Computer Networks 254 (2024) 110734

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Satellite-based positioning enhanced by quantum synchronization ☆

Swaraj Shekhar Nande [a,c,*], Tommaso Rossi [d], Muhammad Idham Habibie [a,c], Mohamed Barhoumi [a,c], Krishna Palaparthy [a], Wassim Mansouri [a,c], Ashwin Raju [a,c], Riccardo Bassoli [a,b,c], Ernestina Cianca [d], Frank H.P. Fitzek [a,b], Mauro De Sanctis [d]

[a] Deutsche Telekom Chair of Communication Networks, Institute of Communication Technology, Faculty of Electrical and Computer Engineering, Technische Universität Dresden, Dresden, Germany

[b] Centre for Tactile Internet with Human-in-the-Loop (CeTI), Cluster of Excellence, Dresden, Germany

[c] Quantum Communication Networks (QCNets) research group, Institute of Communication Technology, Faculty of Electrical and Computer Engineering, Technische Universität Dresden, Dresden, Germany

[d] Department of Electronics Engineering, University of Rome Tor Vergata, Rome, Italy

ARTICLE INFO

Keywords:
Quantum communication networks
Time synchronization
Quantum synchronization
Satellite communication
Localization
Time-sensitive networking
Optical lattice clock

ABSTRACT

This study focuses on the innovative field of quantum synchronization for satellite-based navigation systems including Global Navigation Satellite Systems (GNSSs) and the Non-Terrestrial Network (NTN) component of future 6G networks integrating both communication and navigation services.

By combining a four-qubit system with the theoretical approach of the Lindblad master equation, we transcend the inherent limits of standard synchronization techniques. This achievement represents a quantum leap in satellite-based positioning, highlighting the scalability and cost-effectiveness of our technique for smaller satellites. The study demonstrates the possibility of reducing synchronization errors to less than one meter, significantly improving the reliability and precision of satellite-based navigation systems.

The results of this study may contribute to the future development of both user-centric localization systems (typically GNSS systems) and network-centric localization systems (typically through the NTN component of 6G networks), leading to better positioning performance, more flexible multi-functional systems with the potential to limit both cost and size of satellites.

1. Introduction

Network-centric positioning and user-centric positioning are two different approaches to estimating the location of a user's device through radio signal measurements. The location estimate process in network-centric positioning mostly occurs within the network infrastructure, which is usually under the control of the network operator or service provider. Using uplink signals transmitted by the user's device, network-centric positioning can provide accurate location estimates even for devices with limited computational capabilities, such as Internet of Things (IoT) devices. In user-centric positioning, the location estimation process occurs primarily on the user's device using downlink signals transmitted by the network infrastructure. The Global Navigation Satellite System (GNSS) is a common example of user-centric positioning [1]. For user-centric and network-centric localization systems, several measurements may be employed to form a system of Equations and solve for the unknown user-device position.

On one hand, to accurately compute the distance between the navigation receiver and each GNSS satellite employing time measurements such as time of arrival (TOA) or time difference of arrival (TDOA) [2], precise timing synchronization between GNSS satellites is essential. On the other hand, other Equations based on frequency measurements named frequency difference of arrival (FDOA) [3] may be included in

☆ 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. Joint project QSyncNextG, project identification number: 01MO23031C.

* Corresponding author at: Deutsche Telekom Chair of Communication Networks, Institute of Communication Technology, Faculty of Electrical and Computer Engineering, Technische Universität Dresden, Dresden, Germany.

E-mail addresses: swaraj_shekhar.nande@tu-dresden.de (S.S. Nande), tommaso.rossi@uniroma2.it (T. Rossi), muhammad_idham.habibie@tu-dresden.de (M.I. Habibie), mohamed.barhoumi@tu-dresden.de (M. Barhoumi), palaparthy.krishna@mailbox.tu-dresden.de (K. Palaparthy), wassim.mansouri@tu-dresden.de (W. Mansouri), ashwin.raju@tu-dresden.de (A. Raju), riccardo.bassoli@tu-dresden.de (R. Bassoli), ernestina.cianca@uniroma2.it (E. Cianca), frank.fitzek@tu-dresden.de (F.H.P. Fitzek), mauro.de.sanctis@uniroma2.it (M. De Sanctis).

https://doi.org/10.1016/j.comnet.2024.110734
Received 15 March 2024; Received in revised form 12 July 2024; Accepted 19 August 2024
Available online 31 August 2024

the system of equations to estimate the user-device position. In any case, precise time synchronization and clock/frequency synchronization between navigation satellites is required for both user-side and network-side localization.

Herein, atomic clocks (they are a type of clock that uses the vibrations of atoms to measure time) on board GNSS satellites play a crucial role by providing highly accurate timekeeping [4]. They are based on quantum transitions at microwave frequencies between hyperfine levels in the ground state of the atoms. However, an atomic clock is expensive and has a relatively large size, which does not allow us to carry it on board small and low-cost satellites. Quantum synchronization (QS) represents an interesting new approach to support satellite-based localization systems using low-cost small satellites (e.g., CubeSats) [5].

The introduction of quantum technology heralds new possibilities for satellite communication networks, particularly in synchronization-a vital component for the effectiveness of location manager functions (LMF) within GNSS [6,7]. While adequate to some extent, traditional synchronization approaches fall short of the rising precision requirements in current network infrastructures [8]. It should be noted that the location manager (LM) is a component of the 5G core network functions (CNFs). It is responsible for managing and providing location information to User Equipment (UEs) and other network entities [9]. Also, LM calculates the location of UEs using GNSS. LMF and synchronization are essential components of 5G networks, enabling various applications and services that rely on accurate timing and location information. By providing precise location information and ensuring network synchronization, these functions enhance the overall user experience and improve network performance.

In classical systems, the synchronization includes the adjustment of oscillator rhythmic oscillations to external perturbations such as electromagnetic radiation. This phenomenon has been observed in vacuum tube radio generators, pendulum clocks, and bioluminescent animals such as fireflies, is characterized by oscillators' inherent activity and self-sustainability, which is attributed to their physical features and internal energy sources [10,11]. Moreover, the classical synchronization methods [12,13] often introduce latency [14], which can delay the transmission of data or signals between devices in a traditional communication systems. Among these methods, we underline, e.g., atomic clocks, global positioning system (GPS), software-based solutions, network time protocol (NTP) and precision time protocol (PTP). Although these methods are crucial for decreasing latency and enhancing precision, they have several limitations. For instance, atomic clocks (they use the energy levels of atoms to measure time) can be influenced by external sources of radiation, e.g., electromagnetic interference (EMI) or gravitational waves [15]; where a strong magnetic field or a nearby radio transmitter can cause the atoms to vibrate slightly differently, affecting the clock's accuracy [16]. Also, atomic clocks can be affected by various environmental factors like temperature changes and vibrations, which can cause slight deviations in their timekeeping. In the GPS case, GPS signals can be affected by satellite signal interference, which can cause errors in timing synchronization [17]. GPS receivers can raise noise and jitter into the timing signal, decreasing synchronization accuracy. Furthermore, GPS depends on a network of satellites, which can be impacted by solar energy [18], maintenance, and repairs on the satellites, which could cause synchronization problems or service disruptions.

On the other side, NTP is a protocol employed to synchronize the time and date of computer systems over a network. It is a widely operated protocol that lets devices synchronize their clocks with a reference clock, typically a server or a time source, to confirm that their local clock is accurate. However, NTP can only provide an accuracy of around 10–100 ms, which may not be adequate for applications requiring high-precision timing. NTP depends on an individual reference clock (commonly an atomic clock) to provide time synchronization. If this clock fails, the whole network's time synchronization may be compromised. Instead of NTP, the PTP network protocol (like IEEE 1588-2008 (PTPv1) and IEEE 1588-2019 (PTPv2)) is used for synchronizing clocks in a network, allowing devices to maintain accurate and precise timekeeping. Nevertheless, PTP needs a reliable, low-latency network in order to ensure precise clock synchronization. Errors and time drift may occur from high network latency. PTP can achieve an accuracy of nanoseconds with a typical network and clock stability. High-precision time synchronization in order of subpicosecond or femtosecond is crucial for improving the classical communication network. Notice that high-precision time synchronization ensures that all clocks are aligned, which is essential for reliable data transmission and reception. In this direction, to address these limitations, newer technologies like quantum-based timing systems are being developed to provide even higher accuracy and reliability in synchronizing time. Here QS is a more recent development that leverages quantum mechanics to synchronize clocks [19,20]. QS is a process that uses quantum mechanics to synchronize clocks or other physical systems. It employs entangled particles or qubits to transmit quantum information between two clocks, permitting extremely accurate synchronization. A quantum-enabled GPS system could potentially achieve higher accuracy and robustness compared to traditional GPS systems. Synchronization methods based on entanglement have been extensively investigated [21]. Besides, clock synchronization based on entanglement has already been investigated for localization feature [6]. In this way, QS can be used for enhancing the accuracy of location estimation in various applications, e.g., quantum-assisted localization.

