An overall picture for Time&Frequency and quantum communication in X-WiN

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Content

Summary

The two application areas "Time&Frequency" (T&F) and quantum communication (QuC) have special technical requirements for data networks.

For the transfer of high-quality signals, T&F requires bi-directional amplification, which in conventional data networks requires the signals to be decoupled and re-coupled at each amplifier location, which in turn requires special technical and operational expenditure. At least in the development phase, but sometimes also in the long term, QuC requires data networking that is separate from the usual data communication.

Therefore, in addition to the X-WiN, a limited, additional and separate fiber optic network (QuC-T&F network) financed by the federal government (and possibly some federal states) and operated by the DFN association should be installed, which will be used in the coming decade for research, development and use of applications in both areas without being affected by the operational requirements of other data communications.

Such a German QuC-T&F network would also be the natural starting point for cooperating with other national and European networks currently being set up in both areas.

A) Introduction

The following illustration is intended to describe a supplementary variant for the X-WiN for the two areas "Time&Frequency" (T&F) and quantum communication (QuC), in which an additional and separate fiber optic network operated by the DFN association, the QuC-T&F network, is proposed .

In the two sections B) and C), some current project developments and application prospects are described for the areas T&F and QuC, from which requirements for data communication can be derived. It also explains why these technical network requirements can either not be met at all or only with special technical efforts over the glass fibers of conventional data networks (i.e. in the form of WDM channels).

Section D) shows the potential of a separate but common network structure.

Section E) explains why the DFN association should operate this network structure, which is to be financed separately by the federal government (and possibly some federal states). Rough cost estimates for this are presented.

Finally, Section F) describes the resulting next steps for this task.

B) Area Time&Frequency (T&F)

In recent years, the European National Metrological Institutes (NMIs) have developed many activities for the network-supported provisioning of T&F, which, by providing signals derived from "optical clocks", can lead to more precise time signals becoming available worldwide and which in future will play a role in the areas of metrology and sensor technology.

European concepts for this are being developed in the EU-funded project CLONETS and its successor project CLONETS-DS [CLONETS-DS]. These concepts will enable the provisioning of T&F services in the overall European infrastructure. So far, there have been a large number of smaller, isolated networks at the national level, but also some smaller isolated network structures in cross-border cooperation. An important example of this is the linking of the PTB in Braunschweig with partners in France (LNE-SYRTE, Paris, FR), in Great Britain (NPL, Teddington, UK) and recently in Italy (INRIM, Turin, IT).

B.1) Networking features of T&F

The accuracy of T&F signals in remote locations is determined by the sources (“clocks”), and by the transmission structures and techniques (optical fiber, satellites), with the selected technique depending on the requirements of the respective users and their applications (GPS: medium high; gravitational field measurements: high) oriented.

Some technical aspects regarding the T&F signals:

- Current atomic clocks based on cesium fountain clocks operate in the range of a few 10**(-16) relative uncertainties. They are used to determine the current International Atomic Time (UTC).
- Modern "optical clocks" based on ytterbium, strontium, aluminium, etc. can reach the range of 10**(-18) relative uncertainty. The transfer of such high-precision signals without

deterioration due to the available transmission technologies has so far only been possible in test environments.
- The signals can be transmitted via satellite connections with a relative instability of 10**(-10) with an averaging time of 1 second, so that a relative transfer accuracy of a few 10**(-16) is achieved after an averaging time of around one day.
- Fiber optic connections achieve a relative instability of 10**(-15) after an averaging time of around one second, so that clock comparisons in the range of 10**(-18) relative uncertainty can be achieved after just a few hours of measurement time.

However, the use of high-quality T&F signals transmitted via fiber optics requires bi-directional amplifiers in the transfer networks, since the outward and return paths along separate fiber optics (in the same fiber optic bundle) lead to unacceptable runtime differences. For bi-directional amplification, the corresponding wavelength channels must be decoupled from a data network, amplified bi-directionally and coupled in again. This is done in different network environments in C-Band (RENATER) or in L-Band (SWITCH) and requires some special technical effort.

