Quantum Enhanced Time Synchronisation for Communication Network

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October 31, 2023

Abstract

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Quantum Enhanced Time Synchronisation for Communication Network

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Abstract—It is essential to establish precise times in future communication networks. Any real-time task’s function depends on the system’s ability to synchronise time. Time synchronisation is critical in the current communication network and must be maintained to transmit data packets. The functionality of 6G, the Tactile Internet, Time-Sensitive Networking, and ultra-reliable low-latency communications is highly susceptible to time synchronisation. We investigated the idea of employing time synchronisation across different communication network nodes. The current state-of-the-art employs network protocols like Precision-Time Protocol for synchronising clocks across different nodes. These network protocols are not robust and can generate jitters in data transmission. In this paper, we suggested synchronising the clock time of the node clocks at three different places using Quantum technology. Notably, the oscillation frequencies of each qubit (or oscillator) located at these nodes can be synchronised using the quantum synchronisation technique. This set of three oscillators will work as a single clock and will be the master clock of the network. We propose distributing precise time and frequency standards using quantum synchronisation on node clocks. We can synchronise the three qubits (each placed at one node) to oscillate at an identical frequency by applying an external field of a wavelength of 813.32 nm. We analysed our model for different coupling constants and dissipation rates to provide an analysis of the behaviour of the amount of synchronisation in different experimental configurations. The optimal accuracy for our system is $1.6 \times 10^{15}$ signals per second. Further, we used the Allan deviation to examine the stability of our system for various noise strengths.

I. INTRODUCTION

Synchronisation, often known as synchronous, derives from the Greek terms syn, which means "with," and kronous, which means "time." Events are characterized as synchronous if they take place at the same moment. Huygens first provided a scientific description of synchronisation for classical systems in 1673. He noticed that connecting two pendulum clocks with a bar allowed them to oscillate at a standard frequency [9].

One of the fundamental building blocks of communications is network synchronisation. Transmission of data through any communication network requires three types of precise synchronisation: time, frequency, and phase. The synchronisation quality directly impacts the Quality-of-Service (QoS) experienced by end users. There are two main approaches to time-synchronisation in networks: First, by deploying independently-synchronised clocks at each network node, and second, by packet-based synchronisation of distributed clocks. The former approach consists of equipping each device with a synchronised clock, and the latter aims at transferring time information via frames or packets from a reference clock (master) – a central atomic clock or the Global Navigation Satellite System (GNSS) – over a communications network. However, this implies unexpected delays, and thus synchronisation degradation, due to network communication, hardware and software processing. Synchronisation will not only deal with the network as a whole (as a complex and heterogeneous system), but it will also have to concurrently comply with the end-to-end Key Performance Indicators (KPIs) of several verticals. These verticals can be enhanced mobile broadband (eMBB), augmented reality, vehicular networks, Tactile Internet and FinTech, and Internet of Things (IoT), Device-to-Device (D2D) communications, and smart grids (mMTC).

Contemporary synchronisation in networks and data centres towards an end-to-end perspective will significantly challenge all
the classical standards. These standards will likely need to be replaced by new network synchronisation techniques capable of satisfying the more stringent KPIs in complex and heterogeneous future networks. Given these premises, a promising solution to get accurate network synchronisation efficiently and effectively can come from approaching the problem quantum-mechanically instead of classically. Our approach utilizes a model of synchronised time-measuring devices at three network nodes to help us enhance the KPI of network architecture. Our model is a quantum clock, which works as a Grand Master (GM) clock of a network and is present at three different locations simultaneously, thus extending the coverage area of synchronised timing.

Quantum research primarily focuses on the physical principles that govern particles with quantized basic characteristics. A qubit is regarded as the fundamental quantum unit. Any particle, whether an electron, proton, photon, or atom, expressed by two different eigenstates or in a linear combination of these eigenstates, is referred to as a qubit. Eigenstates of an observable represent the possible basis states for a particle. Further, with the advances of highly phase-coherent lasers, optical atomic clocks containing multiple atoms have demonstrated stability that reaches the standard quantum limit (SQL) set by the available atom number within a clock [19]. These approaches may or may not consider exploiting quantum phenomena like 'entanglement' in their protocols to achieve unprecedented accuracy [10]. When the quantum state of any particle belonging to a system cannot be described independently of the state of the other particles, even when separated by a considerable distance, the particles are referred to as 'entangled particles', and the phenomenon is called entanglement.

We suggest using quantum synchronisation in our suggested paradigm to achieve precise temporal simultaneity. Our methods can be useful for developing a reliable and stable timekeeping apparatus that acts as a global reference standard. As long as each local phase oscillator in quantum synchronisation is self-sustaining, it is possible for them to synchronise their phase oscillation frequencies with one another or with an external oscillator. We consider the qubits as our self-sustaining oscillators [31]. Additionally, a group of synchronised qubits also show particle entanglement [35]. In particular, Roulet and Bruder [23] showed that while the contrary proposition is not always true, quantum synchronisation implies entanglement between the oscillators.

We demonstrate here how these technical boundaries may be motivated to operate a distributed network of quantum clocks that may be a part of various subnetworks of a global network as a unique global clock for the whole network. To obtain more exceptional clock stability and to spread this reliable time scale in real time over the whole network, all members of this configuration should combine their resources in a quantum coherent manner. Furthermore, enabled through quantum communication techniques, such a network can be made secure, so only parties contributing to its operation enjoy ultra-precise timing information. This could also be applied to Future Quantum Internet [34], which will interconnect quantum computers globally and distribute entanglement toward achieving unprecedented computing, communication and security performance.

The article is organised as follows. We first look at the protocols being utilized to implement time synchronization across the current network architecture, like Precision Time Protocol (PTP), and the limitations involved in such configurations. After that, we illustrate the synchronisation phenomenon and discuss some quantum preliminaries. Next, we synchronise the phase oscillation frequency of three distinct qubits placed at different locations to achieve a clock transition frequency of 1.14 GHz at each node. We simulated the spectral density and Pearson coefficient to reveal the characteristics of quantum synchronisation. We also evaluated the GHZ type of entanglement fidelity for our synchronised qubits. Further, from an engineering standpoint, we examined our model for various atom-field coupling constants, dissipation rates, and photon numbers in the resonators. Finally, we will perform a stability analysis of such a clock in terms of Allan deviation, followed by a discussion of our present use cases and future research prospects.