For the localization of UE in a 3D space, considering that the UE is not synchronized with the network nodes, TOA or TDOA measurements operating at least four synchronized nodes (e.g., four-qubit are located at different nodes in our case) are required to solve the system of equations and estimate the UE location since the number of unknowns is four, i.e. $x_{\text{ref}}, y_{\text{ref}}, z_{\text{ref}}$, and δT (where $x_{\text{ref}}, y_{\text{ref}}, z_{\text{ref}}$ are the unknown coordinates) and δT is the synchronization error of the UE concerning the network nodes.

The four-qubit system provides a comprehensive framework for modeling the dynamics of synchronized qubits, enabling an extensive exploration of synchronization processes under various conditions. In this framework, we employ it to determine the UE location based on the Trilateration method. Rooted in the *Lindblad master equation (LME)*, our methodology (see Sections 2.2.3–2.2.5) offers a robust depiction of quantum states' evolution within dissipative environments, ideal for modeling complex interactions within satellite communication networks [22]. Note that the synchronization of three-qubits has already been investigated by Swaraj et al. [7,8], where they precisely synchronized three-qubits to transfer the time information between three satellites (each one contains one qubit), using QS. In this work, we move further steps by synchronizing four-qubits, where the Lindblad master equation [23,24] with a specific collapse (to describe the dissipation) are used to accomplish a coherent synchronization state across the qubits. Herein, we consider a constellation of four satellites and investigate the positioning errors generated by the synchronization and ephemeris errors. Our study indicates that QS systems may achieve synchronization errors below one meter, which leads to a highly accurate location.

2. Related work

QS, a phenomenon resulting from nonlinear interactions among quantum oscillators, has received much attention for its potential applications in advanced communication systems and quantum networks. Lohe [25] established phase synchronization in quantum systems, challenging the traditional view that synchronization in quantum oscillators with constant linear interactions is impossible. This was a foundational milestone. Subsequent research has focused on the dynamics of dissipative quantum systems, emphasizing the need for designed nonlinear dissipation and coherent management in establishing QS. Koppenhöfer et al. [26] demonstrated the experimental realization of

QS via digital quantum simulation, which is a crucial step towards practically implementing QS in technology platforms.

Furthermore, research into spin-based networks and the fundamental constraints of synchronization in quantum systems has provided new insights into the transition from quantum to classical synchronization behaviors. This paper not only investigates the potential of spin-1 systems in capturing the key properties of QS, but also introduces unique synchronization blockade events due to quantum interference effects [27].

The optical lattice clock (is a type of atomic clock that uses a lattice of photons to trap and cool atoms, allowing for extremely precise timekeeping) framework provides extensive ground for the exploitation of phenomena like QS. The study by Origlia et al. (2018) [28] demonstrates a significant advancement in optical lattice clocks (OLCs) by achieving a fractional uncertainty of 2.0×10^{-17} using bosonic strontium atoms. This study demonstrates a 30-fold increase in the performance of bosonic OLCs, highlighting their potential for use in fundamental physics and satellite navigation systems. The precise measurement of the isotope shift between ^{88}Sr and ^{87}Sr with a precision of 12 mHz emphasizes the OLC's metrological capabilities. This achievement paves the way for the deployment of high-precision clocks in space, which will transform global time transfer, geodesy, and the search for dark matter. Furthermore, Schuldt et al. (2021) [29] investigate the advantages of incorporating optical technology, namely optical clocks, into GNSS. These innovations could improve GNSS position determination and enable new GNSS architectures by reducing frequency instabilities and synchronizing distant optical frequency references. The combination of optical clocks with optical inter-satellite communication implies a future where GNSS dependability and precision significantly enhanced.

These studies show the potential for employing quantum mechanical aspects to improve synchronization in communication networks, notably satellite communications and positioning systems. The inclusion of QS into these areas promises to overcome the limitations of current synchronization technologies (see Section 1), resulting in exceptional precision and efficiency.

2.1. Localization overview

Accurately locating items and individuals has become a crucial requirement in the rapidly developing field of wireless technology; applications range from the vital functionality of emergency response to the smooth operation of asset tracking and navigation systems. Here Trilateration is a technique that uses the distances between a point and several reference points to determine the position of a point or item [30]. It is a method of using the distances between three or more known locations to triangulate a position. There are mainly two kinds of trilateration; Triangulation and Hyperbolic Trilateration (this concerns obtaining the location of an object by calculating the distances from the object to three or more reference points). Also, it is commonly employed in different fields [31], e.g., Trilateration is operated to determine the location using GPS signals from multiple satellites (see Fig. 1). Procedures in the Trilateration Process:

- Calculate the distances from the object to three or more reference points. These distances can be estimated employing different techniques such as GPS, etc.
- Compute the center of each sphere employing the measured distance and the coordinates of the reference point.
- Locate the intersections of several spheres. These points show possible locations for the item.
- Remove any solutions that do not fit with other limitations, obstacles or barriers.
- Iterate through steps 2–4 to refine the position until only one solution is left.

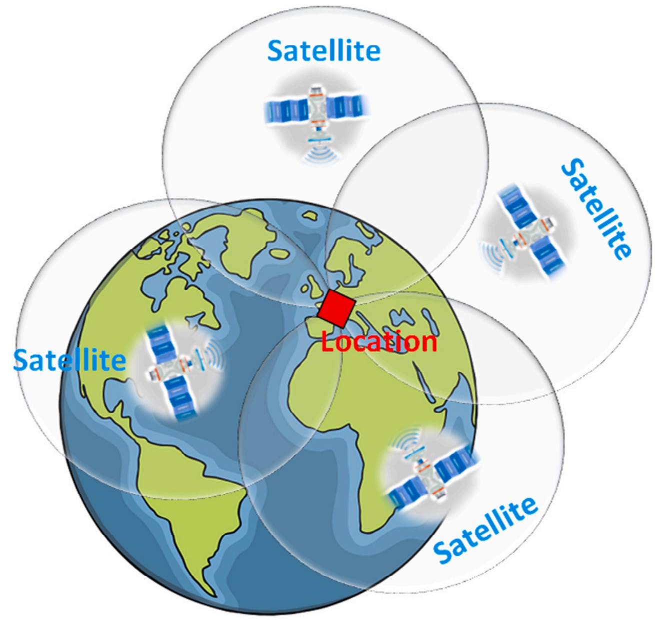

Fig. 1. GPS position (location) relies on trilateration to determine a user's location using signals received from multiple satellites.

In this subsection, two localization algorithms based on time of arrival measurements will be reported. These algorithms have been used in this work to test the localization performance of satellite-based positioning relying on QS technologies.

2.1.1. Time of Arrival (ToA)

The time of Arrival (ToA) localization method hinges on the straightforward notion that the distance between a transmitter and a receiver can be directly calculated by multiplying the measured time taken for a signal to travel between them by the known propagation speed (typically the speed of light). For satellite-based positioning, the basic measurement is the time elapsed between the transmitter (UE) and the receiver (Satellite) [32]. As it noted, $c = 3\times10^8$ m/s, representing the speed of light. Therefore, knowing the radio frequency f, we can estimate the distance d using the formula $d = c\times t$. Thus, considering that the time at the unknown device is indicated as t_u and the time at the satellite side is t_s, the TOA can be written as follows:

$$\mathrm{ToA} = t_u - t_s. \tag{1}$$

For accurate localization to determine the unknown position within the network, a minimum of three satellites is required. This results in three-time arrivals at satellite sides denoted as $t_{s,j}$, where j is the index representing the number of satellites, and J represents the total number of satellites. Let us consider $J = 3$, and assume the unknown position is denoted as $(x_{\mathrm{ref}}, y_{\mathrm{ref}})$. The locations of the satellites are denoted as $(x_{s,j}, y_{s,j})$ respectively, where $j\in J$ represents the satellite index. The objective is to determine the unknown position using signals from three satellites. Thus, the formula is defined as:

$$d_j = \sqrt{(x_{\mathrm{ref}} - x_{s,j})^2 + (y_{\mathrm{ref}} - y_{s,j})^2}. \tag{2}$$

In this case, we can have t_j, which is denoted as:

$$t_j = \frac{d_j}{c}; \qquad j = 1,2,3. \tag{3}$$

A high degree of synchronization between the transmitter and receiver is required for precise ToA measurements. This synchronization ensures that any measured time difference solely reflects the propagation time and not discrepancies arising from clock inaccuracies. ToA main applications are in GNSS and radar systems.

2.1.2. Time Difference of Arrival (TDoA)

ToA uses the time difference between the transmitter and receiver to determine arrival time, whereas Time Difference of Arrival (TDoA) introduces the difference in arrival times at two transmitters. The measurement is done by comparing arrival times at multiple receivers. For example, following the ToA, it could be written as follows [32]:

$$d_j - d_{j+1} = \sqrt{(x_{\text{ref}} - x_{s,j})^2 + (y_{\text{ref}} - y_{s,j})^2} - \sqrt{(x_{\text{ref}} - x_{s,j+1})^2 + (y_{\text{ref}} - y_{s,j+1})^2}. \quad (4)$$

$d_j - d_{j+1}$ is also equivalent to $c \times (t_j - t_{j+1})$.