The co-existence of the T&F channels with data channels has already been shown and is therefore in principle quite possible, but the technical effort in our own glass fibers is significantly lower.

A GEANT project outline [GEANT-T&F-2021] from December 1, 2021 describes the structure of a T&F PoPs in CERN, to which NRENs could link with their national network infrastructures. Previous interested parties are: SWITCH, RENATER, CESNET, PSNC.

B.2) Applications in T&F

The provisioning of T&F signals that are available everywhere has become indispensable worldwide. The best-known "time application" is probably GPS signaling. Improved, i.e. more precise, time signals are already being provided as a service for some special user groups; prominent examples are T&F signals for the financial sectors in London and Zurich.

For the future, the international time UTC should be determined with improved accuracy, i.e. as a new UTC. For this use, global time would have to be defined based on optical clocks. In order to compare such clocks worldwide, transfer accuracies in the range of 10**(-18) (and better) are required. This has not been possible so far, so the global time UTC is still based on Cs clocks.

In the following, medium-value T&F applications are first outlined in order to clarify the wide range of utilization; these applications do not require bi-directional amplification and can therefore be used in classic data networks.
After that, high-value T&F applications are described that require bi-directional amplification and would therefore be prime candidates for separate T&F networking.

B.2.1) Requirements for medium-value T&F applications

One such T&F application is in power grids, where accurate time measurements can help identify network disturbances based on propagation delays; a clock accuracy of up to 1 µs is required for precise local fault location. Microsecond accuracy is also required by the IEC 61850 standard for substation automation.

Precise time and time synchronization is also necessary in Ethernet based seismic systems. In such systems, seismic sensors are connected over the network and thus also receive their time information that way, as these sensors are often located in places where GPS signals cannot be received (in wired sea-bed observatories, in caves, etc.). The accuracy of the time stamps of the seismic data allows the magnitude of an earthquake to be determined and also the epicenter (by evaluating the arrival times of an event) to be precisely located.

In addition, seismic tomography models can be constructed using time differences in P- and S-wave features.

T&F with White Rabbit Technology
White Rabbit (WR) technology is an extension for time synchronization in the network and was integrated into the standards in June 2020. WR achieves sub-ns accuracy (i.e. better than 10**(-9) sec) with bidirectional transmission in a single (standard) fiber optic and is served by the usual data network repeaters. A hardware extension with Synchronous Ethernet (SyncE) is required for clock synchronization; in addition, the exact connection delay must be known. In WR, this precise link delay is achieved by using hardware time stamps, by calculating the fiber asymmetry coefficient required for calibration, and by accounting for fixed hardware-dependent circuit delays.

B.2.2) Requirements for high-value T&F applications

Quantum clocks and gravitational fields
An application example for T&F signals is the linking of high-precision quantum clocks (atomic clocks, optical clocks) with the effects of the general theory of relativity (ART). According to ART, masses (or their gravitational fields) affect time. Time passes more slowly near large masses (e.g. stars, black holes) than in distant empty space. Such time differences can also be measured in the small gravitational variation of terrestrial environments.

In a cooperation between INRIM (Italy) and PTB (Germany), clocks have been placed in Turin and at an altitude of 1000 m on the IT-FR border. The difference in altitude between Turin and the mountain region results in differences in the gravitational force, which is reflected in different time lapses. In the INRIM-PTB experiment, a relative frequency difference of 10**(-13) could be measured, as also predicted by the ART [Italy-BB-2019].

This result shows two points:

- Already terrestrial gravitational differences lead to time and frequency differences of clocks (as predicted by the ART) and can be evaluated with the current measuring devices.

- Such time and frequency differences can be measured with the necessary accuracy via fiber optic networks – however, over noise-prone satellite connections this is only possible with a significantly longer measuring time.