II. NETWORK TIME SYNCHRONISATION

Generally speaking, the activity of Time-Sensitive Networking (TSN) (i.e., the activity of the IEEE task group), 6G, the Tactile Internet (TI) and Ultra-Reliable Low-Latency Communications (URLLCs) is very prone to synchronisation inaccuracies [18]. However, efficient and effective packet-switched solutions for the synchronisation of, e.g., haptic or tactile data streams [27] are still an open research issue [1].

There are three kinds of synchronisation (Figure 1): time-, frequency- and phase-synchronisation.

Time-synchronisation ensures that two systems use the same timestamp. The most simple solution here is to simply send the accurate time from the reference clock to the client, where the client will adjust its clock value to the received time. Depending on the accuracy of the synchronisation process, the clocks can be synchronised on millisecond-level (e.g., Network Time Protocol (NTP)) or more accurate on nanosecond-level (e.g., PTP).

Next, there is frequency-synchronisation. The border between time synchronisation and frequency synchronisation is fluent. If timestamps are exchanged often enough, this will step both clock counters in the same frequency. However, the synchronisation frequency can be reduced, i.e., by not hard overriding the slave clock with the new value, but rather by adjusting its speed slightly to the clock difference. This method is used by PTP and explained in detail in II-A. Furthermore, PTP clocks appear to be synchronised on nanosecond-level but more precisely they often run on sub-nanosecond-level because the slave clock runs slightly faster and slower depending on the time difference.

Finally, there is phase-synchronisation. A servo loop ensures that not only the two clocks have the same frequency, but also the phase of both oscillators are synchronised (see 1). This level of accuracy is provided by, e.g., Synchronous Ethernet (SyncE). Here, the network physical layer (PHY) will recover the transmission clock from the received signal and inject this clock signal into
the device’s local Phase Locked Loop (PLL) from where it can be distributed to other devices.

Each synchronisation mechanism is prone to inaccuracy. The time, frequency or phase deviation has a constant part, called offset, and a variable part called jitter. Each clock synchronisation solution can be described as a servo loop which tries to converge both clocks by minimising the clock deviation. The deviation can be caused by unevenly running clocks or by time deviations injected by the synchronisation process itself. The latter issue is typical for servo loops, which are accelerating over several hops in an Ethernet network. As Ethernet packets typically differ in their transmission time (this is mostly driven by collisions in network nodes, software processing but also in phase differences between network nodes), this network jitter affects also the network clock synchronisation process dramatically.

In order to understand the strong relationship between network synchronisation, 6G, and the TI, the following section describes briefly the main characteristics of spreading time information in networks using packets.

### A. Packet-based Time-Synchronisation using PTP

PTP is a network protocol for clock synchronisation with an accuracy of down to several nanoseconds. It is defined in the standard IEEE 1588 and its evolution IEEE 802.1AS [30]. The protocol can be divided into tree parts: the Bester-Master-Clock (BMC) algorithm, time distribution, and clock adjustment.

The clock distribution is designed as master, slave architecture. In most systems, there is a reference clock, e.g., a GPS-based clock, which has to be distributed to all other nodes. This reference clock is called GM. A “master-capable” PTP-node will announce its clock via broadcast messages and possible clients will respond to these announcements in order to start the synchronisation process. PTP supports Layer 2 and Layer 3 communication.

Beside the network communication layer itself, the communication mode is an important parameter: End to End (E2E) and Peer to Peer (P2P) communication is supported by PTP. In the P2P-mode, master and client are connected directly without intermediate hops. The simplest clock type is the ordinary clock. This clock usually has only one network port and acts as either master or slave. Next to it, a client/slave clock, a so-called boundary clock, can itself become a master clock on another PTP-capable network port and distribute the reference clock to its clients.

In E2E-mode, the GM clock is distributed directly to its clients, which can be connected via multiple hops. For the synchronisation process, the intermediate hops are considered as direct connections (e.g., a cable). To make this assumption true, the intermediate nodes (transparent clocks) have to incorporate the residence time for the synchronisation process. This allows the PTP client to compensate the additional packet delay caused by intermediate hops.

The BMC election procedure is based on the information of a possible master clock distributes in the network. The client simply selects the best clock on the information received with the announcement message. These parameters are not checked, which is why any clock can be labelled as GM, regardless of the actual abilities.

After the clock election process, the master and slave clock begin to exchange synchronisation messages periodically. In these messages, the master clock distributes its actual time to the client. For a precise synchronisation, this information is useless without knowledge about the transmission delay of the synchronisation process. Therefore, a method to measure the packet delay is included into the clock synchronisation messages. 2 shows one possible implementation of this path delay measurement.

To calculate the path delay, two messages are exchanged between client and master. With this, the client receives four timestamps which are the transmit- and receive-times of both messages. The path delay can then be calculated using 1.

\[
\begin{align*}
\text{delay} = \frac{(t_2 - t_1) + (t_4 - t_3)}{2}
\end{align*}
\]

Notably, the accuracy of these timestamps are critical for the synchronisation process.

There are several implementations to provide the timestamps of transmitted or received messages. It is of high importance to measure as close as possible to the actual event. In the case of, e.g., using GNU Linux, an inaccurate mechanism uses the timestamp provided by the Linux kernel by processing the Ethernet packets. To improve the accuracy, the network hardware itself can be leveraged. The hardware can provide an accurate hardware timestamp with the received packet. For packet transmission however, the point of time when the packet leaves the PHY needs to be written into the outgoing packet. This procedure is called one-step timestamping. The process of manipulating outgoing packets at runtime is complex. Therefore, there is a simpler method implemented in PTP, which requires a second to-be-transmitted PTP-packet. In this so-called two-step-mode, the
transmit timestamp of the last packet is reported back to the transmitting process, so the timestamp of the former packet can be transmitted by the follow-up packet. One-step and two-step mode don’t differ in their accuracy, but only in the amount of packets to be exchanged. Since packet transmission is prone to error, this can affect the clock synchronisation.