Once we have calculated all the potential results, we can create a hyperbolic graph, where the graph will identify subsets of different sections. Using this method, we can determine the location effectively [33]. TDOA offers higher operational flexibility compared to TOA because it does not necessitate a direct line-of-sight path between the source and each receiver, making it suitable for scenarios with obstructions or complex environments but synchronization among the receivers within the network is required. TDoA provides precise location estimation, mainly in urban environments where GPS signals may be weak or inaccessible.

2.2. Quantum overview

This subsection addresses the basics of quantum mechanics, detailing the interaction of qubits with external fields, methods for calculating synchronization performance, and other related concepts. We also describe the mechanism of QS, including notation and the synchronization process over a constellation of four-qubits with an external light field using inter-satellite links (ISL). The main principle of QS involves the dynamics of quantum oscillators, which balance energy absorption and dissipation in limit cycle oscillations [34], which will be explained in the following sub-subsections.

2.2.1. Quantum notation

In quantum computing, a bit stores information depending on the determined state in which it is 0 or 1. A quantum bit (called also qubit) due to the superposition principle is in an indeterminate state (can be for instance, pure spin states $|-1\rangle, |0\rangle, |1\rangle$ or mixed spin-states $\neq |-1\rangle, |0\rangle, |1\rangle$) [35–38]. Notice that qubit stores both a 1 and a 0. In our situation, the qubits are used as our self-sustained oscillators. The Bloch sphere, which is depicted in Fig. 2, is employed to determine oscillation for a qubit. The Bloch sphere, a graphical representation of the phase rotation cycle that a qubit exhibits as it changes over time. The points inside the sphere represent the mixed states, while the points on the sphere's surface represent the pure states. Here the probability of the system is defined by $\langle\psi|\psi\rangle = 1$ and the state $|\psi\rangle$ is represented by

$$|\psi\rangle = \cos(\frac{\theta}{2})|0\rangle + e^{i\varphi}\sin(\frac{\theta}{2})|1\rangle. \quad (5)$$

where $\theta(\in [0,\pi])$ and $\varphi(\in [0,2\pi])$ are azimuthal and polar angles, respectively. Here, a state vector is moved from the lower state to a particular point on the equatorial plane of the Bloch sphere by the unitary operator known as the Hadamard operator. To have fully synchronized qubits, we need to let them grow at a similar rate such that their phase difference is almost zero. In our case, the quantum synchronized qubits distributed at different network nodes are achieved. Indeed, to achieve time synchronization, a system of qubits oscillating at similar frequencies needs to provide equal temporal information. Overall, the QS technique, e.g., based on the Lindblad master equation (Eq. (10)) provides the essentially synchronized oscillation frequency to each qubit. Notice that the dissipation (in classical mechanics), which causes coupled autonomous systems with an energy supply to phase synchronize, is a crucial component of synchronization. Therefore, dissipative quantum mechanics formalism needs to be used to analyze QS. This formalism is well-known and depends on the density matrix $\hat{\rho}$ Lindblad master equation [39] explained in Section 2.2.5.

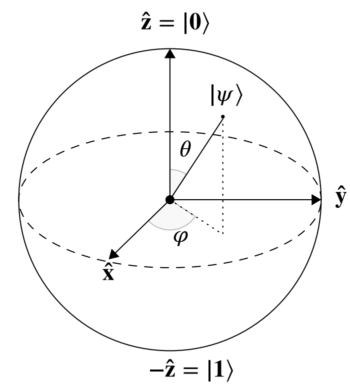

Fig. 2. Bloch sphere representation of a pure single qubit state $|\psi\rangle$.

2.2.2. Energy dynamics

In the quantum domain, oscillators achieve synchronization through mechanisms fundamentally distinct from their classical counterparts. This unique synchronization, manifesting as limit cycle oscillations, emerges from the delicate balance of energy within the system. In this case, the essence of QS is the dynamic equilibrium between energy absorption and dissipation [34]. This balance is crucial for sustaining limit cycle oscillations in quantum oscillators, showcasing the system's capability to maintain such oscillations under diverse conditions. This remarkable attribute of QS leverages coherent interactions within the oscillator, governed by the principles of quantum mechanics. This provides a significant advantage over conventional synchronization methods in critical applications [40,41]. Limit cycle oscillations arise when a system has a nonlinear feedback mechanism.

The synergy between pumping (energy absorption) and dissipation stabilizes limit cycle oscillations, facilitating a profound comprehension of QS phenomena. This includes the development of QS measures that encapsulate the coherence between energy eigenstates, indicative of the phase localization essential for synchronization [42].

The integration of QS into satellite navigation systems illustrates its potential to transform precision timing and positioning technologies fundamentally. The consistent amplitude of limit cycle oscillations enables quantum oscillators to function as dependable reference signals for accurately determining satellite positions. This precision is vital in GPS, where even minor inaccuracies can lead to significant navigational errors, emphasizing the transformative impact of QS on modern technological landscapes.

2.2.3. Interaction dynamics with external optical field

We should find the balance of the interaction between atomic qubits and the external optical field, defined as the strength parameter f. Our work involves this aspect, which is the main principle of QS. This relationship follows the criteria defined by the free Hamiltonian H_0:

$$H_0 = \frac{\hbar\Omega}{2}\hat{\sigma}_z, \quad (6)$$

where $\hbar$ symbolizes the reduced Planck constant, Ω represents the frequency of Rabi oscillations, and $\hat{\sigma}_z$ denotes Pauli's z-operator. This operator is critical in defining the energy states of the qubits, illustrating the quantum system's foundational dynamics:

$$\hat{\sigma}_z = |0\rangle\langle 0| - |1\rangle\langle 1|. \quad (7)$$

Through the application of a one-drive coupling technique, we synchronize the qubits' phase oscillation frequencies to the external field's frequency, a process governed by the Rabi Hamiltonian $\hat{H}_{Rabi}$ as follows:

$$\hat{H}_{Rabi} = -\hbar\Omega(e^{-i\varphi_j}|0\rangle\langle 1| + e^{i\varphi_j}|1\rangle\langle 0|), \quad (8)$$

where φ_j correlates with the phase of the driving laser, relative to a predefined synchronization reference.

2.2.4. The driven Tavis–Cummings model for a four-qubit system

Extending our analysis to a four-qubit assembly necessitates an augmented Tavis–Cummings Hamiltonian [43,44], which intricately captures the qubit–photon coupling and the influences of an external driving field:

$$\begin{aligned}\hat{H} =& \hbar\omega_0(\hat{n} + \frac{1}{2}) + \sum_{i=1}^{4} \frac{\hbar\Omega_i}{2}\hat{\sigma}_z^{(i)} \\ &+ g\hbar\omega_0 \sum_{i=1}^{4} \hat{\sigma}_x^{(i)}(\hat{a} + \hat{a}^\dagger) + f\cos(\omega t)(\hat{a} + \hat{a}^\dagger),\end{aligned} \tag{9}$$

integrating the resonator's frequency ω_0, each qubit's Rabi frequency Ω_i, their respective Pauli operators. g is the coupling constant between the qubit and the photon. The annihilation and creation operators $\hat{a}$ and $\hat{a}^\dagger$, respectively. $f = \hbar\lambda\sqrt{n_p}$ is the driving force amplitude (n_p is the number of photons in the resonator at the resonance $\omega = \omega_0$, where $g = 0$). λ is the dissipation rate in the resonator.

2.2.5. Lindblad equation and dissipation dynamics

In our situation, *the Lindblad master equation (LME)* is used to determine the spectral density, which indicates the synchronization of the qubits. *LME* captures both types of dissipation, allowing us to study the dynamics of open quantum systems in a rigorous and precise manner. Therefore, it is employed to describe the dynamics of open quantum systems, which are quantum systems interacting with their environment. It is a stochastic equation that describes how the density matrix of the system evolves over time in the presence of decoherence and dissipation [45].

The evolution of our system, encapsulating dissipation effects, is adeptly modeled by the master equation:

$$\frac{d}{dt}\hat{\rho} = \frac{1}{i\hbar}[\hat{H}, \hat{\rho}] + \frac{\lambda}{2}(2\hat{a}\hat{\rho}\hat{a}^\dagger - \hat{a}^\dagger\hat{a}\hat{\rho} - \hat{\rho}\hat{a}\hat{a}^\dagger), \tag{10}$$

with $\hat{\rho}$ representing the density matrix of the entire qubit–photon system and λ denoting the dissipation rate. The first-term on the right-hand side represents the unitary evolution of the system, described by the Hamiltonian $\hat{H}$. The second, third, and fourth terms on the right-hand side represent the dissipative interactions between the system and its environment. This equation is critical for understanding the QS in our system, taking into account both coherent interactions and the unavoidable fact of dissipation. Notice that the dissipation dynamics refers to the investigation of how an open quantum system loses its coherence and energy due to interactions with its environment.

