader, the operator of the quantum satellite Micius.

IV. QIT – Status and Development

QIT is developing on experimental and theoretical levels and at the boundary of quantum and classical ICT technologies. The QIT despite its distance from technical maturity, initiates research in the post-quantum direction. At the basis of this direction is the question of whether this is the last possible level of technology development. The post-quantum anxiety is raised by questions about the quantum stage of civilization development and the effective technological mastery of non-locality, entanglement, contextuality, functionalization of teleportation, multiplication of quantum resources, etc. Does the cybersecurity of the quantum era have to be ensured only by quantum methods, or possibly by post-quantum.

Cybersecurity of the NISQ Era is different than for ther UQC. Some of the security estimates are based on the theory of complexity taking into account quantum algorithms, the search for a hypothetical one-way function, the theory of large numbers, and the analysis of the possibility of building a universal UQC quantum computer, or at least a modest version tolerant to errors QET-UQC. NISQ seems to be far from sufficient, but nevertheless gives amazingly good results.

Considerations about the post-quantum age of cybersecurity are rooted in complexity theory and the thesis that quantum complexity theory is a sub-area of the general theory of computation, including theories of automata and formal languages, computability, and computational complexity. Knowing that a Turing machine implementing the most general computational model is realizable by quantum methods, we are looking for differential areas of quantum and classical computability, and properties of these differences. The NISQ epoch, without ensuring the operation on a pure quantum system, like a single photon, cannot provide deep quantum security. Laser clustered Poisson photons are a security hole.

The difference between the thermodynamic and quantum worlds is potentially a resource? The macro world emerges from the quantum world through selective decoherence selection rules. Any such difference between theoretical or laboratory quantum and classical formalisms is a potential resource that could form the basis of a new quantum information protocol or functional device. In assessing the differences, learning about their properties, it is necessary to place them in a formal context. We classify the differences as stronger and weaker. Only strong differences are non-transferable between the two systems and are sometimes called magical or truly quantum. The simplest example of classical unrealizability is the one-qubit Hadamard gate. However, the Hadamard gate belongs to the Clifford group normalizing the unitary invertible Pauli group. The combination of the H gate with the CX gate creates the simplest system, which is strongly quantum and entangling. Such a system also belongs to the Clifford group and does not create quantum magic.

Clifford algebra has no quantum advantage. The Clifford group consists of unitary gates: identity gate I, Pauli group of rotation about the X, Y and Z axes by angle π, phase gate S=P(π/2)=√Z, Hadamard gate H, controlled gate CX=CNOT=XOR and CZ, anti-controlled gate CX=XNOR, double-controlled gate CCX, SWAP, imaginary iSWAP. I,X,Y,Z,H, CX, CX, CZ, SWAP gates are Hermitian and involutionary. Pauli gates X,Y,Z and H are traceless. Pauli's gates squared also belong to the Clifford group. The X gate is equivalent to the NOT - bit flip. The Z gate is a phase flip. Higher order Clifford gates are generated by H, S, CX gates. Clifford gates build efficient quantum systems and have the valuable stabilization feature of spreading prevention and quantum error correction in computing systems and quantum network node. If the Clifford gate A is not in the Pauli group, then neither the gate √A nor the CA gate are Clifford gates. The group of non-Clifford gates includes: quantum gate of any phase shift P(ϕ), CP(ϕ), T=P(π/4) , CS, Fredkin F=CSWAP, etc.

The Clifford group, by the Gottesmann-Knill theorem, does not form a universal gate group. In other words, it does not create a set of gates sufficient to build a UQC. It also does not create a magic level in quantum information systems if it works on quantum pure states. In computing, it means no major computational advantage, since any Clifford system is classically simulated in polynomial time on a classical probabilistic Turing machine. In telecommunications, this means, for example, the lack of agnosticity of such quantum transmission in relation to network nodes, i.e. the need to use intermediary trusted nodes to ensure security. Not such modest achievements are the goal of QIT. The unilaterization of the transformation between the quantum and classical systems, called the use of magical resources, requires the use of gates and quantum calculations outside the Clifford algebra. The complete group building a universal gate quantum processor or a quantum agnostic network is formed by the basic Clifford set supplemented by at least one gate outside this group. In such a universal system of gates, it is possible to act on the quantum magical level, i.e. distillation of entanglement. However, if the Clifford system is powered by quantum magic states, we have a dual situation and despite the lack of a gate outside the group, the system behaves as if it were universal.