In the third step of the synchronisation process, the client has received the GM clock and the path-delay to/from the GM, so it can calculate the exact time of the GM clock. Then, the client compares it to its own clock. Depending on the clock deviation, the client may write a totally new clock value to its counter or it may adjust the rate of its clock counter in the sub-nanosecond range to reach a similar clock frequency as the estimated master clock. The sub-nanosecond adjustable clock is thereby an inherent requirement for a precise PTP synchronisation. In summary, to achieve an accurate clock distribution over an Ethernet network each hop needs to be PTP-aware and should have hardware support for clock and packet-timestamping.

B. Performance Analysis and Limitations of PTP

In this section, we describe the behaviour of PTP time-synchronisation to highlight benefits and weaknesses. We analysed the PTP synchronisation performance in three different P2P-scenarios: a) laboratory environment with optimal conditions using a high-precision TSN-switch and one PTP client, b) laboratory environment synchronising two PTP endpoints with simulated network latency and jitter, and c) long distance synchronisation utilising a research Layer 2 channel between Dresden, Germany and Frankfurt/Main, Germany with an approx. distance of 500 km. The test topology is illustrated in 3. More information on the testbed itself can be obtained from [26].
ment shows clearly that a constant network delay has no visible effect on PTP synchronisation. The results show a direct effect of increasing jitter on the PTP clock deviation from slave to the GM. The more the network latency varies over time, the more difficult it is for the control loop trying to minimise the synchronisation error.

For all six cases the clock synchronisation succeeds even if the network jitter is also applied to the clock synchronisation. A network jitter of 10 μs results in a clock jitter of 4 μs. Fig. 6 depicts the comparison of the PTP synchronisation result for a Local Area Network (LAN) and a Wide Area Network (WAN) environment which corresponds to our optimal configuration from a) and the long distance network from c) respectively. The large jitter of the WAN connection results in a constant clock offset of 4 μs.

Numerical results can be obtained from I and II. The measurement shows clearly that a constant network delay has no visible impact on the PTP clock synchronisation mechanism. On the other hand, a network connection with a network jitter also results in an additional clock jitter. It is nearly impossible to achieve a synchronisation error (clock deviation from a master clock) close to zero due to everlasting changing network conditions and, consequently, Path delay variations. In comparison to the LAN based measurements, the long-range WAN connection results in a high clock aberration of 4.2 μs (median) which will be unacceptable for TSN applications. Furthermore, the clock is not oscillating around the 0 μs, but is constantly behind the master clock. Collisions in shared media cause the jitter in network connections. Two possible solutions can be thought of: organise the medium sharing more strict, e.g., use TSN for the whole connection or change the path from WAN to Interdependent Media, e.g., Quantum-Domain. For the following sections, we will investigate how quantum technologies can help us in improving network time-synchronisation.

III. SYNCHRONISATION

We must be familiar with the mathematical underpinnings of synchronisation in a classical or quantum system to comprehend the function of quantum synchronisation in the existing network infrastructure. Classically, synchronisation is adjusting the rhythm of a self-sustained oscillation of some oscillators to a weak perturbation like an electromagnetic field or any other external coupling. It is a universal feature of several complex dynamical systems like a vacuum tube radio generator, a pendulum clock, a firefly that emits light pulses, and many others. The main universal characteristic of these systems is that they are all active systems that, taken apart or isolated, oscillate in their rhythms, i.e., self-sustained. The system’s physical characteristics dictate the patterns of its oscillations, and the system’s internal “energy source” makes up for its energy loss and sustainably preserves its oscillation characteristics. Such oscillators are autonomous and belong to a category of nonlinear models called self-sustaining or self-oscillatory (auto-oscillatory) systems in physics and nonlinear dynamics. [13]. By removing an oscillator from its environment
and seeing whether it continues to oscillate, we may frequently confirm that it is self-sustaining.

As already discussed, the synchronised systems must oscillate independently and sustainably, that is, oscillate even in the absence of linkage. These systems must, in particular, exhibit stable limit-cycle oscillations. A limit cycle is a closed trajectory in the system’s phase space corresponding to ongoing oscillations devoid of decay or growth. The starting position from which the response began has no bearing on the magnitude of these oscillations. Most crucially, the phase-space trajectory of a self-sustaining LC oscillator attracts other nearby trajectories. Figure 7 illustrates a stable limit cycle with all trajectories in its vicinity converging to it as the time approaches infinity. It indicates that the damping and amplification processes continually conflict with one another, stabilising the system and maintaining the LC trajectory.

Fig. 7. Self-sustaining limit cycle demonstration in a phase space of position and momentum. As the time approaches infinity, all the systems in phase space with various paths merge into the Limit Cycle.

In addition, we should keep in mind that various coupling methods might cause the system to synchronise; for example, see Figure 8, where mutual synchronisation is the synchronisation of two (or more) oscillators with each other. On the other hand, it is also feasible to build a one-directional coupling in which “slave” oscillators synchronise to a “master” system, which may be an external drive. The ”master” system, however, does not alter because there is no backaction [31].

We use qubits as our self-sustained oscillators. A quantum bit or qubit is a quantum mechanical analogue to a classical one. In classical computing, any information is encoded using bits, each of which can have the value zero or one. In quantum information science, the idea is to encode information using qubits. A qubit is a two-level quantum system where its two basis states are generally represented by \( |0\rangle, |1\rangle \). And it can be in state \( |0\rangle, |1\rangle \) or in a linear combination of both the states, which is fundamentally different from a classical concept. To develop our protocol, we would use quantum synchronised qubits distributed at three different network nodes.

We first need to define oscillation for a qubit in order to demonstrate how each qubit’s oscillation frequency is synchronised. To do this, we employ the Bloch Sphere (See Figure 9), which can graphically depict how a qubit carries out phase rotation while changing over time.