This equation is essential for understanding the long-term behavior of quantum systems in synchronization applications because it reveals vital information about equilibrium dynamics, energy distribution, and synchronization efficiency. Indeed, *LME* can be employed to identify the conditions under which synchronization occurs and analyze the stability of synchronized states. Furthermore, it helps us to understand how environmental noise and system parameters affect the synchronization process.

In our calculations, we solve *LME* using *python environment*, where we define the Hamiltonian and Lindblad operators, initialize the density matrix, and set up a time array and solution array.

2.3. Signature of synchronization

The spectral density ($S(\omega)$) is indispensable for analyzing the energy distribution across frequencies within our four-qubit satellite system, offering crucial insights into the QS dynamics. $S(\omega)$ is essential for understanding how coupled qubits interact and synchronize with each other. Defined by the Fourier transform (is employed to convert time-domain data into frequency-domain data) of the auto-correlation function of an observable, the spectral density for our system described by the raising and lowering operators $\sigma_+(t)$ and $\sigma_-(t)$, is mathematically expressed as:

$$S(\omega) = \int_{-\infty}^{\infty} e^{-i\omega t}\langle\sigma_+(t)\sigma_-(0) + \sigma_-(t)\sigma_+(0)\rangle dt, \tag{11}$$

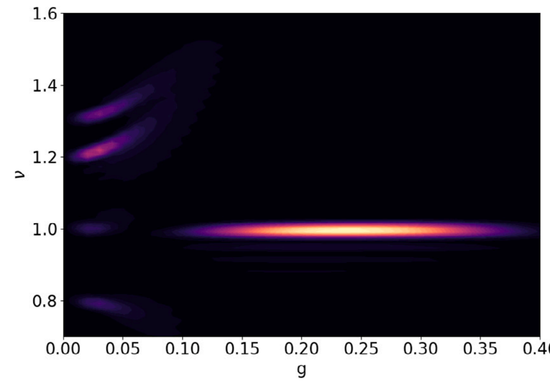

Fig. 3. Spectral density $S(\nu) = f(g)$: Spectral density of a system consisting of three-qubits and 11 photons at a driving frequency of $\omega = \omega_0 = 1.0$, a dissipation rate $\lambda = 0.8$ and Rabi-Oscillation frequencies $\Omega_1 = 1.15$, $\Omega_2 = 1.2$, $\Omega_3 = 0.9$.

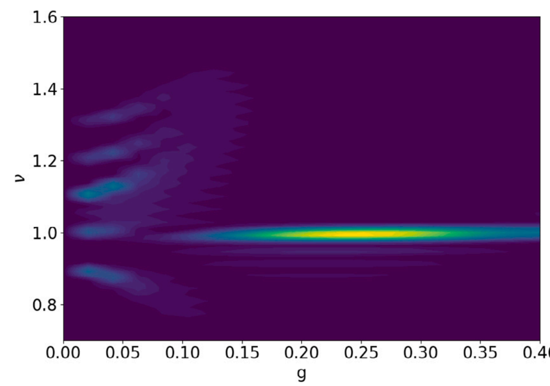

Fig. 4. Spectral density $S(\nu) = f(g)$: Spectral density of a system consisting of four-qubits and 11 photons at a driving frequency of $\omega = \omega_0 = 1.0$, a dissipation rate $\lambda = 0.8$ and Rabi-Oscillation frequencies $\Omega_1 = 1.2$, $\Omega_2 = 1.3$, $\Omega_3 = 1.1$, and $\Omega_4 = 0.9$.

the expectation value $\langle ... \rangle$ encompasses the quantum state dynamics and interactions with external fields. This equation facilitates the exploration of resonance phenomena and energy exchange mechanisms critical for evaluating synchronization efficiency and stability across the satellite network.

Fig. 3 displays a spectral density plot for a system with three quantum bits (qubits). The g on the horizontal axis indicates how strongly each qubit interacts with the light field, while the ν on the vertical axis shows the frequency. As the interaction gets more strong, the colors change, indicating that the qubits align their rhythms with the light's frequency. The best synchronization of the three-qubits appears when the frequency is $\nu = 1$ and the coupling strength g vary from 0.12–0.36, which corresponds to the weak coupling. Note that when qubits interact with one another in a way that is neither very strong nor very weak, it is referred to as having a weak coupling strength. In quantum computing, this is frequently preferred because weak coupling helps minimize the loss of quantum coherence due to unwanted interactions with the environment.

We create further step, synchronizing four-qubits (q_1, q_2, q_3, q_4) employing *LME*. The spectral density $S(\nu)$ of the system consisting of four-qubits as a function of the coupling strength $f(g)$ is sketched in Fig. 4. As clearly seen in this figure, the qubits are not synchronized when g is varied between 0.0 and 0.10. However, they are synchronized when $g \in [\sim 0.12, \sim 0.40]$ with frequency of $\nu = 1$. By comparing with the case of synchronization of three-qubits, we demonstrate that the synchronization depends on the coupling strength, where if the number of qubits increases, the synchronization interval as a function of g increases (i.e., three-qubits well synchronized only when $g \in$

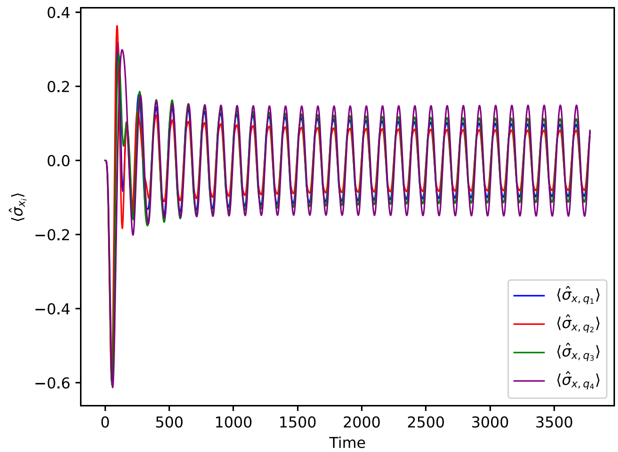

Fig. 5. Expectation values of spin operators $\langle\hat{\sigma}_x\rangle$ in the x-direction at time t for qubits, q_1, q_2, q_3, q_4. The phase and amplitude of the observable are well synchronized, especially when $t \geq 400$.

$[\sim 0.12, \sim 0.36]$, while the best synchronization of four-qubits appears when $g \in [\sim 0.12, \sim 0.40]$).

The synchronization of the four-qubits is confirmed by computing the expectation values of spin operators $\langle\hat{\sigma}_x\rangle$ over time t. $\hat{\sigma}_{x,q_1}$ (blue line), $\hat{\sigma}_{x,q_2}$ (red line), $\hat{\sigma}_{x,q_3}$ (green line), and $\hat{\sigma}_{x,q_4}$ (purple line) are depicted in Fig. 5. Here λ, Ω_1, Ω_2, Ω_3, and Ω_4 are fixed to 0.8, 1.2, 1.3, 1.1, and 0.9, respectively. We choose g as 0.23 since $S(\nu)$ shows a good synchronization under this coupling (as shown in Fig. 4), and the best synchronization appears in a weak coupling regime [8]. Under these values, we find that $\hat{\sigma}_{x,q_1}$, $\hat{\sigma}_{x,q_2}$, $\hat{\sigma}_{x,q_3}$, and $\hat{\sigma}_{x,q_4}$ are synchronized when the time $t \geq 400$ (where the phase and amplitude of these spin operators begin to become equivalent as time approaches infinity).

This synchronization is crucial for the coordinated performance of quantum systems and serves as a cornerstone for advanced quantum network functionalities. Here, we show the simulation results for three (or four)-qubit synchronization. It should be noted that synchronization in higher numbers of qubits has already been demonstrated [46].

3. System model

We envision a constellation of four satellites, each containing a single qubit, which aims to locate the unknown position of the UE. These satellites are linked together by optical inter-satellite links (ISLs), which serve two functions: high-bandwidth data communication and QS. The full systematic figure is given in Fig. 6. Our step approach is given as follows:

1. QS
   Initially, we simulate the synchronization of four-qubits using ISL links among the four satellites respectively, denoted as $|\psi_1\rangle, |\psi_2\rangle, |\psi_3\rangle, |\psi_4\rangle$.
2. By utilizing the Lindblad Master Equation (Eq. (10)) and the Hamiltonian Equation (Eq. (9)), we can achieve a coherent synchronization state across the qubits, verified through spectral density analysis (Eq. (11)), ensuring a robust quantum entanglement network.
3. The UE thus sends signals to all four satellites, and the satellites identify its ToA. The total ToA at each particular satellite is defined as the time reference t_j, where j denotes the index of the satellite, and is then added to the propagation time, denoted as $t_{\text{prop,j}}$. Indeed, the UE transmits a signal to the nearest satellite, which is received by the satellite's transponder. Then, the signal is amplified and transmitted to the next satellite in the constellation. As the UE moves from one area to another, it will hand over its connection from one satellite to another. This process is called handover or handoff. The UE will continuously calculate the signal strength and quality from each satellite and select the best one to maintain communication. Once the signal is received by the second satellite, it is transmitted to the third satellite, and so on, until it reaches the final destination. Herein, ISL enables data transfer between satellites, allowing for efficient communication.
4. All satellites execute an algorithm, such as trilateration, to calculate the position and identify the unknown location of the UE.
5. The satellite evaluates the performance and errors based on the calculated position.