Quantum magical states enable distillation and purification. In these operations it is necessary to know what kind of entanglement we are dealing with. Many very basic quantum algorithms, such as entanglement distillation and quantum error correction, were initially developed using the Clifford group. The discovery of the diversity of pure and mixed entanglement, some of their properties such as: monotonicity, monogamy, distillability, unilaterality, separability and non-separability, non-transferability between some of their different types, allowed to understand the necessary path of creating quantum magic states and implementing quantum systems fault-tolerant and node-agnostic quantum telecommunications.

Quantum NOON, GHZ and cat states, cat qubits and boson codes. NOON represents a multilateral entangled state, a non-local superposition of N qubits, all of exactly one quantum type. Qubits in the NOON state can be any bosonic field that satisfies the canonical commutation relation. Most often it is a photon, hence the NOON state is fundamental for QIT when setting initial conditions for calculations, data transmission, or quantum measurements. NOON states can be very sensitive to external influences and decoherence due to entanglement splitting among a large number of qubits. NOON states are related to GHZ and cat states - a superposition of macroscopically different states of many objects, but also a single object that is simultaneously in two completely different states.

The cat state can be complex and mixed, not necessarily entangled. First-order and higher-order cat states were realized experimentally with various microscopic and macroscopic objects, but also with photons. GHZ states were realized for photons, obtaining stable entanglement of many single photons, as well as hyperentanglement of several photons forming bigger number of qubits. The GHZ state is difficult to create in practice, but it is easy to verify, therefore it is used to evaluate other complex entangled quantum states formed from a group of atoms, or in the nanobiology of entangled molecules. The Wigner quasi-probability distribution is used to describe the cat state of a single qubit.

Cat photon qubits were tested for quantum information coding as well as transmission and teleportation. The larger the superposition system in the cat state, the more susceptible it is to decoherence. On the other hand, single-mode quantum cat states well defined as a superposition of non-overlapping significant positive and negative electric fields, create ideal states resistant to decoherence. Creating cat states from a significant number of photons is difficult. A significant number of photons facilitates the separation of fields in the Wigner function and improves the quality of the cat condition. Cat quantum states formed from a small number of photons are referred to in the literature as Schrodinger kittens. There are methods of creating quantum cat states and qubits by entangling two smaller kitten states, photon subtraction from squeezed vacuum states, multi-photon subtraction, ancilla techniques.

Cat states can be used to encode quantum information in a system of bosonic codes. On the one hand, in the reference system of cat states, Bell states were measured for photons as cat qubits in a linear optical circuit, and the usefulness of the qubit technique for computing and quantum teleinformatics was shown. On the other hand, bosonic codes encode information in an infinite-dimensional Hilbert space of one kind. This is a completely different encoding system from qubit. A significant number of dimensions adds redundancy to the quantum system, which can be used to correct quantum errors. The dominant decoherence channel in the bosonic code system are photon losses. Bosonic coding requires the use of photonic non-linear phenomena to generate stabilization and measurements. The error-proofing of bosonic codes of quantum information is due to large phase-space.

Quantum monogamy defines the dynamics of functional operations on resources? For quantum operation, the computer and the network need resources. For now, it's not always magical resources, but always quantum resources. The computer and the quantum network work also quite well without magic resources. For certain operations, such resources are not absolutely necessary. The implementation of the basic versions of the QKD quantum key distribution technology does not require magic resources. That is why the SatCom technology facilitates distribution so much. There are no intermediate nodes requiring trust. However, we treat the satellite as trusted. Different keys go to their destination directly from the broadcasting satellite. QKD assisted by Alice and Bob's maximum bilateral entanglement uses monogamy to block the possibility of third party entanglement. The entanglement of the third and subsequent parties is the higher school of quantum resource distribution. Used entanglement may be not maximal.

Quantum teleportation, entanglement swapping, quantum pseudo-telepathy. In a quantum network, quantum information must be transferred from the sender to the remote receiver with the assistance of entanglement. Entanglement must be created between A and B and the quantum state restored. A quantum state carrying information is teleported. Information and location are network agnostic. Confirmation of quantum teleportation is related to the transmission of two bits of information from the sender to the recipient, on the basis of which the quantum state is recreated. Quantum teleportation is not enough. The ability to freely switch and then complex distribution of entanglement in the quantum network is necessary. For more complex operations, we need at least two entangled pairs in the network or more, active simultaneously between two parties. The existence of multiple two-sided entanglement between Alice and Bob before functional information is transferred between them makes it possible in some cases to omit information transfer.

