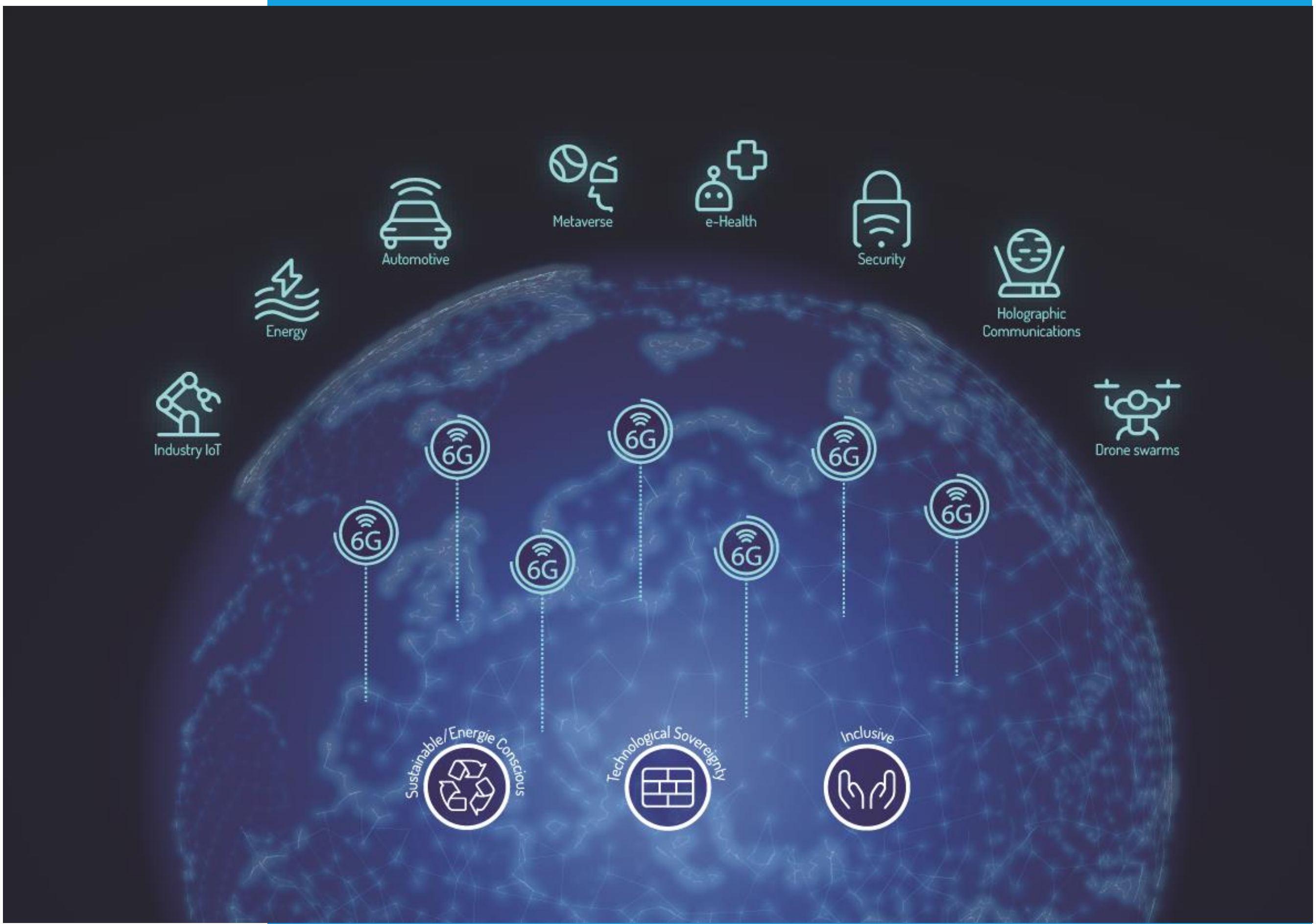
6G Smart Networks and Services Industry Association (6G-IA)



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Position paper

RESEARCH PRIORITIES

QUANTUM TECHNOLOGIES FOR NETWORKING

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1. EXECUTIVE SUMMARY

On 22 April 2026 the 6G Industry Association (6G-IA), the private side of the SNS JU, convened an invitation-only workshop in Brussels kindly hosted and supported by the SNS office to identify quantum-related R&I priorities of relevance to communication and service platforms. Whilst the SNS JU work is focused on 6G mobile networks whose early implementation are planned in 2030, the workshop took a broader perspective addressing the potential of Quantum technologies in multiple types of communication networks including fixed and fiber-based networks. The workshop gathered the European Commission (DG CNECT Units E1 and C2), NetWorld Europe SRIA representatives, seven[1] industry speakers (Nokia, Telefónica, Welinq, Ericsson, Deutsche Telekom, Orange and InterDigital) and six leading research and innovation centres (KTH, CEA-LETI, VTT, UPM, TU Duisburg-Essen and University of Bristol). The goal of the workshop was twofold: (i) to scope quantum networking topics that are considered as shorter term priorities by industrial players with a potential to be addressed in the SNS JU Work Programme 2027 and (ii) to frame longer-term priorities for the FP10 timeframe, in line with the Quantum Europe Strategy, the Draghi report and the upcoming Quantum Act.