Application options can be found throughout geology/geodesy/resource exploration. For example, an analysis of geological formations (rock composition, metal ores, natural gas, petroleum) with the help of the gravitational differences resulting from the different mass densities and their implementation in time/frequency would be conceivable. Another possibility might be the improved prediction of volcanic eruptions, which can be assumed based on previous underground magma movements. And finally, on the basis of the gravitational differences, uniform contour lines can be determined worldwide, for example to measure the rise in sea level - so far, rises in the Pacific or the Atlantic, for example, cannot be compared precisely enough.

Reference signals

Further areas of application can be found in basic physics (e.g. symmetry violations of the equivalence principle in ART or the Lorentz transformation in the earth's movement around the sun or the measurement of the mass ratio of electron and proton and the like), in the provision of precise reference signals for the quantum sensors (see also below) or for the earth-based calibration of satellite navigation systems (e.g. the European Galileo system).

In radio astronomy, the VLBI concept is used to simulate large telescopes with the appropriate resolution. For the next generation of VBLI systems, a position accuracy of 1 mm on a global scale is to be achieved, which requires correspondingly improved reference signals.

In Germany there are potential requirements in the relevant R&D departments of universities and research institutions. An example from the field of geodesy discussed at the end of 2021 concerns a possible cooperation between TUM/Observatorium Wettzell (Prof. Schreiber) with PTB Braunschweig and GFZ Potsdam via a DFN network. This cooperation, - its preliminary proposal has since been approved by the DFG -, is also intended to deal with the evaluation of ISS clock experiments in correlation with clocks on Earth.

C) Area Quantum Communication (QuC)

Quantum communication has been promoted worldwide with high stakes for several years. Drivers for this are mostly security threats and their defense, for which the term QKD (Quantum Key Distribution) stands for. In addition to the USA and Europe, China is very successful in this area, both in scientific work and in technical implementation (e.g. Beijing-Shanghai quantum test bed).

At the European level (flagship project, EuroQCI) and at the German level (QuNet project and others) there is a multitude of QKD activities with experiments and pilot installations (also outside laboratory environments). A prominent QKD showcase was the implementation of a secure quantum VC between offices (not laboratories) in the BMBF and the BSI in Bonn in August 2021. In the GEANT network, a QKD showcase over a distance of up to 600KM is currently being prepared together with TOSHIBA and its twin field technology.

However, QKD is not the only field of application for the quantum communication of the future. Further information on this topic can be found in Chapter C.2.

C.1) Technical networking features for QuC

It can be assumed that E2E quantum communication will initially start in the QLAN and QMAN area, because there the advantages of quantum entanglement can be exploited due to the limited distances without repeaters. In the QWAN area, E2E quantum communication will initially be established using "Trusted Nodes".

In order to be able to optimally use the potential of quantum networks, it is necessary that nodes involved in entanglements and their state measurements are precisely synchronized, otherwise the entanglement states cannot be verified. This means that quantum networks depend on the lowest possible jitter clock distribution. Photon randomization even requires a scale in the picosecond range (10E-12), which is possible with the White Rabbit technology (GPS-based methods only offer sub-nanosecond precision). Although GPS entanglements can still be detected well in the nanosecond range, the background noise in the jitter-limited coincidence interval affects the accuracy noticeably. For quantum systems that require an even higher jitter resolution (femtosecond range 10E-15), optical time transmission systems must be used (cesium atomic clock as a reference signal via fiber optics).

In the future, quantum communication will often be able to coexist with classic data channels on the same fiber; at the current stage of development, however, separate fibers are usually preferred in order to exclude mutual interference (between classic data channels and quantum channels) and to be able to experiment with less interference, e.g. with continuous-variable-QKD (cv-QKD) or with the time transmission systems mentioned.