3.1. Synchronization errors and frequency stability

Quantum synchronization offers highly precise atomic clocks, surpassing classical ones in accuracy. However, quantum systems are intrinsically noisy and prone to decoherence, which can lead to errors in the synchronization process. Therefore, synchronization errors can occur, which means there is a desynchronization between the frequencies of these quantum systems. The synchronization error is directly related to the frequency stability of a quantum atomic clock. The frequency stability refers to the ability of a clock to keep its frequency over time. It is essential because it directly influences the accuracy of the clock's timekeeping. By minimizing synchronization errors, investigators can enhance the frequency stability of quantum atomic clocks, allowing them to maintain their accuracy over longer periods and making them even more valuable for applications like timekeeping and synchronization. For instance, the frequency stability of quantum atomic clocks with ^{87}Sr achieves around 2.2×10^{-18} at 1 s (it is typically calculated by its Allan deviation), representing a threefold improvement over the previous best atomic clock [47]. Nicholson and co-workers in this Ref. [47] conducted experiments in an environment with an ultrastable laser with a coherence time of 10 seconds and a duty cycle of 60%. This calculation incorporates the Stark Shift, which analyzes the shift of energy levels of an atom caused by an external field, and the blackbody radiation shift (BBR), which accounts for external field effects. Both parameters are reduced, the BBR uncertainty is reduced to 1.4×10^{-18}. Thus, the stability frequency of the atomic lattice clock is 0.002 fs. Notice that a frequency stability of 10^{-18} means that the clock's frequency would drift by about 1 s per year.

The objective of our problem is to incorporate the quantum lattice clock into our simulation scenario. The high precision demanded by the quantum lattice clock necessitates advanced computing capabilities to adjust for satellite and positioning errors. Therefore, in this context, a precision of *picoseconds* (ps) is currently required to align with our simulation scenario.

Thus, the stability frequency at the femtosecond level is not applicable in our scenario, such as given by the quantum lattice clock at 0.002 fs. Our solution, therefore, is to employ the *optical lattice clock* with a *frequency comb*. It is a kind of atomic clock that combines a frequency comb and optical lattice trapping to provide timekeeping accuracy. The concept of a frequency comb involves employing a Radio Frequency (RF) that spans from microwave to optical wavelengths, making it relatively measurable in a discrete value [48]. Frequency combs are employed to stabilize and control the frequency stability. They have been widely used since the 19th century to test quantum theory with high precision [49]. The analogy of combs is related to hair combs, where each component is identified as a *tooth*. Each *tooth* represents a discrete value of the frequency. Thus, the frequency comb equation is written as follows:

$$f_n = f_0 + n \cdot f_{\text{rep}} = n^2 \times 2f_s + f_0, \tag{12}$$

where f_{rep} is the frequency repetition which denotes the teeth of the comb that is repeated with n, which is an integer. f_0 is the carrier offset

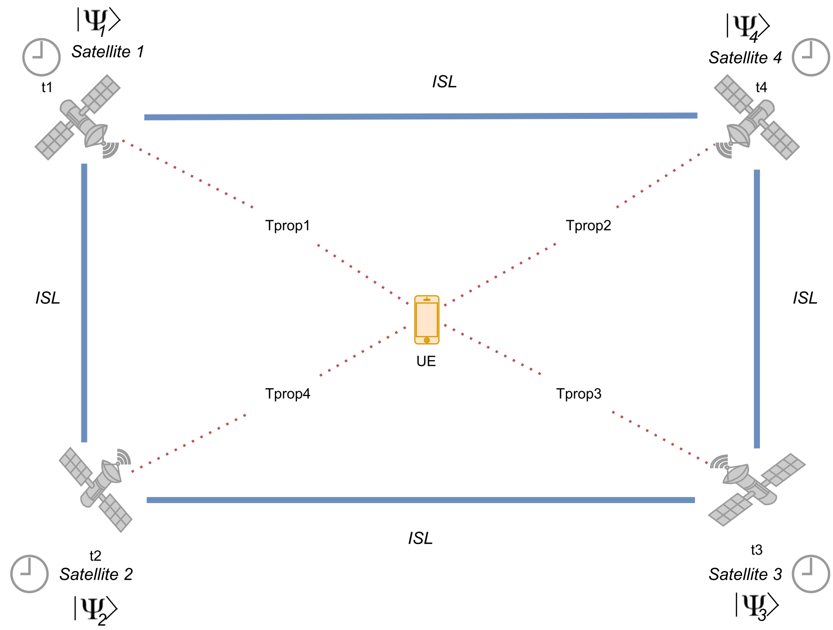

Fig. 6. The systematic figure of identifying the unknown position of UE.

Fig. 7. Ground-tracks of the satellites of the formation flying.

frequency (it is the central frequency of the laser emission, which can be tuned to a specific wavelength), f_s is the frequency comb spacing (the spacing between consecutive frequencies), and f_n is the frequency of the nth comb.

3.2. Synchronization process

- **Initial Synchronization:** The ISLs synchronize the qubits across the satellites from the outset, forming a unified quantum state that spans the constellation.
- **Dynamical Evolution:** The evolution of this entangled state over time is modeled using the Lindblad master equation, incorporating the qubits' internal dynamics and their ISL-mediated interactions.
- **Feedback and Control:** Real-time feedback mechanisms are deployed to dynamically tune the Hamiltonian's parameters, such as adjusting κ_{ij}, based on continuously monitoring the qubits' states to sustain or enhance synchronization.

3.3. Technical considerations

- **Optical ISLs:** These links can be designed to facilitate quantum communication protocols necessary for synchronization and coherent qubit interactions.
- **Environmental Decoherence:** Decoherence is a major barrier to accomplishing quantum synchronization, as it yields the loss of quantum coherence and kills the fragile quantum correlations between photons. To mitigate decoherence effects, techniques such as dynamical decoupling or quantum error correction can be used to maintain the integrity of the entangled state.
- **Real-time Quantum State Monitoring:** Each satellite will have precise measurement and control systems for ongoing quantum state assessment and parameter adjustment.

4. Satellite-based localization

Satellite systems, particularly those leveraging Low-Earth Orbit (LEO) constellations, offer unique capabilities in the framework of network-based localization, supporting both "classical" localization services and Electronic Intelligence (ELINT) applications. In particular, satellite network-based localization has the potential to revolutionize various applications, such as:

- IoT, enabling location-based services and supporting tracking, even in remote or challenging environments, without the need for the IoT device to use a GPS receiver.
- Detection, identification, and location of emitters of electronic signals, such as radars, communication systems, and jamming devices, in the framework of Electronic intelligence scenarios. Satellite systems, providing global coverage and persistent monitoring capabilities, can contribute to the enhancement of situational awareness.
- Autonomous vehicles, providing precise positioning for self-driving cars, drones, etc., especially in scenarios where GNSS signals are unreliable or unavailable (i.e. in dense urban environments).
- Emergency scenarios, supporting location of individuals and assets in disaster zones or in remote locations.
- Precision agriculture, providing real-time positioning data to support monitoring and managing of agricultural activities.

In this framework, one of the most important challenges is the improvement of accuracy to achieve high-precision localization. This can be obtained through different strategies: increasing the number of satellites that can receive the signals transmitted by a particular target

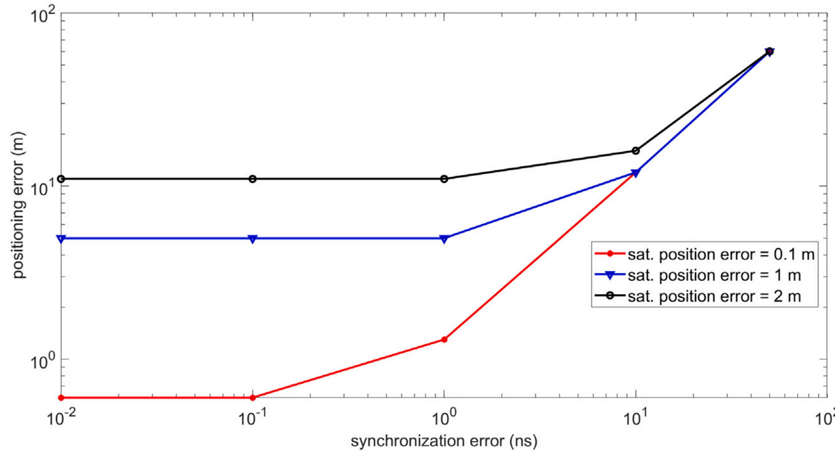

Fig. 8. Positioning errors as a function of the synchronization error.

Table 1
Parameters of the formation of four satellites.