The security use case supported by Quantum Key Distribution (QKD) is the highest-TRL technology of relevance and the natural near-term entry point for SNS, but it is recognised as only a partial element of the future quantum-safe network and still requires further experimental validation, including complementary technological approaches like PQC.. Although several end-to-end QKD testbeds are already operating in various Member States, the discussion underlined that the technology remains at an early stage and will require substantial further research: i) at the component level (e.g. entanglement sources, photon detectors), ii) at the subsystem level (e.g. memories, quantum repeaters, quantum switches) to enable longer distances and at least metro-scale deployments, and iii) on basic coexistence and integration within classical networks. Beyond QKD, use cases were viewed as longer-term and effectively a research topic in their own right. In this context, the strategic research focus shared by industry, operators and academia is on building an entanglement-distribution layer — the basis of a future Quantum Internet — and its early integration with classical 6G infrastructure (control, management, orchestration, monitoring, AI, time and frequency). Quantum computing and quantum sensing were seen as relevant for telecom on a longer time horizon, mainly as services accessed via the network (blind/distributed quantum computing, distributed sensing, ultra-precise timing), and dependent on advances in Quantum Processors. All speakers stressed that progress will require shared experimental infrastructure, common APIs and standards, and close coordination with European initiatives

[1] Thales was invited but eventually could not participate.

as a function of the target time horizon/maturity level such as EuroQCI, the Quantum Flagship, the Quantum Internet initiative, the Chips JU pilot lines and EuroHPC, while leveraging national testbeds and infrastructures where appropriate.

2. CONTEXT, SCOPE & BOUNDARY CONDITIONS

Quantum technologies are identified as one of the five Draghi-report core technologies in which Europe must remain in the leading pack, alongside networking, cloud, AI and microelectronics. The Commission's Quantum Europe Strategy (July 2025) builds on three pillars: (i) the Quantum Europe R&D Programme 2028–2034, (ii) Quantum Made in Europe ("from Lab to Fab") and (iii) safeguarding economic security through resilient supply chains. Of relevance are also the areas of the Strategy outlined in Quantum Europe Strategy, Shaping Europe's digital future, namely: a) Research and Innovation: Consolidating excellence across Europe to lead in quantum science and its industrial transformation; b) Quantum Infrastructures: Developing scalable, coordinated infrastructure hubs to support production, design, and application development; c) Strengthening the Quantum Ecosystem: through investments in startups and scaleups, securing supply chains and the industrialization of quantum technologies; d) Space and Dual-Use Quantum Technologies (Security and Defense): Integrating secure, sovereign quantum capabilities into Europe's space, security and defense strategies; e) Quantum Skills: Building a diverse, world-class workforce through coordinated education, training, and talent mobility across the EU.

The SRIA[2] research and Implementation roadmaps covering computing, communications, sensing, supply, industrialisation and standards are to be updated by end-2026, with public consultation around mid-2026. EuroQCI is the operational anchor supported by the DEP and CEF programs: DEP supports ~7 000 km of terrestrial networks, ~200 end-user nodes, and supports multiple use cases in the defense, health, finance sectors. It is to be complemented with IRIS² connectivity, first with the ESA Eagle 1 LEO satellite for in-orbit demonstration (launch planned in 2027), and a second-generation segment integrated with the IRIS² constellation (long term) for fully operational secure connectivity with terrestrial and satellite assets complementing each other's. CEF supports cross-border interconnection projects with 19 projects covering 25 Member States and 26 cross border links. A very large-scale ongoing project, "Nostradamus", covers test and evaluation infrastructure over the 2024 – 2027 period.

Within this landscape the SNS JU has a specific and bounded role. SNS addresses quantum technologies in subsystem and system contexts — i.e. the integration of quantum building blocks into communication and service platforms and within a broad range of Use Cases

[2] Strategic Research and Innovation Agenda, Quantum 2030: https://qt.eu/about-quantum-flagship/strategic-research-and-industry-agenda-2030

potentially also including private "NPN" networks. From a 6G-IA perspective, basic quantum components (cryogenic devices, photon detectors, superconducting circuits, single-photon sources, qubit fabrication) would best be supported by the Chips JU pilot lines (Qu-PILOT, P4Q, SUPREME, SPINS, DIREQT, CHAM-PION, Q-PLANET), the Quantum Flagship (QSNP, QIA, OpenSuperQ+, EPIQUE, HYPERSPACE) and possibly EuroQCI/EuroHPC. It is hence suggested that SNS-funded actions should partner with these instruments as appropriate where critical components are on the critical path. National programmes (FranceQCI, MadQ/MadQCI, IberianQCI, NQCIS, German BMFTR Quantenrepeater.net, UK NDFF/UKQN, Italian/Finnish initiatives) which are mostly connected to the EU EuroQCI initiative provide an underlying testbed substrate that may be leveraged by SNS projects where appropriate and in view of avoiding duplication and fragmentation.

Two time horizons were used to structure the discussion:

- Medium term — targeting results before 2030, eligible for SNS WP2027 (RIA, low to medium TRL, mainly academic-driven for low-TRL topics; up to TRL 5–6 for system-level industry driven work).
- Long term — beyond 2030, to be considered for a roadmap under the next MFF/FP10, including a flagship-scale activity and a coordinated European experimental infrastructure.

For the rest of this report a third "short-term" horizon (results expected within ~3 years) is also called out where speakers explicitly distinguished it, to better identify topics suitable for a 3–5 M€ low-TRL action under WP2027 versus larger system-level work.

3. SYNTHESYS OF SPEAKER CONTRIBUTIONS

3.1. INSTITUTIONAL FRAMING — EC AND NETWORLD EUROPE SRIA

DG CNECT Unit E1 (M. Gonzalez-Sancho, HoU) outlined the EC telecom policy and the various building blocks of this policy, covering traditional networks, cloud computing and Telco cloud, AI for Telecom, and the importance of microelectronics in the context of future European networks and sovereignty. Quantum networking was depicted in this context as an important additional building block particularly relevant for securing European critical infrastructure and for sovereignty.

DG CNECT Unit C2 (L. Olislager with support from Unit C4) outlined the Commission's quantum strategy, the EuroQCI infrastructure status (see above) and its trajectory: today's QKD is single-purpose and point-to-point; the next step is Quantum Networking, becoming a system contributing to the overall security landscape including quantum functions across multiple nodes, integrating distributed sensing, and supporting entanglement-native services; the long-term vision is the Quantum Internet, a hybrid global entanglement fabric supporting secure communications, ultra-precise sensing and distributed/blind quantum computing and a series of new applications.