Certain requirements (e.g. for discrete-variable-QKD, dv-QKD), in which individual photons have to be transmitted and detected, will probably most likely depend on separate fibers in the long run. It is difficult to imagine that the treatment of single or few photons can be achieved with the necessary signal-to-noise ratio to classical data channels on the same fiber with sufficient operational stability.

At least in the medium term, this will result in the need for our own separate QuC fiber optic structures.

C.2) Applications in QuC

The following descriptions are intended to show that not only security developments but also other applications of the "second quantum revolution" can (and will) use the means of QuC and thus the need for quantum networks will be broader than just from the point of view of secure communication. The possible quantum applications are often divided into three broad areas:
a) Security applications (QKD, ...);
b) (Distributed) quantum computing;
c) Sensor applications.

For a larger number of users in the DFN area (researchers, developers, teachers, etc., i.e. scientists/engineers beyond the QKD developers), the application areas b) and c) could be of increasing interest and thus require access to experimental quantum networks.

C.2.1) Security applications

QKD applications are currently at the forefront of discussions and of most programs/projects and pilot installations. With QKD applications, the attacks on the security-relevant IT infrastructure that are recognizable and expected in the future are to be warded off. It is also in this area of the implementation of QKD technology where most of the technical developments, both in research and in the industry, occur, and it also includes already available devices.

QKD is a way forward to protect data networks and will also be used in the DFN infrastructure in the future. However, the first application environments will certainly take place in the area of politics (security policy) and business (e.g. financial sector) and only then will the general “critical infrastructure” be covered.

C.2.2) Quantum computing

In quantum computing, two areas characterized by different security requirements can be distinguished, the regular "distributed quantum computing" and secured “blind quantum computing”.

a) Distributed Quantum Computing (DQC)
In regular DQC, computationally intensive mainframe applications are processed with the help of quantum computers, with quantum computers often only dealing with particularly suitable aspects. Due to the still low capacity of the individual quantum computers, several (distributed) quantum computers may also be included in the solution of individual problems. A distinction can be made between the independent calculation of a problem on two quantum computers, which in the end only communicate their partial results in the classical way, and the interactive quantum calculation on two quantum computers.

As in the current distributed HPC, it is expected that in the future DQC different classic mainframes and quantum computers will also be linked in different ways via classic data networks and quantum networks.

b) Blind Quantum Computing (BQC)
Here, in a slightly different way of utilization, a quantum computer is made available to third parties for use. However, the users do not want to reveal their confidential applications/data, not only to external attackers, but also not even to the operators of the quantum computer.

The concept of BQC is suitable for these scenarios. The user data is transported from the client as (transformed) QuBit input to the quantum computer via a quantum network; calculations are made there and the result is available as a QuBit output. It is transported back to the client and only there, in comparison with the original input data, can the qubit output data be converted into the desired final classic output data and "be understood". In the quantum computer itself, an attacker (including the operator) cannot “understand” the data. Client and quantum computer (server) must have certain quantum functionalities, such as quantum memory, qubit generation, qubit transport, qubit detection, etc.

Here, too, several quantum computers (servers) may be combined with one client, with even more varying needs for quantum communication or for classic data communication between the client/server components involved.

C.2.3) Sensor applications

The field of quantum sensor applications is very diverse and it is currently difficult to get an overview of its future forms. Some basic properties and some areas of application are outlined below.

In classic sensor technology, many charged particles (usually electrons) or many photons interact with the object under investigation and are then evaluated by detection components that are as sensitive as possible. Examples are optical lenses or detectors of the electrons scattered on the object to be examined.

In quantum sensor technology, a measurement sensitivity that is significantly increased compared to classic sensor technology is made available through the targeted use of single or few quantum objects. Instead of bringing many photons or electrons to the measurement object, in extreme cases a single entangled quantum particle A is introduced into the measurement range (the measurement probe). There it interacts with the environment under examination and the result is evaluated due to the entanglement with quantum particle B, which is located separately in the evaluation component.