Fig. 8. Different synchronisation “geometries”. One can divide quantum synchronisation into different categories as shown in Fig 8. If the coupling is one-directional, then the external reference can be an arbitrary periodic oscillator, i.e., it is not necessarily a limit-cycle oscillator itself.

Fig. 9. State Vector on Bloch Sphere.

A state vector from the Bloch sphere’s centre to its lowest point can be used to depict the lower state of a specific qubit. The state vector from the centre to any point on the surface of the sphere can similarly be used to represent any pure state. In contrast, the state vector that represents any point inside the Bloch sphere may be used to depict mixed states. A qubit in the lower state can become a superposition of its two energy eigenstates by the Hadamard operation. The Hadamard operator is a unitary operator that moves a state vector from the lower state to a specific location on the Bloch sphere’s equatorial plane, as shown in Figure 9. We now allow the state to change over time, which is represented by a state vector circulating on the equatorial plane of the Bloch sphere. So, it gains a phase factor that is dependent on the Hamiltonian of the system. We must allow the system’s qubits to grow at a similar rate for the phase difference between them to be close to zero in order to have completely synchronised clocks. A system of qubits oscillating at comparable frequencies must deliver equivalent temporal information in order
to achieve time synchronisation. Individual local phase oscillators can synchronise their phase oscillation frequencies with those of other local phase oscillators or with an external oscillator in quantum synchronisation, provided that each oscillator is self-sustaining. Therefore, the quantum synchronisation approach may provide the fundamentally synchronised oscillation frequency to each qubit.

Additionally, a group of synchronised qubits can exhibit a concurrence near one, signifying particle entanglement [35]. If two qubits are entangled, it means that measuring one qubit collapses the superposition of the other qubit as well. An entangled state is a multi-qubit quantum state that cannot be expressed as a Kronecker product of single-qubit states [5]. Particularly, Roulet and Bruder [23] showed that quantum synchronisation implies entanglement between the oscillators, but the converse statement is not necessarily true.

IV. QUANTUM SOLUTION PROPOSED

By employing quantum synchronisation in a communication network, we propose to go beyond the mentioned classical trade-off. This can provide a ‘technology-agnostic’ PHY synchronisation process with a boost in performance (e.g. accuracy, reliability and security), leading to an effective and efficient synchronisation service for heterogeneous and complex future networks, which will anyway integrate quantum technologies for various purposes such as distributed computing [2]. From the network point of view, we have a quantum master clock serving as the Telecom Grandmaster Telecom Grandmaster (T-GM), distributed over different network nodes instead of being at one geographical location. On the other hand, Telecom Slave Clock Telecom Time Slave Clock (T-TSC) can have access to the most precise timing which will ultimately reduce the problems related to current network infrastructure like latency, accuracy, reliability, security, jitters, and packet loss. Synchronised and entangled qubits are the basic necessity for establishing such a framework. These qubits are periodically measured to get the reference for the Local Oscillator (LO).

Our suggested framework consists of three nodes at three different places for complete coverage of the globe. An individual qubit is placed inside each node’s optical resonator, which is constrained in an optical lattice. Initially, our system’s three qubits can oscillate at different frequencies denoted by the letters \( \omega_{q_1} \), \( \omega_{q_2} \), and \( \omega_{q_3} \). Even though we are working with similar atoms, we initialise our system with different normalised oscillation frequency. We did this to consider different local factors affecting the oscillation frequency of individual qubits. The energy difference between the two quantum states of a qubit determines how these oscillations behave. We may deduce time information from these fundamental oscillations using various physical protocols. To have comparable time information extracted at each node, they must have synchronised oscillation frequencies with no or constant phase difference. However, it is challenging in a practical situation because our qubits system are driven by an external field and the environment is dissipative in nature. To give global reference time, we suggest using quantum synchronisation techniques that synchronise each qubit’s oscillation frequency to a specific frequency, which may be due to the oscillation frequency of an external light field. It is specifically dependent on the strength of the external field \( f \) and the difference between the oscillation frequencies \( \omega_{EF} - \omega_q \), allowing us to notice that the field strength increases the quantum synchronisation up to a specific limit [14].

As a result, the monochromatic coherent optical field required by our suggested design must be generated between the nodes. This may be done by employing a highly coherent laser source and optical fibres to transfer the field to various places. Each qubit would be synchronised to a given frequency by this external field.

Solid-state lasers are frequently used in optical communication systems since they can establish connections across distances greater than 40 000 km [4]. For these long-distance connections, crystal and semiconductor lasers, commonly referred to as laser diodes, are the most frequently used solid-state lasers. Our primary focus should be determining if these wavelengths are equivalent to the atomic transitions we use to synchronise the phase oscillation frequency of atomic qubits. The materials used to create photons classify various types of lasers. Particularly, the chosen link properties, such as its length, height, presence or absence of environmental losses, and the required receiver’s power level, are considered when choosing the kind of laser. We suggest utilise an AlGaAs laser diode that has an output power of 60 mW and generates coherent monochromatic light with a wavelength of 847 nm. This monochromatic light can establish an optical connection between several nodes using optical fibres. Such optical communication has already been demonstrated for satellite communication [6]. The optical field’s ability to connect with other system nodes may depend on these optical linkages. Based on the ideal design, polarisation-maintaining optical fibres (sometimes referred to as PANDA fibres) with low loss and minimal crosstalk have been produced. These fibres may be beneficial for coherent optical communication systems [24].

Incoherent coupling can cause quantum synchronisation, see [33], where researchers pumped two atomic ensembles incoherently in their model. As a result, the atoms are excited to unstable states, from which they decay into a stable excited state. Following that, the process is a single-mode coherent coupling of atomic ensembles in a cavity. Thus we added coherent coupling to our model. Future studies may stress which coupling will be more beneficial for an application, which will ultimately rely on the type of atoms, optical resonator, optical field, and environmental parameters like temperature.