NetWorld Europe SRIA[3] (C. Cicconetti, CNR-IIT) classified telecom-relevant priorities along three research lines: quantum computing, QKD and quantum networks. The main focus covers QKD with typical issues relating to range extension, multiple hop connectivity, co-existence with optical networks traditional communications, and requirements for a software layer enabling joint management of Quantum and traditional resources. Three issues were highlighted from a short, medium and long term perspectives, namely: i) address the need for QKD peers to be mutually authenticated; ii) Increase key generation rate (esp. in free-space links); iii) Integrate optical fiber-based and free-space networks towards end-to-end full optical networks. The importance of underlying subsystem technology, e.g. relay nodes, repeaters, etc., was outlined as related issue.

3.2. INDUSTRY VIEWS – OPERATORS, VENDORS, START UPS

Nokia

Breaking an RSA 2048 bits key with a Quantum computer has become a very credible perspective in the medium/long term which reinforces the case for Quantum secure communications. QKD is part of the solution but has some limitations (eavesdropping/DoS attacks, limited range, requires specific hardware) which makes the application of PQC based on advanced mathematical algorithm an interesting complement, as a non Quantum based solution (quantum resistant cryptography). This is recognized by the US administration which has defined algorithms standardized at NIST level. Protocols are also standardized at IETF and 3GPP/ITU (for telecom standards).

Another facet of interest is Quantum computing applied to resolve specific and complex problems at RAN level, for RAN optimization, e.g. for resource optimization and traffic management. This is potentially medium term. Another potential Use Case relates to Quantum computers networking through entanglement distribution and networking. This potentially enables distributed Quantum Computing and opens the door to a Quantum Internet. Specific issues are both in hardware (Transmission using photons, Quantum memories, Entanglement stitching) and Software (Quantum protocol stack, Distinct quantum and user planes). This is a longer-term issue together with additional research on Use Cases enabled by entanglement distribution and networking at large.

[3] https://www.networldeurope.eu/sria-and-whitepapers/, new version under finalisation

Telefónica

Telefonica has been active in QCI for more than 15 years and has several demonstrators/PoC deployed through multiple projects, European or national. It is part of EuroQCI-Spain and MadQ-CM. it has also developed PoC with customers (VITHAS, AWS) and its work goes beyond mere QKD with inclusion of hybrid quantum-safe schemes.

Telefonica approach is to build expertise on the full set of activities enabling Quantum technologies deployment and operations. It includes work on technology and technological building blocks, standardization, co-propagation and co-existence with classical networks, management of quantum resources, monitoring and Assurance of Quantum services.

Future domain of investigations and priorities are proposed as follows:

Short term: i) Quantum safe transition with QKD hybridization with PQC to also alleviate distance limitations of QKD; Long distance QKD networks; ii) New network architectures to address long distances coms and interconnections compatible with today Trusted nodes and future Q-repeaters; iii) interconnection of QCI and KMS (Key Management System) including architecture protocols, Terrestrial & Satellite PoC and tested between operators iv) QKD Vendor interoperability with new standards for QKD.

Medium term: i) architectures for classical & Quantum Internet integration with architectural model to organize Quantum Internet research and integrate future protocols, technologies and services within one coherent framework; ii) Control and management with Ctrl & Mgmt new protocols on transition from QCI towards Quantum Internet, monitoring of heterogenous devices & networks, New protocols for routing. Use cases are mainly security related with focus on connectivity for data centers, cloud environments, secure access to computing resources, and support to the "security as a service" approach towards third party applications. QKD Cryptography (prepare & measure, entanglement) to make vendors interoperable (today implementations of subsystems are vendor specific)

Long term: covering issues like teleportation, clock synchronization and sensing.

Of particular importance is the need for open-source emulation platforms to alleviate the fact that current commercial quantum hardware is expensive, rigid and often vendor specific, which may limit flexibility and experimentations. Emulation platform requirements: combining high-fidelity quantum-channel simulation, relying on open (standardized, whenever possible) APIs, allowing users to interact with the emulated network exactly as they would with real quantum hardware, bridging the gap between theory and real-world quantum networks, enabling experimenting at scale, enabling safe, reproducible environment for experimentation with quantum networks. Telefonica is working on the development of such tools.

Welinq

Welinq is a start-up working to establish a full quantum networking stack by 2030. It includes customer source delivery in 2025, customer memory delivery in 2026, deployable network design in 2027, deployed communication testbed with partners in 2028/29, metropolitan testbed in 2030 and cross-border quantum internet beyond 2030. The work has so far delivered Quantum memories that can be inserted in trials. To reach full potential, developments are needed to support large scale deployment with Quantum repeaters (including memory as a building block) and switches to enable long distance communications. Multiple synergies with running project have been established like EuroQCI (simulation of QKD by satellite), Chips JU (laser at 795 nm as photon source), Quantum flagship (preparatory work for testbed deployment). Future synergies are sought in the context of IRIS² (QKD by satellite) and EuroHPC (testbed in the Paris region with F partners).

From the perspective of future activities, the following is suggested:

Short term: control plane development for integration and operation of testbeds; Open-access to testbed for PoC demonstrations (QKD, blind quantum computing, distributed sensing…) with use of already existing infrastructure to validate technological components; development of hardware building blocks for ground-stations (satellite applications)

Long term: Demonstration on shared fibers with classical communication data on existing deployed network; insertion of additional user-nodes to testbeds to extend it from a point-to-point testbed to a metropolitan network with shift from a PoC testbed to a Quantum Internet Pilot-Line; deployment of a ground station to connect testbeds to IRIS² satellite.