This allows the measurement sensitivity to be extended down to the level of individual atoms, which of course can have enormous effects in many areas:

- In medical technology, examinations of the smallest disease structures can be carried out with it.
- Industrial production can achieve unprecedented levels of accuracy and detect the smallest of faults.
- Extensive global measurements in the field of long-baseline interferometry (e.g. VLBI in radio astronomy, uniformly calibrated height measurements for sea level and other earth measurements) can be significantly improved - this is where the above-mentioned high-quality T&F reference signals come into play.

Coordination and synchronization
The use of quantum entanglements provides advantages in all applications where coordination is required and is therefore also suitable for quantum-time synchronization (quantum clocks). Other applications that require great coordination and where one can take advantage of the entanglement property are voting procedures, for example; the coordination of online gaming between two players is also conceivable.

The advantages of coordination arise from the fact that if two qubits are entangled with one another at different locations, a measurement of qubit-1 then of qubit-2 will deliver the same result, although the answer is random and cannot be determined beforehand.

So far, there have been two methods for quantum clock synchronization with the goal of a uniform global time, both of which exchange either light or matter between two points and are therefore susceptible to atmospheric disturbances such as temperature and friction. These methods are on the one hand the Einstein synchronization, where e.g. laser connections are used for time transfer, and on the other hand a quantum adaptation of the Eddington Protocol for slow clock transport. A new third method for quantum time synchronization is now based on entanglement, in such a way that even absolute phase matching is achieved through entanglement purification.

The measuring probe and the evaluation component of a quantum sensor application will often be in close proximity, for which a short-range QLAN will be required at best. However, it is also conceivable that the evaluation component is stationed away from the measuring probe, e.g. in the form of a quantum computer. For this, but also for applications where sensors are geographically distributed over large areas of the earth's surface (see above: coordination and synchronization), extensive quantum networks (QMAN, QWAN) will be required for communication.

Quantum Random Number Generators (QRNG) represent a special quantum service for many quantum applications. Only QRNG generate completely random "random numbers". These must be generated, distributed and used. The properties of quantum networks are also required for this.

D) Combined backbone for T&F and QuC

Both of the work areas described above make special technical demands on network transmission technology. The respective requirements can be implemented at least partially in parallel wavelength channels of the classic data networks with technical effort, but some requirements demand their own fiber optic connections now and at least in the longer development phase or even permanently.

The applications in both work areas also have strong overlaps in terms of content in addition to the network-technical peculiarities. Quantum properties and extremely precise time measurements are physically closely correlated. This affects the so-called "sensor technologies", in which there are very precise time and stability requirements (which are linked via Heisenberg's uncertainty principle of physics), but also the timing in quantum networks. And last but not least, it also affects the security area, in which an economically important time infrastructure (keyword: GPS or Galileo) must be protected against "attacks", i.e. QKD-based security is a future topic.

Against this background, there is a growing discussion in the various T&F and QuC development environments as to whether and to what extent a common fiber optic structure that is separate from the data network can (should) be used for both areas. Examples of this are the description of an Italian backbone [Italy-BB-2019], the planning discussions in GEANT for future network expansions [TNC-2022] or discussions in the T&F-EU project CLONETS-DS [CLONETS-DS].

A (linked) double fiber optic network could primarily serve T&F or QuC applications which are developed and used by the connected users on one single fiber optic cable. However, by giving users access to both fiber optic strands, case-by-case developments could also be carried out that include both areas of work, such as the use of high-quality T&F signals in quantum applications. The key word here is “quantum clocks”, where the vibrations of the crystal of the atomic clock correspond to the oscillation of a clock when measuring time. The network management of this double-fiber structure will include classic tasks but also new "logistic" requirements, such as QKD key distributions.

The procurement of a double-fiber structure, which is customary anyway in networking, could therefore be very useful in both application areas, and would include the possibility of combining the technologies of the high-quality systems in each case.