The existence of an atomic qubit capable of synchronising with the external field frequency is a crucial component in the proposed model. We recommend employing Thullium atoms, which have an atomic number of 69 and belong to the Lanthanides group [7]. We propose to embed these individual qubits in an optical lattice resonator to realise such a quantum clock. We choose an optical lattice clock framework instead of a conventional atomic clock since they surpass the essential Caesium criteria in stability and precision [16]. The fractional frequency uncertainty of optical
clocks for a variety of atoms, such as Yb [25], Yb+ [8], Sr [20] and Al+ [3], can reach a low level of $10^{-18}$.

The optical lattice clock investigated by [7] used the inner-shell magnetic dipole transition $|J = 7/2, F = 4, m_F = 0\rangle \rightarrow |J = 5/2, F = 3, m_F = 0\rangle$. Here, $F$ is the total angular momentum, i.e., $F = I + J$, (where $I$ is the nuclear spin angular momentum and $J$ is the total electronic angular momentum) and $m_F$ is the magnetic quantum number associated with $F$ in $Z$-direction. Using an optical field of a wavelength of 813.32 nm, [7] could trap the atoms in spatially dispersed electric potentials of interfering optical beams by exploiting the fine-structure of the atomic states. This so-called 'magic' wavelength is the wavelength at which the system can perform resonant Rabi oscillation upon interaction with the optical field’s electric field component. The locking produces a clock transition frequency with a wavelength of 1.14 μm. The findings enable the creation of optical lattice clocks based on lanthanides with a relative uncertainty of $10^{-17}$. Therefore, our suggested approach presupposes that our clock qubits are atomic Thulium qubits constrained in an optical lattice structure. To synchronise qubits, we use a laser diode (AlGaAs) that generates an optical field as an external oscillator.

The following is a thorough explanation of quantum synchronisation for our system. We provide our atomic qubits an external optical field with strength $f$. It is anticipated that these qubits will act in accordance with the free Hamiltonian $H_0$ given by:

$$H_0 = \frac{\hbar \Omega}{2} \hat{\sigma}_z$$

where $\hbar$ is Planck’s constant, $\Omega$ is the Rabi Oscillation frequency and $\hat{\sigma}_z$ is the Pauli’s $z$-operators:

$$\hat{\sigma}_z = |0\rangle\langle 0| - |1\rangle\langle 1|$$

where $|0\rangle$ and $|1\rangle$ are the upper and lower energy state, respectively. We synchronise the phase oscillation frequencies of the individual qubits with the frequency of the external light field using the one-drive coupling technique [31]. The Rabi Hamiltonian describe how a two-level atom interacts with an optical field as an external oscillator. The Rabi description how a two-level atom interacts with an optical field using the one-drive coupling technique [31]. The Rabi Hamiltonian describe how a two-level atom interacts with an optical field using the one-drive coupling technique [31]. The Rabi Hamiltonian describe how a two-level atom interacts with an optical field using the one-drive coupling technique [31].

$$\hat{H}_{Rabi} = -\hbar \Omega (e^{-i\hat{\phi}} |0\rangle\langle 1| + e^{i\hat{\phi}} |1\rangle\langle 0|)$$

The driving laser’s phase with respect to the synchronising clock’s zero is expressed as $\hat{\phi}$. We obtain the driven Tavis-Cummings Hamiltonian by extending the protocol to a system of three qubits [29]:

$$\hat{H} = \hbar \omega_0 (\hat{n} + 1/2) + \hbar \Omega_1 \hat{\sigma}_z(1)/2 + \hbar \Omega_2 \hat{\sigma}_z(2)/2 + \hbar \Omega_3 \hat{\sigma}_z(3)/2 + g \hbar \omega_0 (\hat{\sigma}_z(1) + \hat{\sigma}_z(2) + \hat{\sigma}_z(3)) (\hat{a} + \hat{a}^\dagger) + f \cos \omega t (\hat{a} + \hat{a}^\dagger),$$

where the three qubits and the resonator’s photons are described in the first four terms, $g$ gives the coupling between the qubits and the photons, and the last term represents the contribution due to driving field. When dissipation is present, the system dissipation rate is $\lambda$, and its quality factor is almost equal to $Q = \omega_0/\lambda \sim 100$ [36]. The driving force amplitude is denoted by the formula $f = \hbar \lambda \sqrt{n_p}$, where $n_p$ is the number of photons present in the resonator at the resonance $\omega = \omega_0$ (for $g=0$). The measurement results of such an interaction often consist of a statistical ensemble of probabilities rather than a single probability. We shall apply the density matrix formalism of quantum mechanics to handle such a circumstance. The master equation describes how such a system is evaluated while taking into account its dissipative character [36], [17], [32]:

$$\frac{d}{dt}\hat{\rho} = \frac{1}{i\hbar} [\hat{H}, \hat{\rho}] + \frac{\lambda}{2} (2\hat{\rho}\hat{a}\hat{a}^\dagger - \hat{a}\hat{a}^\dagger\hat{a}\hat{a} - \hat{a}^\dagger\hat{a}\hat{a}\hat{a}^\dagger + \hat{a}\hat{a}^\dagger\hat{a}\hat{a}^\dagger)$$

where $\hat{\rho}$ is the density matrix of the entire system (qubits and photons), $\hbar$ is Plank’s constant, $\hat{a}$ and $\hat{a}^\dagger$ are the annihilation and creation operators, respectively. In the suggested model, collective dissipation is used. The length of the resonator, the efficiency of the mirror, the atoms inside the resonator, and numerous external conditions all have a role in how much energy is dissipated by such a quantum clock. We presume that the dissipation at each node is comparable and that the synchronisation is unaffected by local influences. This criterion may be met by regulating the temperature of the area around the optical resonator.

