3.1 Publishable summary

The Q-ESSENCE project exploits quantum entanglement to enable disruptive technologies that will solve outstanding issues in information and communication technologies (ICT) related to trust, privacy protection, and security in two- and multi-party transactions, novel or enhanced modes of operation of ICT devices, reference standards, sensing, and metrology. The practical exploitation of entanglement requires groundbreaking levels of robustness and flexibility for deployment in real-world environments which can be reached only through radically new designs of protocols, architectures, interfaces, and components. Q-ESSENCE targets these breakthroughs by a concerted application-driven effort covering relevant experimental, phenomenological, and fundamental aspects. The objectives of the project are pursued by three closely interacting subprojects that are oriented towards specific application areas of quantum technologies.

The main objective of Sub-Project 1 "Quantum Metrology and Sensing" is to design and implement techniques that enable sensing and measurement beyond what has been possible with classical resources. This includes the use of quantum states of light and/or matter to determine with ultimate precision parameters such as time, distance, magnetic or gravitational fields, as well as to estimate the properties of one quantum system by non-destructively interfacing with another. The key research goals are to sustain super-precision in the face of decoherence in real world applications and to design fully integrated quantum sensors. In the second year of the project again considerable progress has been achieved. Starting from well-developed first sources for non-classical states of light novel tools have been devised, for example for a re-configurable conditional preparation aimed to generate non-Gaussian states or for the de-Gaussification of continuous variable states. Complementary to this, amplification of photonic states was investigated yielding significantly improved measurement precision. Most impressively, combining two continuous-wave squeezed light sources, developed within Q-Essence during the first year, the Einstein-Podolsky-Rosen correlation parameter evaluating the non-classicality of two-mode squeezed states was improved by more than an order of magnitude compared to state-of-the-art. In addition, the consortium has developed several tools analyzing the mathematical structure of the decoherence process. As a result, we found a number of instances, e.g., entanglement in an intermediate regime of the number of qubits, or non-Markovian noise, where the entanglement enhancement can be maintained even in the presence of noise and decoherence.

Important steps have been undertaken towards quantum enhanced imaging and microscopy beyond the diffraction limit and for the future implementation of real-world quantum sensors. In this respect an improved classical encoding was deduced from a quantum range finding scheme, which, however, is still superior under post selection or when sing quantum memories, such as spin-photon entanglement devices. Based on fiber-in-Sagnac or cavity-enhanced down-conversion multi-photon experiments enabled the comparison of 2- 4- and even 6-photon interferometry fringes with a correspondingly increasing resolution for phase estimation. This is combined with an effort pursuing the development of various waveguide platforms enabling integrated sensors in the future. As a first result the consortium implemented the first micro-fluidic quantum sensor, and, using entangled two-photon states, the protein concentration in a bovine serum in an aqueous buffer was successfully measured. The novel opto-fluidic device was designed to couple a waveguide interferometer to a micro-fluidic channel. Small refractive index changes, of about 1% were observed using two-photon coincidences from a 2-photonN00N state showing the promising potential of practical quantum metrology to light sensitive samples in biological scenarios.

The ultimate goal of a measurement is to observe a quantum system by means of another one. The investigation of such a quantum-quantum interface resembles directly the measurement concept as described by von Neumann and will enable unprecedented measurement sensitivity and the ultimate studies of decoherence. In close interaction between theory and experiments the consortium addresses the coupling between nanomechanical systems and various quantum states of light in order to enable ultrasensitive read out of otherwise inaccessible properties of complex systems by direct coupling and state transfer along the quantum-quantum interfaces. Various coupling mechanism have been proposed for different systems such as nano-cantilevers or membranes with a quality factor Q exceeding 10^6 at room temperature. The state of the mechanical system can be read out using cw-squeezed or pulsed light and is designed to achieve strong coupling and cooling at the same time. Alternatively, coupling to spin systems or to electronic circuits is under discussion. Particularly attractive is the usage of pulsed light fields. Theory was developed showing that various kinds of linear and non-linear coupling of the light field with the nano-mechanical system are possible, ranging from a standard beam splitter operation to quantum non-demolition and three-wave mixing non-linear interactions. The latter will allow the preparation of squeezed mechanical states or of two-mode squeezed states, where the entanglement between light and mechanical states will enable teleportation across the quantum-quantum interface.