Distillation of magical states. Magic state distillation is the concentration of non-ideal resources represented by numerous non-ideal quantum strongly entangled mixed states into less numerous states useful for performing operations that are difficult to simulate classically. Combining Clifford gates with a non-Clifford gate yields a UQC. Conversely, the use of magic states in the Clifford system also yields a universal quantum computing system. So we are not afraid to use the very convenient Clifford algebra in quantum computing and telecommunications, provided that we use purified magic states in quantum computational operations. In the process of multilateral entanglement distillation one has to take into account the monogamous nature of quantum states, and therefore the dilution of entanglement between many sides of the process in a qubit system. One should also take into account the Holevo limitation regarding the upper limit of the available mutual information in a two-party system A and B and its extended counterpart for a multilateral system (a node of a quantum telecommunications network). A possible path to the concentration of quantum resources in a network node, by circumventing the monogamy and Holevo limits, is to use a multi-level kudit system, instead of a two-level qubit system. Purification of resources is completely different in multi-level system, due to the orthonormality of qudit quantum states at different energy levels. Quantum multipartite systems are fundamentally different from bipartite ones. Quantum multi-level systems are different from two-level systems. We are now talking about twolevel and bipartite systems. The future is quantum multi-level and entangled multipartite systems.

Quantum purification algorithms. Many purification algorithms have been developed for the distillation of magic states of qubits. Purification requires the use of many non-ideal, mixed quantum states in order to obtain a state as close as possible to the pure state. In the unitary Bloch sphere, the mixed state is given by three parameters, two angles and the length of the vector, and the pure state by only two angles, since the vector is unitary. The possibility of effective purification combined with the imperfection of current physical qubit technologies leads to the need for an abstract programming logic layer of idealized qubits, error-tolerant, effectively error-free and operating on magic or pure states. The ability to tolerate quantum errors means that a logical qubit must consist of many physical qubits. The five-qubit Bravyi-Kitaev code is the smallest quantum error correction code that protects a single logical qubit against any error. Errors are discovered on the basis of symptoms and measurements of the states of the ancilla qubits. The quantum measurement process is repeated until the assumed distillation state is reached.

Quantum stabilization codes. Such codes define a qubit stabilized logic layer. Increasing the requirements regarding the acceptable quantum error rate, in computing or transmission systems, causes an exponential increase in the necessary number of physical ancilla qubits that make up a logical qubit. The stabilization formalism of quantum error correction is generally based on redundancy, adding ancilla qubits to the protected qubits. The quantum code and the stabilization system transforms the protected state into a Hilbert subspace of a larger dimension. The highly entangled quantum state of many local qubits enables local error correction. Without such a correction, neither quantum computing nor quantum telecommunications with the functional depth of quantum systems are possible. Some of the classical stabilizing codes that meet the conditions of self-orthogonality can be transferred to the quantum domain.

Ebits and quantum stabilization formalism. Ebit is a specific quantum state of two qubits representing the simplest and maximum quantum entanglement. The four allowable ebits are Bell states, or EPR pairs. Ebits are generated in a circuit of H and CX gates. Ebit is in the state of entanglement saturation, it supports only a bipartite system with the assistance of entanglement. Nothing more can be added to the ebit.

The entanglement-assisted quantum error correction stabilization formalism is an extension of the stabilization formalism without using non-local entanglement between Alice and Bob. The entanglement of states used for purification (also non-local in nature but functionally localized for distillation) should not be confused with remote entanglement between sender and receiver in a telecommunications system. Remote bipartite entanglement, shared before the transmission of useful information in the telecommunication channel, allows the sender to apply Clifford algebra, any set of Pauli operators, and appropriately use the shared ebits to form a code for correcting quantum errors. The global stabilizer, spanning two sides, becomes a commutative, abelian group, the sender's Pauli operators need not a priori form an abelian subgroup of the Pauli group on n qubits. In the transmission system and the assisted stabilization formalism, we assume that the entanglement-assisted quantum code encodes k-information (logical) qubits into n-physical qubits using c-ebits. The speed of an entanglement-aided code can be interpreted in several different ways, depending on how the values of n, k, and c are treated. These quantities treated differently in different application conditions determine the efficiency of the code.