Now, we will investigate two of the common synchronisation quantifiers for our model i.e., the spectral density, and the Pearson coefficient.

a) Spectral Density: The spectral density $S(\nu)$ [36]

$$S(\nu) = \left| \int_0^\infty dt \exp\{-i\nu t\} Tr\{\hat{\rho}(\sigma_x(1) + \sigma_x(2) + \sigma_x(3))/2\} \right|^2$$

of laser-driven qubits can be used to analyse the system synchronisation characteristics. It is the observable intensity of the light inside the resonator with frequency $\nu$ for a fixed coupling $g$ and dissipation rate $\lambda$. The state $\rho$ of the system can be obtained by solving the master equation for each time step.

b) Pearson Correlation Coefficient: The Pearson correlation coefficient $C_{xy}$ is another significant measure of synchronisation [11]. It effectively quantifies the linear correlation between two discrete variables $x$ and $y$ according to:

$$C_{xy} = \frac{\Sigma_t (x_t - \bar{x})(y_t - \bar{y})}{\sqrt{\Sigma_t (x_t - \bar{x})^2} \sqrt{\Sigma_t (y_t - \bar{y})^2}}.$$  

Like in [11], for $x$, $y$ we choose the expectation values of the spin $\langle \hat{\sigma}_x(t, q_1, q_2) \rangle$ in $x$-direction at time $t$ for qubits $q_1, q_2$ respectively. The quantity $\bar{x}$ is the average of these expectation values over a time period $\Delta t$:

$$\bar{x} = \sum_{t \in \Delta t} \langle \hat{\sigma}_x(t, q_1) \rangle, \quad \bar{y} = \sum_{t \in \Delta t} \langle \hat{\sigma}_x(t, q_2) \rangle.$$
expectation value of the spin in x-direction can be calculated from the solution \( \hat{\rho}(t) \) of the master equation at time \( t \) by 
\[
\langle \hat{\sigma}_x \rangle(t) = \text{Tr}[\hat{\rho}_i(t) \hat{\sigma}_x],
\]
where \( \hat{\rho}_i(t) = \text{Tr}_{\text{rest}} \hat{\rho}(t) \) is the reduced density operator of the \( i^{th} \) qubit, which is obtained by tracing out the other qubits and the photons. In the simulation the time intervals \( \Delta t \) are overlapped by a smaller interval \( \delta t \) in order to avoid jumps of the Pearson coefficient.

V. Numerical Evaluation

Using the solution of the master equation, we are able to simulate for spectral density and Pearson coefficient. The numerical method for this is presented in the following. To obtain the solution for different time steps, we first reshaped the master equation (6) as a matrix vector multiplication:

\[
\hat{\rho} = \mathbf{V} \tilde{\rho}, \quad \text{where} \quad \tilde{\rho} = \begin{pmatrix} \rho_{0,0} \\ \rho_{0,1} \\ \vdots \\ \rho_{1,0} \\ \rho_{1,1} \\ \vdots \end{pmatrix}
\]

consists of all the entries of the matrix \( \hat{\rho} \). The components can be expressed as \( \rho_i = \rho_{\lfloor \frac{i}{N} \rfloor, i \mod N} \) if \( N \) is the dimension of \( \hat{\rho} \). The coefficients \( V_{a,b} \) of the matrix \( \mathbf{V} \) are

\[
V_{a,b} = \left[ \frac{\hat{H}}{i\hbar} - \frac{\lambda}{2} \hat{a}^{\dagger} \hat{a} \right]_{i,m} \delta_{nj} + \lambda \hat{a}_{i,m} \hat{a}_{n,j} \\
- \left[ \frac{\hat{H}}{i\hbar} + \frac{\lambda}{2} \hat{a}^{\dagger} \hat{a} \right]_{n,j} \delta_{im},
\]

where \( i = \lfloor \frac{n}{N} \rfloor, j = a \mod N, m = \lfloor \frac{m}{N} \rfloor \) and \( n = b \mod N \). We numerically solve the master equation by using a third order Taylor-expansion to determine \( \hat{\rho} \) for a next time step:

\[
\hat{\rho}(t + \Delta t) \approx \begin{pmatrix} 1 + \mathbf{V}(t,g) \Delta t + \left( \mathbf{V}(t,g) + \mathbf{V}^2(t,g) \right) \frac{\Delta t^2}{2} \\
+ \left( \mathbf{V}(t,g) + 2\mathbf{V}^2 + \mathbf{V}^3 \right) \frac{\Delta t^3}{6} \end{pmatrix} \hat{\rho}(t,g)
\]

The time evolution matrix which contains the terms in the rectangular bracket, is periodic in time with the frequency \( \omega \), since it contains its time-dependency from the Hamiltonian. Therefore, after evolving an initial state \( \hat{\rho}(0) \) to one period \( T = \frac{2\pi}{\omega} \), the time evolution matrices will be identical. We can use this periodicity to calculate \( \hat{\rho} \) for many periods fast. Throughout this paper we used a constant time step of \( \Delta t = 0.08 \) and range the simulation from \( t = 0 \) to \( t = 50T \). The initial state \( \hat{\rho}(0) \) is set to the ground states of the qubits and the photons.

a) Spectral density:: We first simulated the spectral density for 10 photons and for different normalised frequencies \( \Omega_1 = 1.2, \Omega_2 = 1.3, \Omega_3 = 0.8, \omega = 1.0 \) and \( \lambda = 0.5 \), figure 13. The associated spectral density has peaks at these frequencies if the qubits oscillate at frequency \( \Omega_{1,2,3} \). The spectral density exhibits dominance at \( \omega \) after the qubits are synced with the laser frequency \( \omega \). This simulation clearly signifies that there is quantum synchronisation possible for a range of coupling constants \( g \) even when atoms are not oscillating at similar frequencies which may be because of local factors. We can clearly observe that the spectral density of oscillation frequencies of individual qubits scatters off after \( g \approx 0.07 \), and a dominance of the spectral density at the external field frequency, with maximum synchronisation (maximum spectral density) at \( g \approx 0.14 \).

b) Pearson Coefficient:: We simulated the expectation values of the spin operator in x-direction \( \langle \hat{\sigma}_x \rangle \) for all three qubits and the corresponding Pearson coefficients \( C_{12}, C_{23} \) and \( C_{13} \), see figure 11, and figure 12 for the qubit states \( \rho(t) \) of the spectral density simulation at \( g = 0.14 \). The other simulation parameters are \( \Delta t = 500, \delta t = 480 \). Since all the Pearson coefficients are close to one after some time, we see that also this synchronisation measure shows strong synchronisation of the qubits with the external field.