Ericsson

Ericsson views quantum technologies through the same adoption lens as any transformative technology: demonstrable economic advantage, alignment with telecom-relevant use cases, ecosystem maturity, and standards readiness. Within this perspective, Ericsson is actively exploring the impact of quantum technologies across telecom networks and distributed compute infrastructures, spanning quantum computing, quantum networking, and quantum sensing. Ericsson's primary focus is on hybrid quantum–classical computing models, where quantum accelerators complement classical computing and HPC systems for solving computationally intensive telecom problems such as network optimization, AI-native network control, machine learning, and large-scale combinatorial and enumeration tasks. This vision implies the evolution of distributed hybrid HPC–quantum compute services interconnected through the network, including research into networking architectures for hybrid classical–quantum datacenters, deterministic transport, synchronization, and advanced timing frameworks potentially leveraging technologies such as TSN and next-generation network clocking. Ericsson also identifies hybrid quantum–classical orchestration, runtime environments, and resource management frameworks as key research priorities for scalable deployment of distributed quantum services. Beyond computing, Ericsson sees distributed quantum sensor and clock networks as emerging network-level capabilities for high-precision synchronization, positioning, and timing services. In parallel, Ericsson positions post-quantum cryptography (PQC) as the scalable and standards-aligned foundation for building quantum-safe telecom networks and infrastructures.

Deutsche Telekom

DT places Quantum networking as an enabler of a range of innovative Use Cases including distributed Quantum computing, Quantum based security of networks, and Quantum sensing with possibility to reach GPS/GNSS free ultra precise positioning and timing/synchronization. This is enabled / enhanced through Quantum networks featuring a collection of nodes capable of exchanging qubits and distributing entangled states amongst themselves to enable new, non-classical applications. The target hence becomes distributed entanglement with “Entanglement-as-a-Service” becoming part of the service portfolio of the operator.

This service capability is based on availability of a number of technologies and subsystems with following functions: i) request and intent, from application to networks (including API availability); ii) entanglement generation; iii) entanglement distribution over Quantum channel; iv) detection and verification; v) entanglement purification and error detection; vi) entanglement storage; vii) entanglement swapping; viii) entanglement routing; ix) entanglement delivery; x) service delivery and API exposure.

These functional blocks correspond to the most elaborated version of Quantum networking represented by the Quantum Internet where entanglement status can be routed over a complex network including multiple nodes and repeaters, which is a long-term prospect.

T-Labs has established a demo platform in Germany which has been used so far to experiment point to point links over a maximum range of 100km. The short-term evolution of this platform includes additional nodes. High fidelity Entanglement Distribution has been tested in a Metro-scale, field-deployed fiber network in point-to-point mode (through various loops) and over various distances up to 100 km. Results have shown i) a received rate at 30 km of about~500 coincidences/min. but significantly lower at 100 km; ii) Entanglement Fidelity at distance of 30 km of about 99%, 85%at 100km. Co-propagation of regular traffic was not tested here.

Quantum teleportation in the field was showcased at MWC 2026. Co-propagation was added to the test.

A follow up is planned with the set up a second quantum-capable node in Berlin metro test network towards the end of 2026. It includes the developing of concepts for covering E2E Entanglement provisioning capabilities

Regarding future activities, DT identifies the following issues as priorities;

Short term, with two types of activities: i) Wide-area Entanglement Distribution enabling a Multi-point network with the possibility to perform Entanglement swapping to cover inter-city distances (~300 km), the possibility to have Quantum memory with long enough coherence times and Quantum repeater implementation (estimated 20283) to perform such swaps; ii) Realistic constraints of telco operations for EDaaS design which covers Quantum channel stabilization and respective controls, monitoring related challenges regarding quantum links, Co-existence with normal traffic and optimal deployment schemes.

Medium to long term: Evolution of a multi-point network that flexibly and reliably distributes Entanglement to selected user pairs to support the evolution of diverse applications that make use of Entanglement at various service levels (including demonstrations) and to possibly: explore non-locality of Entanglement and its use for novel ways of controlling quantum networks.

The target experimental platform of T-Labs is made of an infrastructure mixing both Quantum and classical communication components with precise time and frequency distribution. It covers several cities and nodes in Germany. Interconnection with non-German platforms would require checking compatibility and interoperability of vendors equipment.

Orange

Orange view is that EU initiatives need to bridge the gap between quantum research and innovation and its industrialization and commercialization, while ensuring a sufficient talent pool. This implies that the priority activities relate to most mature Use Cases and in particular security/QKD aspects. Orange participates in multiple national and EU activities including EuroQCI and technologies developed under the CEF programme. A pilot B2B system is in place with Toshiba, since 2025. 3 main domains of investigations are outlined:

Enabling technologies: with needed progress on Quantum memories, Quantum repeaters, MDI-QKD, Enablers for Quantum Access Networks (lower cost, point-to-multipoint, multiplexing, etc.)

System solutions: Includes progress on entanglement distribution and quantum networking (e.g. routing, QoS, management); Integration with classical networks: hardware, management and orchestration; Simulators/Digital-Twins, towards safe environment for systems and architectures validation at scale; AI-based tools for planning & automating quantum network operations; Satellite for intercontinental & backup of QKD path with constellations for scalable architecture.

Extension of services: including Quantum Safe Networking; Quantum connectivity between Quantum devices: Distributed Quantum Sensing, Quantum Computing as a Service (QCaaS), Blind Quantum Computing; Distributed Quantum Co-processors to enhance AI processing (towards Quantum AI) and towards network management

These are framed by requirements aimed at creating an ecosystem of vendors, notably through interoperability between devices and solutions, standardisation and integration of Quantum solutions within classical fiber networks.