Semi major axis	7150 km
Eccentricity	0 rad
Inclination	1.7 rad
Argument of perigee	0 rad
RAAN	0; 0; 0,05; 0,05 rad
Mean anomaly	0; 0.05; 0; 0.05 rad

location or improving signal processing algorithms. The first approach is the most expensive in terms of cost, deployment time and management; the latter requires significant efforts and high computational resources to provide a meaningful performance improvement. In this context, the possibility to achieve ultra-high synchronization accuracy between satellites, though quantum-based techniques, can be used to improve algorithms performance. As a matter of fact, synchronization accuracy is a key parameter fer every localization algorithm. In a classical scenario the synchronization between LEO satellites is provided by GNSS receivers but the coming of quantum-based techniques can represent a breakthrough in satellite network-based localization.

5. Simulation results

5.1. Scenario

In order to evaluate the performance enhancement provided by QS systems, we consider the specific scenario of a formation of four satellites aiming at the location estimation of a UE transmitting an RF signal which can be detected by each satellite of the formation. It is worth noting that, from the positioning performance point of view, a formation of four satellites is also representative of a satellite constellation having a redundancy coverage factor equal to four.

This scenario could represent a real medium-term application of satellite QS because:

- The distance between LEO satellite is not so large to demand high power optical Tx-Rx systems, hence reducing P/L dimensions to a size compatible to medium LEO platforms; moreover, the short distance between the satellites reduces the problems related to the maintenance of synchronization over long distances;
- The capability of the constellation to work in formation flying reduces the impact of Doppler effects that could introduce errors in QS;
- ISL is not subject to atmospheric effects that could degrade optical signal quality.

The set of orbital parameters of the satellite formation is reported in Table 1. The ground-track of the considered formation of satellites and the location of the user equipment (i.e. Rome, Italy) are shown in Fig. 7. This simple scenario can be easily extended to the case of a constellation of satellites with a redundancy of coverage of at least four satellites.

The orbital position of each satellite has been propagated for one single satellite pass over the user equipment with a time step equal to 1 s. The simultaneous visibility of the four satellites of the formation lasts about 10 min. In each time step of the simulation, the position of the user equipment is estimated using TOA measurements and Equations taking into account the considered sources of error. Therefore, for each set of parameters, the positioning accuracy has been averaged using 600 estimates.

5.2. Results

Positioning error, defined as the Euclidean norm of the vector difference between the true position vector and the estimated position vector, is the ultimate performance indicator of a positioning system. In this Section we report the simulation results of the previously considered scenario for a range of synchronization errors, from the values achievable with QS systems to the values achievable with GPS receivers (tens of ns) on-board the satellites.

For the considered satellite formation, positioning errors as a function of the synchronization error is shown in Fig. 8. On one hand, considering that, a GPS receiver on-board a satellite allows to achieve a synchronization error from 20 to 50 ns, the resulting positioning error is above 15 m. On the other hand, assuming satellites synchronized through a quantum approach having a synchronization error below 0.01 ns, the resulting positioning error may be lower than 1 m depending on the error about the satellite position (ephemeris).

These results about positioning have been achieved using a TOA approach. However, QS may be also used to achieve frequency synchronization with high accuracy. In this case, a hybrid TOA/FOA may be used to increase the number of measurements and to decrease the positioning error.

6. Conclusions

Localization through constellations of small satellites represents a revolution in the landscape of navigation and terrestrial monitoring. The potential of small satellite constellations for localization is vast and promising. However, the limitations of cost and size of on-board technologies for small satellite missions do not allow to embark atomic clocks for synchronization as in the case of current GNSS constellations. In this work, we propose to exploit optical ISLs to serve two functions:

high-bandwidth data communication and QS, thus replacing atomic clocks with QS systems. It is worth considering that the current trend is to design a satellite constellation carrying out both communications and positioning services.

Then, we considered a set of four satellites for localization and simulated the system performance in terms of positioning errors as a function of the synchronization error and the ephemeris error. We have shown that the synchronization errors achievable with QS systems allows to achieve a very high positioning accuracy, i.e. lower than 1 m.

In conclusion, our research underscores the potential of QS for positioning services in future small satellite constellations, even under conditions of high localization accuracy requirements. Our findings not only contribute to satellite navigation but also opens up new possibilities for the future of terrestrial monitoring and communication technologies for 6G.

The next steps are; (i) To enable more complicated applications and more connection, the technology will need to be scaled up in order to accommodate larger satellite networks. (ii) To create robust and reliable protocols for establishing and sustaining quantum entanglement between distant satellites. To accomplish these steps, some potential obstacles in applying QS to real-world systems should be considered, e.g.,

- Space conditions are intrinsically noisy, compromising the sensitive state of entangled particles.
- The satellite distance is a major obstacle to QS. Maintaining a steady connection becomes more difficult as the entanglement signal weakens with increasing distance.
- Ensuring the security of the information between the satellites (note that QS needs the exchange of information between satellites) is necessary to stop eavesdropping or tampering.

CRediT authorship contribution statement

Swaraj Shekhar Nande: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Tommaso Rossi:** Writing – original draft, Conceptualization. **Muhammad Idham Habibie:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Mohamed Barhoumi:** Writing – original draft, Conceptualization. **Krishna Palaparthy:** Formal analysis, Methodology, Software. **Wassim Mansouri:** Writing – original draft, Conceptualization. **Ashwin Raju:** Investigation, Conceptualization. **Riccardo Bassoli:** Writing – review & editing, Supervision, Conceptualization. **Ernestina Cianca:** Writing – review & editing, Supervision, Conceptualization. **Frank H.P. Fitzek:** Writing – review & editing, Supervision, Conceptualization. **Mauro De Sanctis:** Writing – original draft, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] R. Filjar, M.C. Damas, T.B. Iliev, Resilient satellite navigation empowers modern science, economy, and society, IOP Conf. Ser.: Mater. Sci. Eng. 1032 (1) (2021) 012001, http://dx.doi.org/10.1088/1757-899X/1032/1/012001.

[2] F. Zafari, A. Gkelias, K.K. Leung, A survey of indoor localization systems and technologies, IEEE Commun. Surv. Tutor. 21 (3) (2019) 2568–2599, http://dx.doi.org/10.1109/COMST.2019.2911558.

[3] A. Kalantari, S. Maleki, S. Chatzinotas, B. Ottersten, Frequency of arrival-based interference localization using a single satellite, in: 2016 8th Advanced Satellite Multimedia Systems Conference and the 14th Signal Processing for Space Communications Workshop, ASMS/SPSC, 2016, pp. 1–6, http://dx.doi.org/10.1109/ASMS-SPSC.2016.7601472.

[4] E. Boldbaatar, D. Grant, S. Choy, S. Zaminpardaz, L. Holden, Evaluating optical clock performance for GNSS positioning, Sensors 23 (13) (2023) http://dx.doi.org/10.3390/s23135998, URL https://www.mdpi.com/1424-8220/23/13/5998.

[5] A.V. Miller, A fast and efficient algorithm for time synchronization in satellite quantum key distribution, J. Phys. Conf. Ser. 2701 (1) (2024) 012017, http://dx.doi.org/10.1088/1742-6596/2701/1/012017.

[6] V. Giovannetti, S. Lloyd, L. Maccone, Quantum-enhanced positioning and clock synchronization, Nature 412 (6845) (2001) 417–419.

[7] S.S. Nande, O. Lhamo, M. Paul, R. Bassoli, F.H. Fitzek, Quantum time synchronization for satellite networks, in: 2023 IEEE Aerospace Conference, IEEE, 2023, pp. 1–9.

[8] S.S. Nande, M. Paul, S. Senk, M. Ulbricht, R. Bassoli, F.H. Fitzek, H. Boche, Quantum enhanced time synchronisation for communication network, Comput. Netw. 229 (2023) 109772.

[9] Q. Tang, O. Ermis, C.D. Nguyen, A.D. Oliveira, A. Hirtzig, A systematic analysis of 5G networks with a focus on 5G core security, IEEE Access 10 (2022) 18298–18319, http://dx.doi.org/10.1109/ACCESS.2022.3151000.

[10] A. Pikovsky, M. Rosenblum, J. Kurths, A. Synchronization, A universal concept in nonlinear sciences, Self 2 (2001) 3.

[11] V. Anishchenko, T. Vadivasova, Synchronization of self-oscillations and noise-induced oscillations, J. Commun. Technol. Electron. C/C Radiotekh. Elektron. 47 (2) (2002) 117–148.

[12] F. Sivrikaya, B. Yener, Time synchronization in sensor networks: a survey, IEEE Netw. 18 (4) (2004) 45–50, http://dx.doi.org/10.1109/MNET.2004.1316761.

[13] H. Puttnies, P. Danielis, A.R. Sharif, D. Timmermann, Estimators for time synchronization—Survey, analysis, and outlook, IoT 1 (2) (2020) 398–435, http://dx.doi.org/10.3390/iot1020023, URL https://www.mdpi.com/2624-831X/1/2/23.