c) Parametric Conditions:: After simulating for the spectral density and Pearson coefficients, we evaluated our model for different coupling factors \( g \), collective dissipation factors \( \lambda \), and numbers of photons. We exploited our model to cope up with the engineering perspective of creating such hardware. Particularly, we first evaluated the coupling factors for which maximum synchronisation took place, which can be obtained by the spectral density simulation, with respect to different collective dissipation rates. Then we simulated this for different numbers of photons as shown in figure [13]. Analysing different dissipation rates and coupling factors may lead us in determining the type of atoms and optical resonator (environment) to construct for practically
Fig. 11. Expectation values of spin operators \( \langle \hat{\sigma}_x \rangle(t, q_1, q_2, q_3) \) in the x-direction at time \( t \) for qubits, \( q_1 \), \( q_2 \), and \( q_3 \) respectively. It signifies the possibility of quantum synchronisation after some initial period of time. We see that the phase and amplitude of the observable tends to become equivalent as time approaches infinity.

Fig. 12. Pearson coefficients \( C_{12}, C_{23}, \) and \( C_{13} \) with respect to time. After some initial period, we can observe for all cases the linear correlation between the expectation value of spin variable tends to one, signifying strong synchronisation.

realising it. We observed that for additional photons, we often need a weaker coupling to achieve the best synchronisation.

d) Entanglement fidelity after synchronisation: Further, quantum synchronisation between oscillators implies that there is entanglement between them. We particularly exploited the synchronised density matrix \( \hat{\rho} \) dependent on time for 10 photons, \( \lambda = 0.03 \) and \( g = 0.07 \) to calculate the fidelity \( F = \sqrt{\langle \psi | \hat{\rho} | \psi \rangle} \) between \( \hat{\rho} \) and one of the possible entangled states i.e., the Greenberger–Horne–Zeilinger (GHZ) state

\[
|\psi\rangle = \frac{|000\rangle + |111\rangle}{\sqrt{2}}.
\]

Figure 14 shows the fidelity dependent on the time, which is measured in the periods \( \frac{2\pi}{\omega} \) of the external field. We see that we reach almost \( F = 0.7 \), which means that with a probability of 0.7\(^2 = 0.49 \) state will be in \( |\psi\rangle \). Other types of entangled states apart from the GHZ are also possible in this scenario, which can be investigated in future studies.

VI. Analysis

In order to analyse the stability of our system, we will suppose that a perfectly synchronised clock generates uniformly spaced-apart "ticks." The perfect clock’s ticks occur at periods \( 0, \tau, k\tau, (k+1)\tau, \ldots \), since its tick interval is \( \tau \) while \( K \) is an integer. Every time the standard clock emits a tick, the time of the clock being tested reads its time, and the time-differences are \( \alpha_k, \alpha_{k+1}, \ldots \) at time \( k\tau, (k+1)\tau, \ldots \), respectively. The two-sample standard deviation, also known as the Allan deviation and determined by using the square root of the two-sample zero dead-time variance, is what we advise for employing the stability study of our suggested clock. If there are \( N \) time difference data with indices \( 1, 2, \ldots, N \), then the Allan variance at averaging time \( \tau \) is defined as the average of the \( N - 2 \) calculations, which is as follows:
\[ \sigma_n^2(\tau) = \frac{1}{2(N - 2)\tau^2} \sum_{k=2}^{N-1} (\alpha_{k+1} - 2\alpha_k + \alpha_{k-1})^2 \] (10)

and the square root of this value is the Allan deviation. Figure 15 shows the average number of days required for an Allan deviation of \(10^{-16}\) for a signal with a qubit transition wavelength of \(\lambda = 1.14\mu m\) dependent on the noise strength which is given by the standard deviation of a gaussian distributed random noise. The stronger the noise the higher the deviation from the oscillation’s phase \(\omega = 2\pi/\lambda\) and therefore more time is required to achieve an Allan deviation of \(10^{-16}\).

![Figure 15. Average number of days required to achieve an Allan deviation of \(10^{-16}\) dependent on the strength of the noise applied. The error bars show the standard deviation of the average number of days.](image)

VII. DISCUSSION & FUTURE WORKS

To ensure timely data transfer, enable protocols, and distributed computing, communication networks primarily rely on synchronisation. A network that misses this, especially for real-time systems, is flagged as failed even if the outcome is accurate. The strict latency requirements of contemporary systems are the subject of ongoing research projects like Time-Sensitive Networking (TSN). But having a shared understanding of time among all network devices is a need for TSN (and related standards). The common time synchronisation system known as Precision Time Protocol (PTP), used in TSN, uses GNSS receivers to provide exact time information. Research to improve synchronisation protocols is urgently needed, given the expanding developments in next-generation networks and sophisticated real-time applications.

We use the quantum synchronisation phenomenon to establish temporal synchronisation across three nodes situated at three separate places. We observed that it is possible to stabilise the oscillation frequency of individual qubits. Particularly, we demonstrated how an external drive could help us achieve quantum synchronisation for a set of three qubits. These phase oscillations are fundamental and can provide us time using a protocol like Ramsey interferometry [12].

We establish time synchronisation at the femtosecond level using such a clock system. We show, that the three qubits can be synchronised very well by evaluating their spectral density and Pearson coefficients inside the optical resonators. This means that each qubit oscillates at the same frequency after being synchronised by a single external optical driving field. The quality of synchronisation tells how precise our quantum clock is. The Allan deviation may be used to determine how consistent the accuracy of our clock is over time. We demonstrated the stability of our clock on the order of \(10^{16}\). A quantum clock of this kind will be accurate for a very long time, approximately 300 million years. Further, as our model uses a single coherent laser source for a three-node network. This may lead to a chiral network, as discussed by [15]. A Non-loop ring can well describe our model, i.e., a three-node network with common travelling modes connecting each pair of nodes.