Following examples are proposed from a time frame perspective:

Short term: Quantum safe networks including technology for cellphones, security modules in base stations and core network encryption engines; Quantum-Safe Network segments: hybrid approach with QKD between network elements.

Medium term: Quantum sensing, leveraging Quantum techniques for enhanced detection. Based on Rydberg Atom-Based Quantum Receivers for 6G as potential revolution for 6G receivers and ultra-precise timing and synchronization

Long term: Quantum computing for network management and resilience, covering enhanced network planning, increased resilience by detecting network nodes that need extra robustness to failure, Power Network Digital twins to explore large spaces of optimization possibilities, computing efficiency with QPUs distributed through edge/core/cloud, including for AI

timing/synchronisation, and Rydberg-atom-based quantum receivers for joint communication–EM-field sensing.

InterDigital

Quantum communication is seen as having potential from multiple perspectives: i) Quantum cryptography for which products are already available; ii) Synchronization, with ability to achieve extremely high synchronization accuracy. It has been demonstrated in optical fibers, and may achieve ps-level synchronization; iii) Operation at very low SNR with individual photon detection. Micius (China) has demonstrated QKD with 1200km and very low photon flux; iv) Interlinking of quantum computers but there is today, no protocol to link two quantum computers; v) Potential for capacity gains with entanglement-based communications; vi) sensing which may be seen as a “low hanging fruit”.

From an InterDigital perspective key issues to solve relate to the probabilistic nature of quantum networking and entanglement generation/detection to manage fidelity constraints and possible degradation over time, which has an impact on the underlying hardware performances and on the way resources are consumed and managed from the perspective of a cycle including reserve/establish/consume/refresh/release of specific resources (e.g. memory).

Other key issues include error coding for a probabilistic channel, Quantum channel modelling, Quantum repeaters, use of AI to support quantum communications: e.g. quantum-aided federated learning scenarios with distributed AI models feeding a global centralized quantum AI model via quantum information exchange.,

From a priority perspective, the following is outlined:

Short term: Expansion of QKD networks and key management integration. It includes early multi-node quantum networking pilots focused on metropolitan-scale entanglement distribution, interoperability demonstrations, and operational procedures. It also targets increasing integration with classical optical and IP network control/management stacks.

Medium term: Early deployments incorporating quantum-repeater elements and limited multi-hop entanglement services in controlled environments including inter-domain networking concepts (service federation, routing policy, and operational assurance) to move towards large scale interoperability.

Long term: Progressive scaling toward wider-area entanglement-based networking with more mature repeater chains, switching, improved quantum memories, and standardized service models enabling distributed quantum applications at scale.

The importance of standardization is also mentioned through opportunities offered by the ETSI TC QT which started in Q4 2025. It includes an ongoing road-mapping effort and intends to extend the scope to work on framework aspects for quantum networking. Entanglement as a service is covered by this initiative which includes service abstraction, service identifier together with underlying requirements such as required QoS.

3.3. RESEARCH AND INNOVATION CENTERS

KTH (NQCIS project, Sweden).

KTH reports on practical aspects of QKD deployment and lessons learnt from the Stockholm/Linköping testbed. Attenuation is the main obstacle (must be characterised accurately for network design), background photon noise is highly unpredictable in shared ("dark") fibers, polarisation effects are manageable, phase stability and chromatic dispersion are problematic only in specific protocols. CV-QKD performs better than DV-QKD in noisy conditions and is commercially available from a European start-up. SNSPDs are mature but require air-cooling and polarisation-maintaining versions for deployment. Standardisation of IP integration, key management (ETSI 014, inter-KME) and certification of security (trusted-device assumptions, quantum hacking) remain open. Drawbacks of QKD devices are reported as follows: user friendliness (no plug and play capability, varies from vendor to vendor), instabilities (need of software fixing), predictability of performance (not fully accurate models in spite of progress), security aspects (security models not fully disclosed, need of trusted device assumption.) These results are obtained as part of the Swedish NQCIS project that is also part of EuroQCI.

CEA-LETI

The presentation covers optical technologies at component level supporting Quantum communication. It covers typical issues such as entangled photon generation and single photon detectors. Typical projects include Quantum communications with development of integrated circuits to be exploited by partners on their QKD testbeds; Quantum photonics platforms (SOI and SiN) with development of a library of quantum-grade integrated components; Quantum Computing with development of quantum processing circuits compatible with QD-based single photon sources. The available toolbox for Quantum communication is based on an SOI photonic platform that cover multiple components (waveguides, couplers, splitter, mux/demux, filter, modulator, transceiver..). it includes a comprehensive library of mature components @ 1310 and 1550 nm and allows for integration of new materials. CEA-LETI also provides a SiN photonics platform @ 925 nm for photonic quantum computing.

The future plan include i) further development of the quantum photonics toolbox with performance improvement (e.g. fully integrated turnkey source of entangled photons…), maturity increase; ii) further development of next-generation quantum photonic processing chips for measurement-based photonic quantum computing with feed-forward; iii) provision of open-access through EU quantum pilot lines (Qu-PILOT and P4Q); iv) collaboration to discuss miniaturization of quantum technologies for a broader range of applications, including 6G.

VTT

Finnish Q ecosystem is quite developed with50-qubit superconducting quantum computer connected to LUMI for hybrid quantum-classical computing, planned 300-qubit procurement by 2027, coordination of the Finnish QKD test network. VTT has bold participation in European Quantum Flagship research programs, notably: European superconducting quantum computer OpenSuperQ+; European pilot fabrication capabilities Qu-Pilot, SUPREME;

European hybrid quantum computing infrastructure EuroHPC QCI. Multiple technological activities are ongoing to scale up Quantum computing capabilities.