Assuming that the entanglement resources between A and B are arbitrary and costless, the entanglement-assisted rate is given by k/n. Assuming limited entanglement resources between A and B and the associated costs, the efficiency of a quantum system is given by a pair of quantities: k/n - the number of noiseless qubits generated for use in the channel, and c/n - the number of ebits used in the channel per unit use. The optimal quantum block code for this entanglement-assisted case minimizes the number of ebits c used for a given number of k-information qubits and n-physical qubits. Assuming that entanglement bits are created at the expense of transmitted bits, there are two scenarios for creating entanglement between Alice and Bob - in a perfect quantum noiseless channel or in a noisy quantum channel using stabilization coding. Then the catalytic code rate [n,k; c] is (k-c)/n.

Quantum error correction. QEC is a technique to protect quantum information from errors caused by decoherence and quantum noise. The QEC process is necessary in order to build a quantum processor and fault-tolerant quantum network. Quantum errors occur at every stage of operations with quantum information: memories, gates, operations on quantum states, measurement of quantum states. QEC allows the construction of processors and quantum networks with greater resources. QEC is related to the introduction of redundancy. The purpose of QEC is to detect the error syndrome, and the purpose of the stabilization formalism is to design the processor layout or network node topology to prevent the replication of errors. QEC is implemented by creating a logical layer in the structure of the processor or network node. Syndrome measurement in QEC is a multi-qubit operation supported by multipartite entanglement. Shor's QEC algorithm uses strong nine-partite entanglement storing information in one information qubit. Syndrome-based multi-qubit measurement does not perturb the quantum information in the information qubit, but reproduces the error information. The correction of the error, depending on its type, is done in a suitable simple Clifford gate. Applying the syndrome to multipartite entanglement-assisted correction preserves quantum information.

Quantum information and its measures. Quantum information is contained in the quantum state of the qubit. QI can be processed by quantum methods. Quantum information is related to the Von Neumann entropy equal to S=-tr(d ln d), where tr-matrix trace, d-matrix of qubit quantum state density, ln - natural matrix logarithm. Von Neumann entropy is equivalent to the Shannon entropy in the classical version. The measure of QI in the form of Von Neumann entropy is also expressed as conditional and relative entropies. Quantum information is described by a theory analogous to Shannon's classical information theory. The Turing machine is realizable in the quantum version.

Quantum computing and quantum transmission can be conducted under noise conditions if error correction methods are used. Operations on quantum information are subject to quantum no-go theorems. The time evolution of quantum information is expressed by the unitary operator, which means the principle of global conservation of information. QI storage is hampered by the impossibility of copying quantum states. QI storage is facilitated by quantum error correction codes. QI can be sent via a quantum channel with a limited bit rate Q/s determined by the capacity of the quantum channel.

Quantum algorithm. An algorithm that describes an executable model of quantum computing or the operation of a quantum network. Most often presented in the form of a qubit gated quantum circuit. The difference from the classical algorithm is the use of quantum superposition and/or quantum entanglement. Many QAs have been discovered and new ones are sought, either solving classical problems faster or defining new classes of quantum complexity.

Quantum Channel. The most perfect of them is outer space as a channel and a photon as a carrier. For single photons moving in the ballistic mode between the transmitter and the receiver, losses and distortions practically do not occur. For a photon, in its frame of reference, emission and absorption are instantaneous simultaneous phenomena. This is a quantum ideal situation when we master the full technological loop of a single photon. First, a single photon bears the signatures of its source and is most effectively absorbed only by that source operating in the absorber mode, not the emitter mode. Such a source cannot be a laser, not only because it cannot work as a detector, but also because it is a Poisson source that clusters photons. Ideally, we need a deterministic photon-on-demand source, preferably with attosecond, maybe femtosecond timing accuracy. Secondly, hitting a single ballistic photon at a distance of a million kilometers, perfectly matched to the transmitter, a dual detector with 100% quantum efficiency is unrealistic.