Thus, we formulate the quantum mechanical description of time synchronisation in communication networks. We described the theoretical framework, simulation results, choices for experimental configuration to establish a unique master quantum clock, which will work as T-GM and is distributed over several nodes of the current network infrastructure. We propose to offer accurate and reliable time measurements by exploiting quantum synchronisation to synchronise the oscillation frequencies of the atomic qubits in optical lattice potential traps. We propose expanding the experimental set-up presented by [28] from a single fixed location to our suggested network of three nodes.

After the previous discussion on time synchronisation of a communication network, future works will focus on the simulations for the exact parametric configuration, i.e. the difference between the external field frequency and the Thulium atomic transition frequency inside the optical resonators. Furthermore, from communication network perspective, future work will deal on specific use cases to clarify the quantum advantage and some important related metrics. Let’s consider the synchronisation of Base Stations (BSs) in future generation networks. Normally, the Radio Access Network (RAN) employs time-division duplexing (TDD) to multiplex on a common frequency the uplink signals (from user to Base Station), and downlink signals (from Base Station to user). The network is multi-tier, so different kinds of BSs are in place (macro, micro, etc.). Moreover, the baseband processing of the RAN is virtualised and virtual baseband units (BBUs) are offloaded on to edge data centres [22]. This means a critical part of the PHY processing is performed remotely. By considering verticals with very stringent KPIs (e.g. URLLC services), it is essential to provide ultra-precise timings (in the order of few nanoseconds) and reliable synchronisation approach.

VIII. CONCLUSIONS

In this work, the authors have proposed a time synchronisation approach working on the principle of Quantum Synchronisation. This methodology, which applies quantum physics, may be able to synchronise the current communication network’s time to femtosecond levels. Current state-of-the-art uses PTP for synchronising two-node clocks, which needs prior exact topological information of the clocks and is constrained with several issues as illustrated in previous sections. Our proposed idea can be very beneficial in getting away from the limitations of PTP.
The proposed approach provides a drastic change of perspective in the concept of synchronisation from a ‘classical’ perspective. By the idea of quantum non-locality, the synchronised system is seen as distributed, but it behaves as a unique Master clock. This means that our system is a ‘single’ quantum clock, which synchronises the local oscillators of the network nodes, which could be seen as the ‘classical’ slaves. The first aim of this study was to motivate the application of quantum science in future communication networks. Packet-based solutions like PTP cannot afford the targeted performance. The next goal of this study was to present the notion of employing quantum synchronisation to perfectly synchronise the oscillation frequencies of far-off clocks and, as a result, derive exact time information from them that may be transmitted across the world. Our simulations show that three qubits, each inside an optical resonator, can be synchronised using one coherent external field and thus provide time information to the respective nodes. Further we analysed our model for different parametric configurations which can be seen as a starting point to investigate optimal synchronisation configurations for such a quantum system.

Future use cases which need ultra-low latency communications may be made possible by fully synchronised timekeeping capable of satisfying the more stringent KPIs in complex and heterogeneous future networks. This new approach of synchronisation of node’s clocks can cover a very large geographical area. Hence using the proposed approach, the telecom network will have a unique master quantum clock T-GM distributed at different nodes that can operate as an individual global clock for the whole network. We assume, our proposed systems of quantum mechanically synchronised and entangled qubits at different network nodes can play a benchmark in establishing the quantum network synchronisation in the future classical and quantum communication network.

IX. ACKNOWLEDGEMENT

This work has been partially funded by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) as part of Germany’s Excellence Strategy – EXC2050/1 – Project ID 390696704 – Cluster of Excellence “Centre for Tactile Internet with Human-in-the-Loop” (CeTI) of Technische Universität Dresden. The authors also acknowledge the financial support by the Federal Ministry of Education and Research of Germany in the programme of “Souverän. Digital. Vernetzt.”. Joint project 6G-life, project identification number: 16KISK001K. This work was also funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), projects “TICCTEC” – grant 01MC22007A, “5G-OPERA” – grant 01MJ22008A, and “stic5G” – grant 01MJ22018C, and by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) as part of Germany’s Excellence Strategy – EXC 2050/1 – Project ID 390696704 – Cluster of Excellence “Centre for Tactile Internet with Human-in-the-Loop” (CeTI) of Technische Universität Dresden.

ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>BMC</td>
<td>Best-Master-Clock.</td>
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<td>BS</td>
<td>Base Station.</td>
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<td>E2E</td>
<td>End to End.</td>
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<td>ECDF</td>
<td>Empirical Cumulative Distribution Function.</td>
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<td>GCL</td>
<td>Gate Control List.</td>
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<td>GHZ</td>
<td>Greenberger–Horne–Zeilinger.</td>
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<td>GM</td>
<td>Grand Master.</td>
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<td>GNSS</td>
<td>Global Navigation Satellite System.</td>
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<td>IoT</td>
<td>Internet of Things.</td>
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<tr>
<td>KPI</td>
<td>Key Performance Indicator.</td>
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<td>LAN</td>
<td>Local Area Network.</td>
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<td>LO</td>
<td>Local Oscillator.</td>
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<td>NTP</td>
<td>Network Time Protocol.</td>
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<td>P2P</td>
<td>Peer to Peer.</td>
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<td>PHY</td>
<td>Physical layer.</td>
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<td>PLL</td>
<td>Phase Locked Loop.</td>
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<tr>
<td>PTP</td>
<td>Precision Time Protocol.</td>
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<tr>
<td>QoS</td>
<td>Quality-of-Service.</td>
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<td>RAN</td>
<td>Radio Access Network.</td>
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<td>SyncE</td>
<td>Synchronous Ethernet.</td>
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<td>T-GM</td>
<td>Telecom Grandmaster.</td>
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<td>T-TSC</td>
<td>Telecom Time Slave Clock.</td>
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<td>TAS</td>
<td>Time-aware Shaper.</td>
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<tr>
<td>TI</td>
<td>Tactile Internet.</td>
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<tr>
<td>TSN</td>
<td>Time-Sensitive Networking.</td>
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<tr>
<td>URLLC</td>
<td>Ultra-Reliable Low-Latency Communication.</td>
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<tr>
<td>WAN</td>
<td>Wide Area Network.</td>
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