[14] M. Leng, Y.-C. Wu, On clock synchronization algorithms for wireless sensor networks under unknown delay, IEEE Trans. Veh. Technol. 59 (1) (2010) 182–190, http://dx.doi.org/10.1109/TVT.2009.2028147.

[15] A. Loeb, D. Maoz, Using atomic clocks to detect gravitational waves, 2015, arXiv:1501.00996.

[16] E. Peik, T. Schumm, M.S. Safronova, A. Pálffy, J. Weitenberg, P.G. Thirolf, Nuclear clocks for testing fundamental physics, Q. Sci. Technol. 6 (3) (2021) 034002, http://dx.doi.org/10.1088/2058-9565/abe9c2.

[17] J. Machaj, P. Brida, N. Majer, R. Sčehovič, Impact of GPS interference on time synchronization of DVB-T transmitters, Mob. Inf. Syst. 2021 (1) (2021) 8812333, http://dx.doi.org/10.1155/2021/8812333, arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1155/2021/8812333, URL https://onlinelibrary.wiley.com/doi/abs/10.1155/2021/8812333.

[18] A.P. Cerruti, Solar radio burst effects on global positioning system receivers, 2007.

[19] N.S. Azahari, N.Z. Harun, C. Chai Wen, S.N. Ramli, Z. Ahmad Zukarnain, Review of clock synchronization in quantum communications, in: Proceedings of the 2024 13th International Conference on Software and Computer Applications, ICSCA '24, Association for Computing Machinery, New York, NY, USA, 2024, pp. 350–356, http://dx.doi.org/10.1145/3651781.3651834.

[20] C. Spiess, S. Töpfer, S. Sharma, A. Kržič, M. Cabrejo-Ponce, U. Chandrashekara, N.L. Döll, D. Rieländer, F. Steinlechner, Clock synchronization with correlated photons, Phys. Rev. Appl. 19 (2023) 054082, http://dx.doi.org/10.1103/PhysRevApplied.19.054082, URL https://link.aps.org/doi/10.1103/PhysRevApplied.19.054082.

[21] P. Komar, E.M. Kessler, M. Bishof, L. Jiang, A.S. Sørensen, J. Ye, M.D. Lukin, A quantum network of clocks, Nat. Phys. 10 (8) (2014) 582–587.

[22] T. Weiß, Nonlinear Dynamics in Quantum Synchronization and Topological Transport, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 2017, URL https://open.fau.de/handle/openfau/8704.

[23] A. Roulet, C. Bruder, Quantum synchronization and entanglement generation, Phys. Rev. Lett. 121 (2018) 063601, http://dx.doi.org/10.1103/PhysRevLett.121.063601, URL https://link.aps.org/doi/10.1103/PhysRevLett.121.063601.

[24] M.A. Nielsen, I.L. Chuang, Quantum Computation and Quantum Information: 10th Anniversary Edition, Cambridge University Press, 2010.

[25] M.A. Lohe, Quantum synchronization over quantum networks, J. Phys. A 43 (2010) 465301.

[26] M. Koppenhöfer, C. Bruder, A. Roulet, Quantum synchronization on the IBM Q system, Phys. Rev. Res. 2 (2020) 023026.

[27] M. Koppenhöfer, A. Roulet, Optimal synchronization deep in the quantum regime, Phys. Rev. Lett. 123 (2019) 124301.

[28] S. Origlia, M.S. Pramod, S. Schiller, Y. Singh, K. Bongs, R. Schwarz, A. Al-Masoudi, S. Dörscher, S. Herbers, S. Häfner, et al., Towards an optical clock for space: Compact, high-performance optical lattice clock based on bosonic atoms, Phys. Rev. A 98 (5) (2018) 053443.

[29] T. Schuldt, M. Gohlke, M. Oswald, J. Wüst, T. Blomberg, K. Döringshoff, A. Bawamia, A. Wicht, M. Lezius, K. Voss, et al., Optical clock technologies for global navigation satellite systems, GPS Solut. 25 (2021) 1–11.

[30] H.C. Roh, Y. Choe, J. Jung, H. Na, Y. Cho, M.J. Chung, Position estimation of landmark using 3D point cloud and trilateration method, in: 2014 11th International Conference on Ubiquitous Robots and Ambient Intelligence, URAI, 2014, pp. 298–302, http://dx.doi.org/10.1109/URAI.2014.7057438.

[31] S. Zekavat, R.M. Buehrer, G.D. Durgin, L. Lovisolo, Z. Wang, S.T. Goh, A. Ghasemi, An overview on position location: Past, present, future, Int. J. Wirel. Inf. Netw. 28 (2021) 45–76.

[32] H.C. So, Source Localization: Algorithms and Analysis, John Wiley and Sons, 2012.

[33] G. Shi, Y. Ming, Survey of indoor positioning systems based on ultra-wideband (UWB) technology, in: Q.-A. Zeng (Ed.), Wireless Communications, Networking and Applications, Springer India, New Delhi, 2016, pp. 1269–1278.

[34] F. Impens, D. Guéry-Odelin, Shortcut to synchronization in classical and quantum systems, Sci. Rep. 13 (1) (2023) http://dx.doi.org/10.1038/s41598-022-27130-w.

[35] M. Barhoumi, J. Liu, G. Lefkidis, W. Hübner, Laser-induced ultrafast spin-transfer processes in non-linear zigzag carbon chain systems, Phys. Chem. Chem. Phys. 25 (2023) 24563–24580, http://dx.doi.org/10.1039/D3CP02483K.

[36] M. Barhoumi, J. Liu, G. Lefkidis, W. Hübner, Ultrafast control of laser-induced spin-dynamics scenarios on two-dimensional Ni3@C63H54 magnetic system, J. Chem. Phys. 159 (8) (2023) 084304, http://dx.doi.org/10.1063/5.0158160, arXiv:https://pubs.aip.org/aip/jcp/article-pdf/doi/10.1063/5.0158160/18100762/084304_1_5.0158160.pdf.

[37] M. Barhoumi, The density functional theory and beyond: Example and applications, in: D. Glossman-Mitnik (Ed.), Density Functional Theory, IntechOpen, Rijeka, 2021, http://dx.doi.org/10.5772/intechopen.100618.

[38] M. Barhoumi, J. Liu, W. Hübner, G. Lefkidis, Using single and double laser pulses on the molecular Ni4@C48H36 system to design integrated nanospintronic units, Phys. Chem. Chem. Phys. 26 (2024) 16070–16090, http://dx.doi.org/10.1039/D4CP00523F.

[39] S.B. Jäger, T. Schmit, G. Morigi, M.J. Holland, R. Betzholz, Lindblad master equations for quantum systems coupled to dissipative bosonic modes, Phys. Rev. Lett. 129 (2022) 063601, http://dx.doi.org/10.1103/PhysRevLett.129.063601, URL https://link.aps.org/doi/10.1103/PhysRevLett.129.063601.

[40] T.E. Lee, H. Sadeghpour, Quantum synchronization of quantum van der pol oscillators with trapped ions, Phys. Rev. Lett. 111 (23) (2013) 234101.

[41] A. Mari, A. Farace, N. Didier, V. Giovannetti, R. Fazio, Measures of quantum synchronization in continuous variable systems, Phys. Rev. Lett. 111 (10) (2013) 103605.

[42] M. Koppenhöfer, Nonclassical states and quantum synchronization of dissipative nonlinear oscillators (Ph.D. thesis), University_of_Basel, 2020.

[43] J.A. Campos-Gonzalez-Angulo, R.F. Ribeiro, J. Yuen-Zhou, Generalization of the Tavis–Cummings model for multi-level anharmonic systems, New J. Phys. 23 (6) (2021) 063081, http://dx.doi.org/10.1088/1367-2630/ac00d7.

[44] I.P. Vadeiko, G.P. Miroshnichenko, A.V. Rybin, J. Timonen, Algebraic approach to the tavis-cummings problem, Phys. Rev. A 67 (2003) 053808, http://dx.doi.org/10.1103/PhysRevA.67.053808, URL https://link.aps.org/doi/10.1103/PhysRevA.67.053808.

[45] D. Manzano, A short introduction to the Lindblad master equation, AIP Adv. 10 (2) (2020) 025106, http://dx.doi.org/10.1063/1.5115323, arXiv:https://pubs.aip.org/aip/adv/article-pdf/doi/10.1063/1.5115323/12881278/025106_1_online.pdf.

[46] M.A. Lohe, Quantum synchronization over quantum networks, J. Phys. A 43 (46) (2010) 465301, http://dx.doi.org/10.1088/1751-8113/43/46/465301.

[47] T. Nicholson, S. Campbell, R. Hutson, G. Marti, B. Bloom, R. McNally, W. Zhang, M. Barrett, M. Safronova, G. Strouse, W. Tew, J. Ye, Systematic evaluation of an atomic clock at 2 x 10-18 total uncertainty, Nature Commun. 6 (1) (2015) http://dx.doi.org/10.1038/ncomms7896.

[48] R. Holzwarth, M. Zimmermann, T. Udem, T. Hansch, Optical clockworks and the measurement of laser frequencies with a mode-locked frequency comb, IEEE J. Quantum Electron. 37 (12) (2001) 1493–1501, http://dx.doi.org/10.1109/3.970894.