E) DFN as operator, expenses

The DFN-Verein organizes national and international data communication for the German R&D community, starting with the basic technical network infrastructure up to high-level applications. In this respect, the DFN-Verein is also the natural partner for the German R&D community in the operation of special data networks that cannot (yet) or not easily be integrated into the current data network architecture.

In the EU project CLONETS-DS, corresponding concepts for the operation of special networks by the NRENs are already being developed by T&F users. For the QuC area, the need for a separate QuC infrastructure is likely to grow with increasing QuC experiments in the German R&D area. As described above, there are technical and content-related reasons for supplying both work areas with a combined T&F and QuC infrastructure.

The operation of this infrastructure by the DFN-Verein will probably be met with great approval from (potential) users.

The investment and operating costs of a separate T&F and QuC infrastructure cannot be raised from the existing financing structures of the DFN-Verein, neither through the user fees of the X-WiN users, which in most parts serve the operation of the commodity services, nor via the membership fees of the DFN association.

In the longer term, such costs must be provided from federal funds via the BMBF (and the BMWi?). Some federal states (e.g. Bavaria and Thuringia) have also started state initiatives on quantum communication, in which universities and research institutions are also involved. There can be synergies here in the QuC-T&F backbone structure to be set up, namely technically, operationally and also financially.

A more precise cost estimate can only be worked out in connection with a detailed project specification. The following rough estimates can therefore only show the dimensions of the costs:

- Fiber optic costs: A network over 2000 KM with 550 EUR/KM (DFN internal average) requires approx. 1.1 million EUR/year for the lease of a (twin-wire) fiber optic cable.
- Personnel costs: 4-8 people at 120 KEUR/year require approx. 0.5-1.0 million EUR/year.
- Investment costs for the devices in the QuC-T&F network (classic and special QuC-T&F components): A few million EUR (currently still difficult to estimate: 10-20 million EUR?)

The expenses required by the (potentially) involved user groups for their substantive R&D work remain completely outside the considerations here and must be provided elsewhere via R&D projects.

All in all, the amount of the necessary financing of the operation of the QuC-T&F network infrastructure is likely to be in the low single-digit million EUR range each year, plus the investment costs to be spread over the years.

F) Upcoming Tasks

A large number of decision-making and work processes are required to implement the objectives described above. Roughly speaking, this includes the following stages:

a) Discussions should be conducted with important stakeholders and institutions in the QuC/T&F areas (DLR, MPG, FhG, FZ Jülich, PTB, various universities) for support of the concept.
b) After that, DFN and the supporters should hold talks with the BMBF (and possibly other cost bearers) to secure the concept financially.
c) If there are positive signals from the BMBF, fine-tuning can begin at the same time. Depending on the progress of the discussions and planning, the detailed elaborations must be carried out in working groups:

- Identify potential user groups;
- derive a topology of the T&F/QuC backbone;
- analyze the special technical network requirements;
- identify the special network devices with their availability;
- compile the costs for construction and operation;
- gather the interface requirements of the potential user groups to the define T&F/QuC backbone.

All partial results will finally lead to an overall project plan, the funding of which will be approved by the BMBF and which can then be implemented.

G) Literature

Literature on scientific and technical issues in the areas of T&F and QuC is almost inexhaustible and is developing very dynamically. There is extensive information on this on the website of the X-WiN Laboratory (https://www.win-labor.dfn.de/en/) in the Quantum Technologies section.

Here are just a few references that deal specifically with the issue of T&F and QuC backbones:

- [CLONETS-DS]: [https://clonets-ds.eu and private Communication]
- [TNC-2022]: [GEANT-WP6-TNC2022-proposals, Nov.2021, unpublished]
- [GEANT-T&F-2021]: [GEANT-Draft: T&F hub CERN, V3, Dez. 2021, unpublished]
- [Italien-BB-2019]: [Calonico, D; Clivati, C; Italien Quantum Backbone, 2019, Il Nuovo Saggiatore, Vol. 35, No 3-4]