It is necessary to use a photon beam. The beam is divergent, many photons are lost with increasing distance between A and B, proportional to the square of this distance. However, the collimated beam easily enables photon communication over a million kilometers but we give up the uniqueness of the quantum technique of single photons. Shaping a single photon, giving it parameters such as wavelength, spectral components, two-photon and multi-photon signatures, wave packet envelope, polarization - axial spin, as well as chirality - orbital spin, takes place in the source. Some of these parameters of a single photon can also be shaped using classical, non-linear optics, but changing some of them requires interaction in superlens systems or meta-optics that manages all components of the near field as precisely as possible. The non-propagating near field is potentially non-uniform depending on the source and the interaction of the photon with matter. There may be several of these near-field components of various order.

A quantum channel is a communication channel capable of transmitting quantum and classical information, including classical information with the assistance of entanglement. Quantum channel is a quantum operation with reduced dynamics, a completely positive linear map between C* algebras preserving trace between operator spaces. The quantum channel is an open quantum system, coupled with the environment, performing temporal evolution of the density matrix of transmitted quantum states as quantum information. In the ideal case of entanglement support, the sender and receiver communicating with each other through a quantum channel can share an unlimited amount of noiseless entanglement between them. The entanglement-assisted classical capacitance of a quantum channel is a natural generalization of Shannon's classical formula for noisy channels. Such capacity is equal to the mutual information of the quantum channel.

Quantum network and its nodes. The essence of building a quantum network is to master the node. The node is subject to quantum laws, it cannot copy quantum states of qubits or broadcast quantum information. Quantum wires reaching a quantum network node are only identity transformations, unitary, ensuring a reversible flow of time in both directions, so they work completely differently than in the case of classical transmission lines. Ensuring the reversibility condition required in the systems and node of the quantum network must be ensured through redundancy. The operation of a quantum system supporting an idealized network node in the Clifford algebra area does not generally require the use of redundancy. Redundancy will be necessary if the node is real, physical, vulnerable to decoherence and quantum errors. Redundancy is also necessary in the case of going beyond the Clifford algebra to a universal system of gates building a universal quantum system not only on pure but also mixed states. Elementary functional components of quantum network nodes, such as quantum repeaters, quantum purifiers/distillers, entanglement concentrators and switches, quantum memories, qudit registers, quantum multiplexers and demultiplexers, are theoretically and experimentally tested at various advanced technical levels.

The construction of a quantum network is related to the node paradox. The task of a node, in the simplest solution of the network, is performed perfectly by a single qubit. We entangle it, measure, teleport the quantum state. The network, whether classical or quantum, is greedy for resources. The development of the node's capabilities is based on the use of a qubit register. The register needs to be managed, so it will be a quantum node computer. The classic fiber optic system operates in DWDM technology. We convert the qubit register into a multi-level qudit register. The quantum signaling situation gets very complicated, but the quantum internet cannot be realized otherwise. In a node, we must have the right number of degrees of freedom and quantum resources.

Maximum qubit entanglement in a choice of up to four Bell states is only bipartite. A network node does not generally act as a superposition of only bipartite states. Multipartite distribution of signals is necessary. We cannot entangle qubits at a network node as much as possible to allow entanglement of the third and more parties. We can possibly tangle up to the maximum but qudit must be used. We can also entangle maximally if we measure the quantum state. Only non-maximal entanglement of mixed states, and energetically multi-level ones, opens the full capacity of a quantum network node. A node is modeled as a multidimensional polyhedron in Hilbert space. The signal analysis is geometric in such a multidimensional system in Hilbert space. The walls define orthonormal regions for which other individual Bell inequalities, defining non-locality and quantum magic, hold. The two maximally entangled three-qubit states W and GHZ are orthonormal to each other, and completely mutually non-transformable. The reduction of the threepartite state W to the two-qubit twopartite form leads to the Bell state. No mutual quantum resource is lost. The GHZ state loses its entanglement completely when reduced to a bipartite state.

Quantum resources, classification and measures. Quantum entangled states of qubits are treated as computational and QIT resources. Different classes of entanglement measures result from the fact that different quantum states are not equally valuable as resources, and also differ in the type of entanglement. Some of these types are mutually non-convertible. The reference level is the entanglement-free LOCC class of operations. Entanglement-assisted LOCC allows for a wider class of quantum operations. Entanglement classes are defined by convertibility, separability using only LOCC operations. The LU class means mutual convertibility by means of a local unitary operation. The SLOCC stochastic class means the need to measure a quantum state with a probability greater than zero. The distillable class means the ability to transform any number of copies (approximate, mixed) of a quantum state into one entangled pure state.