For the next generation quantum metrology systems the consortium aims to extend the concepts and thus also the performance of current state-of-the-art methods by generalizing to non-linear evolution sand the possibility to simultaneously determine several phases. The phase measurement enhancement was investigated for various quantum states to the measurement of unknown nonlinear phase shifts. It has been shown that the optimal phase estimation precision of the even entangled coherent state (ECS) is better than that of the NOON states and of odd ECS states with the same average particle number $\langle n \rangle$. Quantum enhancement of the measurement has been derived for nonlinearities of arbitrary order of the unitary nonlinear phase evolution operator. A very general, simple geometrical method was developed which allows to calculate precision bounds on linear quantum metrological schemes with generic decoherence models. Multi-parameter estimation was developed and demonstrated experimentally for the first time along two alternative routes. The first is based on introducing an external reference beam which in addition to enable the access to two independent phases increases the precision in the presence of loss. Secondly, symmetric Dicke states where shown to enable the simultaneous measurement along two usually complementary directions (σ_x, σ_y) on the Bloch sphere. This does not contradict the Heisenberg uncertainty relation as the expectation value for σ_z vanishes. Sub-shot noise phase estimation was demonstrated for up to six photon states.

The Sub-Project 2 “Enabling Technologies for Quantum Communication” is targeting the development of resources and methods needed to overcome limitations for both high-speed and long-distance quantum communication, with an emphasis on the distribution and storage of bipartite entanglement suitable for diverse quantum communications tasks. This effort integrates the development of architectures, protocols and component technologies while targeting improved robustness, interconnectivity and scalability in systems that can exploit existing real world communication infrastructures.

Last year of the project has seen significant advances for detector operation, including self-differencing InGaAs avalanche photodiodes(APDs) with gigacount/s and record low after pulsing rates for telecom detectors. Silicon(Si) photon number resolving(PNR) detectors have also been demonstrated with > 70% efficiency. So called red-enhanced Si APDs have achieved efficiencies of 40% while maintaining good jitter and dark count characteristics that ideal for free space communication. The SME partner IDQuantique has commercialised a detector module (id210) with an order of magnitude increase (now 100MHz) in operational rates over previous systems. The consortium has developed the first waveguide coupled detectors based on superconducting parallel nanowires. These devices are expected to provide 90% absorption for the incoming field, overcoming one of the principle problems facing previous coupling techniques.

The project also continues to develop sources suitable for: long-range high-speed quantum communications (free space and fibre), quantum interfaces, memories and repeaters, quantum metrology, and quantum information processing .This year we have several exciting firsts including small (100 micron long) 4-wave missing sources in silicon photonic crystal waveguides and new approach for generating pure narrow band telecom photons in integrated optical parametric oscillator waveguide cavities. Semiconductor photon sources have also been realised with emission rates reaching 19% and device efficiencies of 24%, as well as triggered entangled photon pair sources that have demonstrated two-photon interference visibilities of up to 57%. We have also advance the efforts for comparing photonic sources with an updated comparison table as well as initiating plans for a review article, involving input from across the project, for publication in the final year.

A multitude of technologies are being developed within SP2 with the aim of improved device and system efficiencies. Significant progress has been made across the board, ranging from the spin storage measurements in quantum dot (12ns) and atomic frequency comb (10 μs) memories as well as >150 micros for Zeeman qubit storage times in neutral atoms. Stokes/Anti-Stokes emission for high bandwidth quantum memories using diamond has also been observed this year. All partners also contributed to updating a comparison table with a view to dissemination of specifications and needs associated with the different systems under development that may be of use to other members of the consortium.

In the area of design and comparison of quantum communication technologies, research has continued on both objectives 1 and 2, with significant results presented on both themes. For 1, we present a significant new quantum repeater protocol and a detailed study of how detector imperfections can affect conclusions about entangled sources for repeaters that they are used to characterize [UNIGE]. Clearly this latter contribution is also important for verification scenarios that employ such detectors, and thus 2. The main results for 2 comprise three quantitative verification methods for quantum resources and we note that one of these methods arises from collaboration between experimentalists and theorists and one has been tested experimentally on a photonic cluster state.

The consortium also continued efforts to demonstrate the technologies for long-distance quantum communication. To achieve global communication infrastructure technologies for both satellite-based free space systems and fibre-optic telecommunication networks are developed. There have been several landmark demonstrations this year, including: the entanglement distribution between remote (20m) single atom quantum memories; the demonstration of quantum entanglement between two separate macroscopic objects which was maintained for as long as an hour, as well as first results for experimental device independent QKD, demonstrating a heralded single photon amplifier in the telecom regime.

Sub-Project 3, entitled “Distributed Quantum Information Processing”, is concerned with exploratory research developing new modes of distributed quantum information processing. In the focus of attention are novel theoretical ideas, thinking outside the box, as well as new experimental techniques and technological developments. The effort is grouped into five workpackages. In the second reporting period, again a plethora of strong results could be achieved, both in theory as in experiment.