For Quantum communications, research focuses on Test environments based on COTS components with own HW development in: i) Fiber to PIC(photonic integrated circuit) coupling using 3D-printed polymer lenses; ii) SiN photonics PIC technology; iii) SNSPDs (Superconducting Nanowire Single Photon Detector) iv) Monolithic SNSPD integration into SiN PIC; v) Cryogenic SiGe readout for SNSPD; vi) Quantum memory

Related technological developments are integrated in a QKD/QC lab at VTT premises with important research focus on SNSPD's and Quantum memories. This will fuel the future Kvanttinova hub targeted to become a major European microelectronics + quantum R&D facility in Finland.

UPM

UPM with Telefonica operates the largest deployed quantum network in Europe (MadQCI, ~700 km of fiber, 30 locations, 19 institutions, 32 quantum systems — 23 QKD + 9 QRNG — from 10 different vendors), in production with strict SLAs and classical services running concurrently. It runs on a UPM provided SW stack. Quantum Abstraction Layer (QuAL) and SDN-based orchestration of QKD nodes are implemented. Active integration with TLS, IPsec, MACsec, PQC and hybrid modes; one-to-many high-security scenarios using MDI-QKD; certification work via Nostradamus. Though based on standards (ETSI) many standards are still missing, e.g. for Key management layer. Multiple Use cases are implemented (Health, defense..). Evolution planned towards multi nodes connectivity, repeaters and switching, co-existence with optical fiber networks.

TU Duisburg-Essen

The presentation takes a long term approach which covers wireless Quantum optical multipath communication and information-theoretic channel modelling beyond 300 GHz. The PHY transceiver concept addresses classical-to-Quantum preparation, Quantum-to-classical detection and fully quantum operation, requiring a dedicated low-TRL research agenda on Quantum channel models — an under-served topic at European level. It also addresses a Quantum level transmitter/receiver which would replace classical RF front end, e.g. RF or baseband for wireless and wireline Quantum optical single path and multipath communication. This is directly related to wireless and wireline teleportation of information, e.g.as over the air, a potentially very long term topic.

University of Bristol

The Quantum networking “ingredients” including related research challenges are outlined as follows: i) use of light and generation of entangled photons; ii) use of optical fiber for propagation of free space; iii) modulation and polarization; iv) trusted nodes and quantum repeater as range extenders; v) switching of quantum information for compatibility with networked environments. At Use case level, priority is put on demonstration of quantum advantage in security, efficiency and precise timing for future telecom.

The current challenges for scalable Quantum networking are outlined as follows:

Physical Layer: Source scalability: brightness vs spectral purity vs indistinguishability; synchronization across distributed nodes; polarization and phase stability in field fiber; multi-user interference and noise management; new fiber use such as hollow-core fiber; Quantum memories;

Network Layer: Dynamic entanglement routing and switching; Resource allocation (wavelength, time, spatial modes); Multi-protocol coexistence (QKD + entanglement + classical)

System Layer: Heterogeneous hardware integration; Interoperability and standardisation (ETSI, etc.); Certified quantum services

Control & Intelligence: Real-time monitoring and feedback; AI-driven optimisation and automation; Digital twin for predictive network operation

From a research perspective the following priorities over time are proposed:

Short Term: Metro-scale entanglement distribution; Coexistence with classical networks; Monitoring and control frameworks; Early orchestration capabilities – providing entanglement as a service to the 6G.

Medium Term: Dynamic multi-user entanglement networks; Deployment of quantum switching; Inter-city entanglement links; Integration with 6G architecture;

Long Term: Quantum repeater-based networks; Fault-tolerant long-distance entanglement; Global quantum internet; Distributed quantum computing networks; Blind quantum computing

Experiments in the Bristol university for entanglement distribution are based on The UK Quantum Network which is built on the National Dark Fibre Facility (NDFF). It includes 410 km main trunk quantum communication line and connects Bristol and Cambridge, a

Metropolitan quantum network in Bristol and Cambridge. It uses entanglement distribution at metropolitan scale.

4. RECOMMENDATIONS FOR PRIORITY R&D TOPICS BY TIME HORIZON

From the above perspective, multiple actions may suggested for future activities under SNS or FP10 with different time horizon and TRL levels.

4.1. SNS WP2027, LOW-TRL ENABLING TECHNOLOGIES

These topics cover long term issues starting at low TRL level (TRL 2 to 4) and address focused problems and challenges. Multiple use cases may be considered in that respect:

- The classical QKD/PQC use case requires progress on underlying technologies to reach the full maturity for entanglement distribution over long distance, multiple nodes and interoperable infrastructures. In this category the target is to distribute entanglement over a complex multi domain infrastructure requiring innovative approaches at subsystem level such as entanglement generation, distribution over Quantum channel, detection and verification/authentication, entanglement purification and error detection, storage, swapping, routing and delivery. Additional issues may target co-existence with classical fiber networks, open source modeling and emulators with digital twins to simulate an overall infrastructure.
- Other Use cases may be considered. In particular, the long term prospect of using distributed Quantum computing as a computing environment to solve complex management problems, either at RAN level or at transport/core level. Sensing, ultra precise location and timing are other Use cases that may be part of low TRL exploratory work.