Another classification of entanglement is based on the type of correlation between the entangled parties. For bipartite entanglement there are three cases: non-local, quantum controllable states, and neither non-local nor quantum controllable states. The most common measure of bipartite entanglement is the entropy. It is a direct measure for entangled pure states. Different measures are used for quantum mixed states: entanglement cost, distillable entanglement, state creation entanglement, concurrence, entanglement monoton, relative entanglement entropy, crushed entanglement - CMI, negativity, and others. Most measures of entanglement are reducible to pure states and entanglement entropy. Some measures are irreducible and show a different nature of entanglement.

V. ARTES Quantizes Europe and Poland ?

Optional Program of the European Space Agency ESA Advanced Research on Telecommunications Systems ARTES, established in 1993, currently in the next edition of ARTES 4.0. is strongly complementary to European national projects on research, innovation and the space industry, especially the SatCom satellite telecommunications sector. The pillars of the ARTES 4.0 Program are: research for the future, development of basic competitiveness, running partnership projects and supporting business applications. The strategic layer of the Program covers several different technological functional levels of the SatCom sector: 5G, security and protection, ScyLight optical telecommunications.

In each of these levels, a quantum component is now being introduced. The principle of supplementing national project initiatives by ARTES consists in their co-financing at the level of 50-100% of total costs, depending on the degree of technological readiness. Funded activities are selected through periodic calls for tenders from an announced list of annual priorities, or through a constantly open path of new active submissions. The current ARTES 4.0 list of co-financing opportunities for 2023 initiatives includes in the SatCom sector: 6G Precursor, Integrated Photonic System, IIoT, Cybersecurity as a factor enabling secure satellite communication and resilient 4S applications (space systems for safety and security). In principle, quantum components can be proposed in any of these priorities for co-financing by ARTES 4.0.

The goals of ARTES 4.0 are extremely constructive and focused on the development of innovation and competitiveness in the SatCom satellite communications sector. The fundamental task is to maintain and improve the competitive capabilities of the industry of ESA member countries operating on the global SatCom market. Completion of such a task implies a number of macro-scale transnational activities, such as industry consolidation and unification, promotion of industrial initiatives around large-scale partnership projects, necessary to catalyze significant investments resulting in a rapid development of competitiveness and global economic impact. Adequate science-industrial and business teams should define, evaluate and promote the use of satellites and space-related systems for innovative services in advance.

Joint development activities in the SatCom sector must be related to expanding the community using space-based business applications and to supporting the development and growth of new and sustainable implementations stimulating economic development, improving the lives of citizens and maximizing the socio-economic impact of the programme. Technological developments are demonstrated effectively through ground and orbital experimental and pilot missions, confirming or demonstrating future market potential. Experimentation and introduction of new satellite techniques should show economic competitiveness, advantageous features that complement or develop existing ground and orbital systems. The use of advanced technologies should be promoted in emerging new services.

Thales Alenia Space TAS, which is a joint venture between Thales and Leonardo, has signed an agreement with the ESA to lead the TeQuantS project on the technological development of quantum resource distribution. Already in the name of this project there is a new understanding of quantum telecommunications of the Quantum 2.0 era, departing from the classical base of Quantum 1. Quantum telecommunications of the Quantum 2.0 era will consist in the distribution of quantum resources and not in the classic transmission of signals between cable and satellite network nodes, even in the quantum version. There is quite a long way to go to this stage, and we now have a busy scientific and technological journey through the intermediate stages.

Such a stage was announced in Cannes on January 24, 2023, the massive Quantum SatCom project. The goal of TeQuantS is the development of secure quantum SatCom technologies in the direction from the satellite to the Earth. TeQuantS is part of the ARTES 4.0 program to strengthen Europe's competitiveness in the field of telecommunications and quantum information technologies. The strategic partners supporting the TeQuantS project, apart from TAS as the coordinator, are the French National Space Research Center CNES and the Austrian Space Agency ALS.