[49] S.A. Diddams, K. Vahala, T. Udem, Optical frequency combs: Coherently uniting the electromagnetic spectrum, Science 369 (6501) (2020) eaay3676, http://dx.doi.org/10.1126/science.aay3676, arXiv:https://www.science.org/doi/pdf/10.1126/science.aay3676. URL https://www.science.org/doi/abs/10.1126/science.aay3676.

Swaraj Shekhar Nande is a PhD researcher at The Deutsche Telekom Chair of Communication Networks, TU Dresden. He is currently working on "Quantum Synchronization Techniques to reduce the synchronization errors in 6G", as in the precision time protocol (PTP) case.

He completed his five-year Integrated Master's Degree major in Physics at ISERC, Visva-Bharati University, Santiniketan, in 2021, a World Heritage University. He did his master's project on "The study of Optical Nonlinearities in various multilevel atomic systems" at CSIR-NPL, New Delhi, in Non-linear Quantum Optics. After finishing his Master's Degree in India, he worked as a Guest Scientist in Theoretical Quantum Optics at Helmholtz Institute Jena, Germany. Swaraj's research interest focuses on the implementation of Quantum Mechanical Techniques for Communication Networks and Quantum Internet applications.

Tommaso Rossi is currently an Assistant Professor with the Department of Electronics Engineering, University of Rome "Tor Vergata," Rome, Italy, where he teaches digital signal processing, signals and multimedia processing and communication. He is currently a Co-Investigator of the Italian Space Agency Q/V-band satellite communication experimental campaign carried out through the Alphasat "Aldo Paraboni" Payload. He has authored or coauthored more than 90 papers on journals and conference proceedings. His research interests include space systems, extremely high frequency satellite and terrestrial telecommunications, satellite and inertial navigation systems, digital signal processing for radar and telecommunications applications. He is an Associate Editor for the Space Systems area of the IEEE Transactions on Aerospace and Electronic Systems.

Muhammad Idham Habibie is a Postdoctoral Researcher at Technische Universität Dresden in Germany. He earned his Bachelor's Degree from the University of Indonesia. Subsequently, he joined an industrial company, Ericsson Indonesia, as a Network Engineer. There, he was a part of the transmission team focusing on the radio access network for nearly four years. He later completed his M.Sc. in Telecommunication Engineering at University College London. During his master's, his thesis work was carried out at Cobham Wireless in the UK, where he concentrated on implementing the 3GPP standard on physical hardware. He then continued his academic journey at INSA (Institut National des Sciences Appliquées de Lyon) in Lyon, France, obtaining his Ph.D. in 2023. His doctoral research centered on Enhanced Grover's Algorithm Solutions for 5G Active User Detection, with Grover's algorithm being classified as a quantum algorithm. At present, his research at TU Dresden revolves around quantum synchronization.

Mohamed Barhoumi is a postdoctoral researcher at the Deutsche Telekom and chair of communication networks in Quantum Communication Networks Research Group at the Faculty of Electrical and Computer Engineering at Technische Universität Dresden. He achieved his Master's in Physics (finished with very good) between the University of Monastir-Tunisia and the University of Lorraine-France in 2015. Also, he pursued his Ph.D. in Physics (from 2016 to 2018) at the University of Monastir-Tunisia and the University of Lorraine-France (completed with very honorable). After that, he worked as a teacher and researcher at the ISSATKAS University of Kairouan-Tunisia. Besides, he worked as a teacher and researcher at the Faculty of Sciences of Monastir. He taught semiconductors, solid state, optics, magnetic, electrostatic, and mechanics. Next, he worked as a postdoctoral fellow at Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau (RPTU Kaiserslautern-Landau)-Germany. Here, he systematically studied the Ultrafast laser-induced spin-dynamics scenario on a carbon material to which four spin centers are attached.

Krishna Palaparthy is currently a master's student of the course Computational Modeling and Simulation at TU Dresden with research interests into open quantum systems, light–Matter interactions, quantum information and quantum many-body physics. He previously worked as a simulation engineer in the field of computational fluid dynamics at CADFEM, after his bachelor's in Mechanical engineering from Vignana Bharathi Institute of Technology, Hyderabad.

Wassim Mansouri is a PhD Researcher at the Deutsche Telekom Chair of Communication Networks in the Quantum Communication Networks Research Group at the Faculty of Electrical and Computer Engineering at Technische Universität Dresden.

Ashwin Raju is a PhD Researcher at the Deutsche Telekom Chair of Communication Networks in Quantum Communication Networks Research Group at the Faculty of Electrical and Computer Engineering at Technische Universität Dresden.

Riccardo Bassoli is a Juniorprofessur (US Assistant Professor, UK Lecturer) at the Deutsche Telekom Chair of Communication Networks and Head of the Quantum Communication Networks Research Group, at the Faculty of Electrical and Computer Engineering, at Technische Universität Dresden. He is member of the Centre for Tactile Internet with Human-in-the-loop (CeTI) , Cluster of Excellence, Dresden. He is also member of the EU Quantum Internet Alliance (QIA) and of the EU flagships for 6G Hexa-X and Hexa-X II. He is principal investigator in the 6G-life research hub of Germany. He got his Ph.D. from 5G Innovation Centre at University of Surrey (UK), in 2016. He was also a Marie Curie ESR at the Instituto de Telecomunicações (Portugal) and visiting researcher at Airbus Defence and Space (Elancourt, France). Between 2016 and 2019, he was postdoctoral researcher at Università di Trento (Italy). He is IEEE and ComSoc member. He is also member of the Glue Technologies for Space Systems Technical Panel of the IEEE AESS. He is co-founder and member of the association "SIGN – Scienziati Italiani in Germania Network".

Ernestina Cianca was born in L'Aquila, Italy, in August 1972. I received the Laurea degree in Electronic Engineering (summa cum laude) in 1997, from the University of L'Aquila, Italy, and I got the Ph.D. in Microelectronics and Telecommunications Engineering in 2001, defending my thesis on "Power management in CDMA-based satellite systems".

Aalborg University, Denmark, has employed her,), as a Research Engineer (2000–2001) and as an Assistant Professor (2001–2003) in the Wireless Networking Groups (WING) coordinated by Prof. R. Prasad. In 2003, I won a competition for a permanent position as an assistant professor at the Department of Electronic Engineering at the University of Rome Tor Vergata.

Frank H. P. Fitzek, Professor and Chair of the "Deutsche Telekom Chair of Communication Networks" at TU Dresden, leads at the forefront of telecommunications research in Germany. As the spokesperson for the DFG Cluster of Excellence CeTI and the 6G-life hub, his contributions have significantly shaped the field of communication networks. Educationally, Fitzek completed his diploma in electrical engineering at RWTH Aachen, Germany, in 1997, followed by a Ph.D. in Electrical Engineering from the Technical University Berlin in 2002. That same year, he embarked on his professorial journey at the University of Ferrara, Italy, and further expanded his academic influence to Aalborg University in 2003 as a Professor. An entrepreneurial spirit, Fitzek co-founded over ten startups, beginning with acticom GmbH in 1999. His global research footprint includes prestigious institutions like MIT, VTT, and Arizona State University. Fitzek's groundbreaking work in MIMO MDC earned him the YRP award in 2005, alongside the Danish Young Elite Researcher Award. His innovative contributions were recognized with the NOKIA Champion Award annually from 2007 to 2011, the Nokia Achievement Award in 2008 for cooperative networks, the SAPERE AUDE research grant in 2011, and the Vodafone Innovation prize in 2012. In 2015, he was honored with the "Doctor Honoris Causa" degree from BUTE. His research ambitiously spans 5G/6G communication networks, in-network computing, network coding, compressed sensing, post-Shannon theory, quantum and molecular communication, and immersive human–machine interaction in virtual environments.

Mauro De Sanctis is Associate Professor of Telecommunications in the Department of Electronics Engineering, University of Roma "Tor Vergata" (Italy), teaching "Information Theory and Data Science". He received his Ph.D. degree in Telecommunications and Microelectronics Engineering in 2006 from the University of Roma "Tor Vergata" (Italy). He is a founder member of the university spin-off RadioPoints s.r.l. (www.radiopoints.it). He was with the Italian Space Agency (ASI) as holder of a two-year research scholarship on the study of Q/V band satellite communication links for a technology demonstration payload, concluded in 2008; during this period he participated in the opening and to the first trials of the ASI Concurrent Engineering Facility (ASI-CEF). In 2006 he was a post-doctoral research fellow for the European Space Agency (ESA) ARIADNA extended study named "The Flower Constellation Set and its Possible Applications". He is serving as Associate Editor for the Command, Control and Communications Systems area of the IEEE Transactions on Aerospace and Electronic Systems and as Associate Editor for the Signal Processing and Communication area of the IEEE Aerospace and Electronic Systems Magazine. He published more than 130 papers on journals and conference proceedings, 7 book chapters, one book and one patent.