The first work package assesses the potential of continuous-variable entanglement distribution, focusing on aspects of network compatibility and the ability of distillation, including approaches combined with photon counting, multipartite and bipartite settings, in theory and experiment. Continuous-variable approaches are expected to have significant advantages in local area networks when very high speeds and network compatibility through typically well defined modes are the predominant figures of merit to be optimised. In the second year, progress was fast. In particular, experiments have been realized sending a squeezed laser field over a free link of 1.6 km length and measured about 1 dB of squeezing. A 4 mode bound entangled state has been prepared, now including an improved detection of Gaussianity. The distribution of two-mode squeezed entangled light with a non-classical bandwidth of more than 1 GHz has also been realized. New theoretical work introduces two new schemes for continuous-variable long-distance entanglement distribution. Experiments towards the first entanglement distillation counteracting real environmental noise (atmospheric fluctuations) have been performed, as well as further steps towards pulsed bulk-optics implementation of the Brown-Eisert-Plenio CV entanglement distillation scheme. A big-picture goal is implementing a genuine iterative distillation protocol. Significant challenging technical issues had and have to be overcome to pave the way for this goal.

Work package 3.2 aims at exploring new modes of distributed and secure processing and communication in QIFT in the first place, having the potential to give rise to groundbreaking applications in distributed, multi-user information protocols. In the second reporting period, a number of new and quite promising protocols could be identified. Research focused to a large extent on the potential improvement of feasible quantum-based privacy protocols, such as anonymous voting, anonymous function evaluation and others. Important results include a comparison between quantum and classical voting protocols with respect to security under certain types of attacks, as well as notions of privacy and verifiability. A number of unexpected new results have also been achieved: This list includes schemes for distributed continuous-variable measurement based computing, ideas of directed percolation effects emerging from super-additivity of quantum networks and other novel schemes based on quantum networks. In summary, a rich portfolio of new schemes could be collected in the second reporting period.

Work package 3.3 is concerned with developing novel tools for systems identification, the certification of success, and the measurement of properties of states and processes. Just as in the previous period, work has progressed at a fast pace, both with new theoretical developments. Notably, a quantum detector tomography method for the reconstruction of the POVM of a coherent optical detector has been introduced. This work both has a computational classical component, was well one directly relating to experiments with detectors having a weak phase reference. In other work novel tools for studying non-Markovianity as well as estimating decoherence rates have been proposed. New ways of analysing the effective continuous-variable entanglement with a channel length of up to 40 km have been established. The common paradigm that in the overwhelming majority of experiments in classical and quantum physics an a-priori assumption about the dimension of the system under consideration has been successfully challenged. A new theory of quantum compressed sensing for continuous-variable systems has also been introduced, significantly outperforming standard quantum state tomography based on homodyning or direct measurement of the Wigner function. Again, theoretical and experimental work was closely intertwined in this reporting period.

Work package 3.4 has essentially two components: On the one hand, it collects work on actual implementations of distributed protocols. On the other hand, work on classical control theory provides tools to actually experimentally implement new protocols in a resource-efficient way. Progress has been made in both directions of research. In particular, a method of least-square approximation by elements from matrix orbits by gradient flows on compact Lie groups has been introduced, a unifying programming framework in order to compare, optimize and benchmark quantum control algorithms has been formulated, and ways of performing optimal control for generating quantum gates in open dissipative systems have been investigated. Significant progress was also made concerning experimental implementations. This includes the quantum simulation with light and the experimental generation of complex noisy photonic entanglement. A highlight was the implementation of blind computing and a dynamical quantum simulation.

Work package 3.5, finally, is a work package that collects theoretical efforts of entanglement-based quantum information processing. Again, in this second reporting period, work in this work package was prolific beyond all expectations, and a very large number of results could be achieved. The body of work is too large to give a detailed overview, and for this, we refer to the deliverable report and the list of publications. Significant new results could be achieved on notions of information causality, and on new notions of non-locality. New ideas on resource theories related to notions of quantum statistical received quite some attention, as well as new ideas that quantum noise can actually help in achieving protocols, not be detrimental, here in cooling by heating in opto-mechanical small thermal machines by partner FUB. This work is in context with ideas of non-Markovianity assisted steady state entanglement and the robust dynamical decoupling with concatenated continuous driving. Notions of undecidability have been introduced into the computer science assessing the hardness of certain quantum tasks, and a difference in analogous quantum and classical problems has been found, relating also to other work of the computational complexity in this work package. In summary, this has again be a creative period for this work package giving theoretical guidance to the SP as a whole.

Project public website: **www.qessence.eu**