Satellites are attractive and irreplaceable option for long-distance quantum telecommunications because, with the unavailability of operational-grade photonic coherent quantum repeaters to ensure fiber-optic security, direct quantum links are limited to a length of 300 km or less. In the cybersecurity layer, the role of TeQuantS is to develop secure distribution systems from the QKD quantum key satellite to European and partner users around the world. The need to develop satellite QKD technologies is a response to the growing threats associated with the use of classic cryptographic keys in telecommunications networks. As part of the TeQuantS project, TAS and its partners are expected to build, by the end of 2026, a demonstration network of satellites and ground optical base stations showing both the limiting capabilities of current quantum technologies and the operational parameters of long-distance quantum satellite links. The TeQuantS consortium includes Airbus Defense and Space, SME and startups such as: ALPAO, AUREA Technology, BERTIN Technologies, MIRATLAS, OGS Technologies, QTlabs, SIGMAWORKS, two research laboratories: LIP6 laboratory from the Sorbonne University, INPHYNI from the University of the Côte d'Azur and CNRS.

It is worth noting that the European turning point for potentially pre-implementation tests of quantum satellite cybersecurity in the field of QKD technology as part of ARTES TeQuantS is 2026. No units from Poland related to space research and the satellite industry participate in these tests. Since 2016, such tests have been effectively carried out by the Micius quantum satellite, which will probably soon be completed in the form of a constellation and a quantum experimental network will be created. Or maybe this stage will be modified and a generation of a satellite test and operational network will be created at once? It is not completely out of the question considering the wide, already completed research scope of the Micius satellite, the significant development dynamics of the Chinese space industry and the pressure of competition from the USA and China. Undoubtedly, the results obtained by Micius put strong pressure on the quantum plans for SatCom in Europe.

VI. Eagle-1 2024-2027

European Quantum Flagship - EQF, TeQuantS - ARTES and others are not the only European initiatives in the field of QIT. There are many parallel initiatives related to remote sensing, computing and quantum telecommunications aimed at building the elementary components of the future secure quantum network. ARTES is an optional, complementary program for development. EAGLE-1 is one of many regular ESA development projects. EAGLE-1 is a telecommunications satellite currently under construction in Europe, intended to be placed in the LEO orbit in 2024. The satellite's lifetime is expected to be three years. The goal of the EAGLE-1 project is to build a fully operational test, secure, effective quantum satellite system capable of distributing the QKD quantum key in Europe.

The EAGLE-1 project is financed by ESA and the European Commission and implemented by a consortium of twenty European companies led by the telecommunications company SES SA from Luxembourg. The EAGLE-1 project is a demonstration and validation project as part of a wider European Union plan to launch an autonomous telecommunications network using quantum technologies. It is expected that the operational phase of EAGLE-1 will be used by EU government organizations and selected business sectors for test access to the reference QKD system. EAGLE-1, depending on the success of the tests, is to pave the way for the EU to launch a constellation of satellites ensuring secure QKD telecommunications. The scope of the EAGLE-1 project includes: satellite hardware and software, ground optical station, scalable quantum operational networks, quantum key management system, interfaces to national quantum telecommunications systems.

VII. Micius 2016-2023

The long-term series of quantum experiments and demonstrations shown by the Micius satellite is a good basis for building a satellite quantum network. A pioneering satellite from the Chinese Academy of Sciences about the possibilities of quantum communication showed practically many experiments. Micius is a LEO satellite orbiting at an altitude of 500 km coordinated with several receiving stations on different continents. The entangled photons generated on the satellite by the SPDC method as heralding and heralded are distributed between the two locations of Delingha and Lijang, which are 1,200 km apart. Photons maintain a high-quality entanglement state.

In 2016, right after orbiting, Micius began QKD experiments to distribute a quantum key to the ground station in Beijing. At that time, the decoy-state BB84 protocol was used. In 2017, long-term experiments were conducted on quantum security for videoconferencing between Beijing and Vienna. A 128-bit quantum key was used, renewed every second. In these experiments, the network node on the satellite was trusted. For now, transmission quantum experiments are performed at night to avoid the sun's daytime optical noise. Long-term quantum teleportation and entanglement switching experiments were also conducted. As a satellite, LEO Micius has a limited coverage of the QKD distribution area. Satellites in much higher orbits are required for efficient QKD distribution.

Despite this, the Micius experiments indicate not only the possibility of building SatQuant class technical systems, but also conducting basic experiments at the junction of quantum physics and the theory of relativity. The velocities, distances and changes in gravity available in space experiments will allow to study how gravity affects quantum phenomena, which could pave the way for the development of a quantum theory of gravity.