4.2. LONG TERM - SNS WP2027 SYSTEM-LEVEL

The objective is to address the long term system perspective of the Quantum Internet vision, to be developed under FP10 time frame, through a preparatory actions under a flagship initiative acting as a bridging phase between SNS and its successor. The activity is part of a larger scale system vision of future networks (Hexa-X model) and is best placed to address all issues related to integration of Quantum technologies and Use cases within a larger network and services platforms. The target TRL level is broadly TRL 4, and the support flagship vehicle is a RIA. The action define the European positioning vis-à-vis the QIA-SGA roadmap, the US Quantum Internet initiative and the Chinese long-distance demonstrators. Typical issues include:

- End-to-end Quantum Internet — fault-tolerant repeater-based long-distance entanglement, multi-domain entanglement-distribution fabric, integration with satellite assets including IRIS²
- Wide area entanglement distribution over a complex long-range infrastructure based on multiple nodes, with swapping, switching and memory components fully integrated in the network structure;
- Distributed quantum computing across data centres and across the wide-area network, including blind/delegated quantum computing, distributed quantum co-processors enhancing classical AI workloads ("Quantum AI"), and consensus/Byzantine-agreement protocols
- Quantum-native networking architecture and applications: teleportation as a transport primitive, deterministic networking, multiplying bandwidth via entanglement-assisted classical communication, certified deletion, scalable distributed payments
- Rydberg-atom-based quantum receivers for 6G — joint demodulation of communication signals and high-precision EM-field sensing, quasi-monostatic sensing for mobile targets ("6G radar"), ultra-precise timing (Orange, DT).
- Exploration of non-locality for novel ways of controlling networks
- European supply-chain sovereignty for the underlying hardware electronics addressed in partnership with Chips JU pilot lines and the Quantum Flagship as appropriate
- Full co-existence of the Quantum and classical fiber (or satellite) networking;
- End to end orchestration of hybrid resource and full characterization of an operational software stack including C/Plane extension to operate an hybrid fiber/Quantum infrastructure;
- Network management backed by Digital twins and full-scale emulation/simulation capabilities including for training and education;
- Interconnection of Quantum computers and related interfaces with one target priority Use case based on distributed management and including AI support;
- Distributed quantum sensing-as-a-service for infrastructure monitoring, ultra-precise timing and synchronisation across the network, and 6G PNT
- Hybrid HPC–Quantum compute orchestration exposed as a network service (Quantum Compute as a Service, including blind/delegated computing) — software and runtime frameworks for heterogeneous QPU integration
- Continued certification ecosystem development (post-Nostradamus), security assurance, formal models and protection against side-channels and quantum hacking
- Vendor-agnostic key-management evolution towards SDN/NFV-native, multi-domain operation, including Quantum Abstraction Layer concepts.

4.3. MEDIUM-TERM — EXTENSION OF CURRENT STATE OF THE ART THROUGH EXPERIMENTAL PLATFORMS

This action addresses the extension of the current State of the Art through experiment and testbeds that go beyond the existing demonstration capabilities today, i.e. moving towards State of the art point to point connectivity and limited range for demos whilst increasing the fidelity and reliability level of the entanglement generation, distribution and decoding. It piggybacks on national/EU developments where appropriate. Typical issues that may be addressed by such an experimental project (Stream C in SNS terminology): Quantum safe transition with QKD hybridization with PQC to also alleviate distance limitations of QKD, range extension of QKD networks.

- Network architectures to address long distances coms and interconnections compatible with today networks and future Q-repeaters;
- Orchestration, synchronization, and networking frameworks for distributed hybrid HPC–quantum infrastructures.
- Wide-area Entanglement Distribution enabling a Multi-point network with the possibility to perform Entanglement swapping to cover inter-city distances (~300 km), the possibility to have Quantum memory with long enough coherence times and early Quantum repeater implementation to perform such swaps;
- Expansion of QKD networks and key management integration. It includes early multi-node quantum networking pilots focused on metropolitan-scale entanglement distribution, interoperability demonstrations, and operational procedures. It also targets increasing integration with classical optical and IP network control/management stacks.
- Early deployments incorporating quantum-repeater elements and limited multi-hop entanglement services in controlled environments including inter-domain networking concepts (service federation, routing policy, and operational assurance) to move towards large scale interoperability.
- Early control plane development for integration and operation of testbeds, Open-access to testbed for PoC demonstrations (QKD, blind quantum computing, distributed sensing…) with use of already existing infrastructure to validate technological components
- Early demonstration on shared fibers with classical communication data on existing deployed network; insertion of additional user-nodes to testbeds to extend it from a point-to-point testbed to a metropolitan network with shift from a PoC testbed to a Quantum Internet Pilot-Line; deployment of a ground station to connect testbeds to satellite capability;
- interconnection of QCI and KMS (Key Management System) including architecture protocols, Terrestrial & Satellite PoC and tested between operators

- QKD Vendor interoperability with new standards for QKD cryptograpy (prepare & measure, entanglement) to make vendors interoperable (today implementations of subsystems are vendor specific).

5. CROSS CUTTING ISSUES

Several themes were emphasized and should be considered for future SNS actions.

Standardisation and interoperability.

ETSI ISG-QKD, ETSI Quantum technology Technical Committee, IETF QIRG, ITU-T FG-QIN/SG13, IEEE P1913, CEN/CENELEC JTC 22 and ISO JTC3 are all developing quantum-related standards. European projects must contribute coherently and in coordination, as the absence of common interoperability profiles is the single largest obstacle to multi-vendor deployment. Dedicated standards for KMS, APIs for service access by third party application are typical issues to address.

Reuse of existing infrastructures.

Multiple infrastructures were outlined as available in Europe: MadQCI, TEFQCI, IberianQCI, FranceQCI/Paris-region testbed, UK Quantum Network/NDFF, Berlin QTFC, NQCIS, Finnish QKD test network and in the future, the Eagle 1 / IRIS² space segment. These represent considerable investment and opportunities to reuse such developments under SNS should be encouraged where appropriate.

Synergies with other EU instruments.

Chips JU pilot lines (Qu-PILOT, P4Q, SUPREME, SPINS, DIREQT, CHAM-PION, Q-PLANET) cover the component layer; the Quantum Flagship (QSNP, QIA-SGA1/SGA2, OpenSuperQ+, EPIQUE, HYPERSPACE) covers fundamental research; EuroQCI covers deployment (EQUO, QUID, etc); EuroHPC/QCI covers hybrid quantum-classical computing; IRIS² covers space connectivity (but in the future). Where applicable, SNS future actions should articulate explicit interfaces with these instruments, particularly for components explicitly out of SNS scope.