VIII. European Quantum Policy

European quantum policy is defined on several levels - central by implementing sectoral flagship programs, international by European institutions such as EDA, ESA and others, and national. In addition, efforts are made at the central and political level to coordinate such a complex structure. The EQF European Quantum Flagship recognizes the activities of European organizations as well as larger national initiatives. The result is periodic studies on the European development vision in this sector, such as the European Quantum Research and Industrial Agenda - EQF-SRIA [9]. If you look closely at these European documents, they are similar to relevant global studies from other regions, in particular from the US and China. Everywhere in the research area there are three, four or more ICT pillars: quantum computing and simulations, telecommunications and ICT, sensors, telemetry and metrology, timing and synchronization.

Cross-sectional areas, orthogonal to the pillars, but containing overlapping or common technologies, are mentioned as an important element of these pillars. In the area of necessary quantum resources, innovation, industrialization and social impact, many factors are mentioned, such as: basic and applied research and the balance between them; technical solutions and technologies enabling development; education and development of a specialist workforce; standardization; public and private development financing; intellectual property; international cooperation and regulation of import-export processes; rules of ownership and management of large infrastructures under construction.

The currently existing heterogeneities in the development of quantum information technologies result from fundamental differences in the level of difficulty in developing some missing components of computing and teleinformatics systems. Some of the components have reached a high level of technical sophistication and are even commercially available. The essence of the policy is to direct research and innovation into new applications that fill gaps, increase the flexibility of designing larger systems, and ensure long-term development.

The development of the QIT theoretical layer is necessary in order to further understand the laws of conservation of quantum information in much broader aspects than at present. For example, it is about aspects such as the use of quantum resources and the energy level of these processes. Quantum processes such as non-locality and selective decoherent transformation to the thermodynamic world and the nature of the differences between these worlds are still poorly understood.

The research covers the subtle nature of decoherence phenomena in theoretical aspects and more practical aspects of how to control it, and when it is possible. Such studies of fundamental phenomena are orthogonal to potential application fields in computing, QIT, ICT and metrology. Theoretical research complements our knowledge necessary to develop new technologies for single photon sources and detectors, quantum memories, photonic nanocavities for the transfer of quantum information between stationary and flying qubits, ion traps, integrated circuits with mobile atomic qubits, OMEMS systems, etc.

Basic research on QIT is looking for correlations with other fields such as quantum biophotonics, nanomedicine, quantum energy and thermodynamics, quantum metrology, high energy experimental physics, science and materials engineering, in terms of building a wide range of new applications.

Development in the area of QIT research and innovation requires the following correlated activities: introducing quantum technologies to hybrid solutions of devices in order to improve their operating parameters; application of new solutions and architectures of qubit circuits, memory, protocols and algorithms for remote distribution of entanglement; introducing scalable methods for building a quantum network node operating with multi-qubit and multi-level, multipartite hiper-entanglement; introducing QIT technologies to other areas of science and technology; identification and quantitative description of quantum phenomena that do not have classical counterparts, and the study of the possibility of functionalization of such phenomena.

IX. Conclusions

The development of common technologies and technical solutions for all QIT pillars includes: production, testing and development of pilot versions using new resources specialized in QIT and industrial micro and nanotechnology resources; integration of quantum and classical devices and construction of hybrid systems with new functionalities; photonics quantization; development of quantum optimal control techniques and protocols. Within a decade, the development of advanced demonstrators of many quantum devices with improved, extended or new functionalities, produced by industrial methods, is assumed. Standardization of quantum technologies in software and hardware should lead to some degree of technical uniformity. The extension of the industrial production of QIT devices will be related to appropriate changes in the education of staff at the university and professional level, as well as changes in the field of intellectual property rights. The development of the market for hybrid functional devices will change the financing models and together all these components will create a kind of quantum ecosystem.

References

[1] European Quantum Flagship, Strategic Research and Industry Agenda, 2023
[2] ARTES, ESA, Your business powered by space 2023
[3] Airbus Secure Communications 2023
[4] IBM Quantum Cloud 2023
[5] The first quantum-cryptographic satellite network will be Chinese, Science and Technology, September 2nd 2017
[6] Ch-Y Lu, et al., 2022, Micius quantum experiments in space, arXiv:2208.10236
[7] R.S.Romaniuk, 2023, Kwantowa Europa, kwantowa Polska, Przegląd Telekomunikacyjny 2, 2023
[8] European Quantum Industry Consortium EQIC, 2023, [euroqic.org]
[9] EQF-SRIA, 2023