Skills, talent and a European supply chain.

Bridging research, industrialization and commercialization while ensuring a sufficient talent pool is a recurring theme of the EU Quantum Strategy and was repeatedly mentioned. SNS actions should systematically include open-access experimental components and open-source software releases.

Quantum Hardware Abstraction Layer

would simplify and speedup the development of quantum platforms, services, and applications, as another major obstacle hindering developments and large deployments of Quantum Networking and Computing infrastructure is that, today, the industry has not yet consolidated around one type of quantum hardware technology. This would support Applications and Services Developers to start using the abstractions of the underneath platform.

Hardware-first prioritization in the short term.

The closing discussion concluded that hardware (chips, sources, detectors, memories) is the binding constraint in the short term and that software is tier-2 — but that channel modelling, the protocol stack and management software must be addressed in parallel to avoid a software gap when the hardware matures.

ANNEX 1. PARTICIPANTS AND CONTRIBUTIONS

6G-IA: Alexandros Kaloxylos, Executive Director; Bernard Barani, Senior Consultant (moderator).

SNS JU Office and hosting organisation: Javier Albares (Head of programme); Pavlos Fournogerakis (Deputy Head of Programme)

Institutional speakers:

- European Commission — DG CNECT Unit E1 Head of Unit, Miguel Gonzalez-Sancho.
- European Commission — DG CNECT Unit C2, Laurent Olislager, DG CNECT Unit C4
- NetWorld Europe SRIA / CNR-IIT — Claudio Cicconetti.

Industry speakers:

- Nokia Bell Labs — Werner Coomans.
- Telefónica Innovación Digital — Antonio Pastor.
- Welinq — Romain Demur.
- Ericsson Research — Tomas Sundin.
- Deutsche Telekom T-Labs — Oliver Holschke.
- Orange Research — Eric Hardouin.
- InterDigital — Philippe Sartori.

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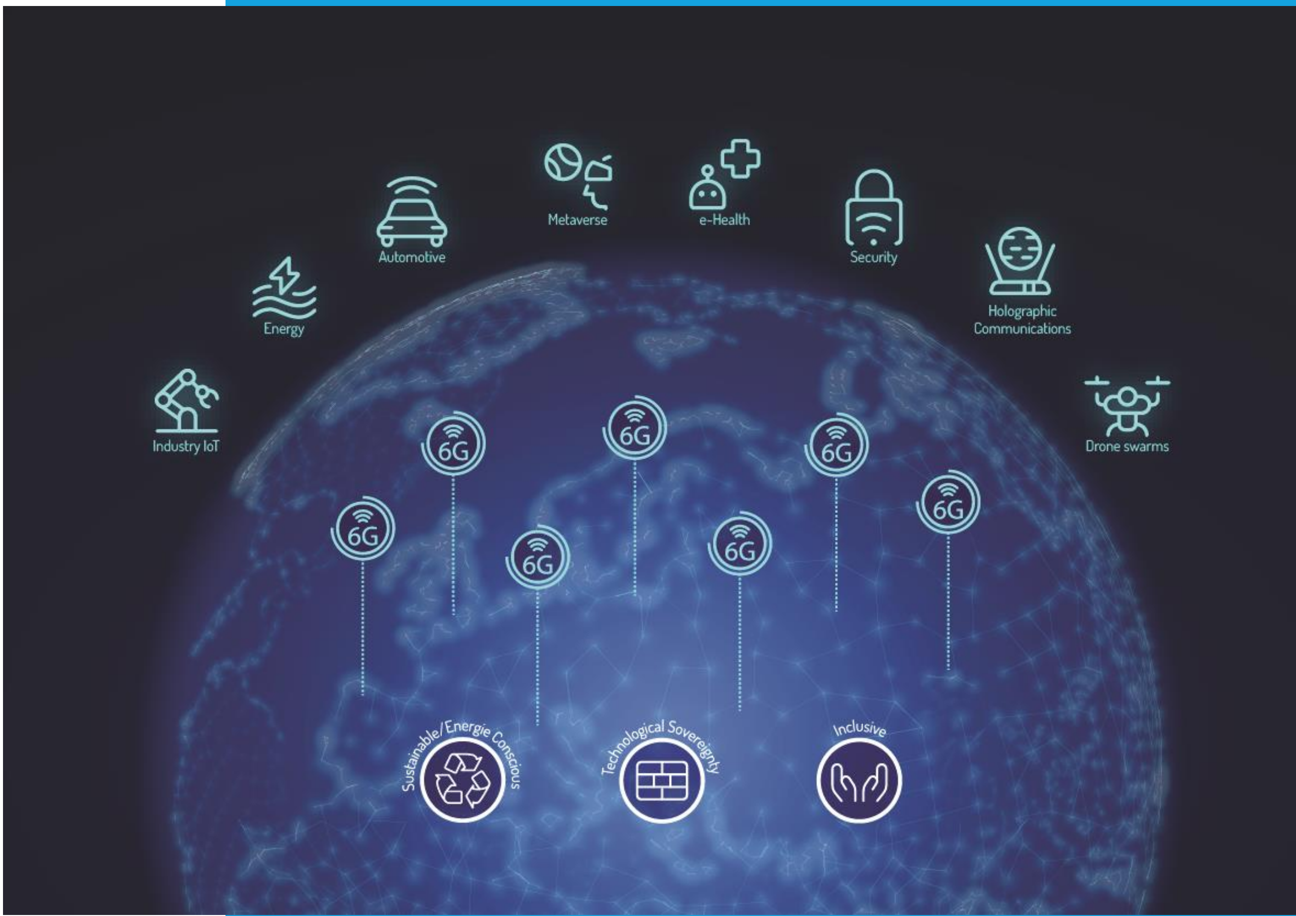

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