Quantum Networks – a new platform for Aerospace

Kathy-Anne Brickman Soderberg,*

Air Force Research Laboratory, Rome, NY, 13441, USA

Daniel J. Gauthier†

Department of Physics, The Ohio State University

Paul G. Kwiat‡

Department of Physics, Illinois Quantum Information and Technology Center, University of Illinois Urbana-Champaign

and

Raghavendra Srinivas§

Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, U.K.

The ability to distribute entanglement between quantum nodes may unlock new capabilities in the future that include teleporting information across multi-node networks, higher resolution detection via entangled sensor arrays, and measurements beyond the quantum limit enabled by networked atomic clocks. These new quantum networks also hold promise for the Aerospace community in areas such as deep space exploration, improved satellite communication, and synchronizing drone swarms. Though exciting, these applications are a

---

[*] Senior Scientist for Quantum Science and Technology, Air Force Research Laboratory, Information Directorate. Corresponding Author: kathy-anne.soderberg@afrl.af.mil.

[†] Professor of Physics, Department of Physics, The Ohio State University.

[‡] Bardeen Professor of Physics; Executive Committee Chair, Illinois Quantum Information Science & Technology Center.

[§] EPSRC Quantum Technologies and Balliol Early Career Fellow, Department of Physics, University of Oxford.

long way off from providing a "real-world" benefit as they have only been theoretically explored or demonstrated in small-scale experiments. An outstanding challenge is to identify near-term use cases for quantum networks - this may be an intriguing new area of interest for the Aerospace community as the quantum networking field would benefit from more multi-disciplinary collaborations. This review article introduces quantum networking, discusses the difficulties in distributing entanglement within these networks, highlights recent progress toward this endeavor, and features two current case studies on mobile quantum nodes and an entangled clock network, both of which are relevant to the Aerospace community.

I. Introduction

THE internet fundamentally changed how we live our lives. It not only allowed new ways to communicate, but also disrupted the status quo, from the music and television industries to the way society does business on a daily basis. Similarly, quantum networking stands to be an extremely disruptive quantum technology, as it will not only enable a new platform that offers theoretically secure communication protocols [1], but it will also provide a novel way to connect sensors and computers through entanglement distribution. These entanglement-assisted operations promise advanced capabilities that are impossible with classical technology [2, 3, 4, 5] and may enable applications of interest to the Aerospace community, such as novel time transfer protocols, quantum-enabled long-baseline interferometry, and distributed timing and sensing.

A quantum network is a collection of quantum devices connected via distributed entanglement, similar to a classical network but with new constraints imposed on the network by the requirement to maintain the "quantumness" of the information as defined more precisely below. It is likely that quantum networking will progress in a similar manner to the related field of quantum computing. Many recent quantum-computing demonstrations are special-purpose devices with limited capabilities. These early devices help to inform researchers as the field moves towards the long-term goal of a fault-tolerant (or "universal") device that can solve many more problems than these early special-purpose models. Similarly, near-term quantum network demonstrations will operate over data-center or metropolitan-scale distances and have topologies designed for limited applications. The far-term goal is a universal network that connects many devices for more general purposes, similar to how the internet connects various devices for a myriad of functions [6]. We stress that quantum networking will not replace the internet as we know it (just as quantum computers will not replace our current computers) but will instead provide complementary functions that work in unison with these classical counterparts to provide new capabilities. We primarily focus on these long-distance networks in this article to motivate a broader range of applications that will be possible in the future.

Of the three areas of Quantum Information Science (QIS) - simulation & computing, sensing & metrology, and communication & networking - quantum networking is arguably the least mature (even though some of the early quantum key distribution protocols pre-dated any quantum computing implementations). This is due to the difficult challenge of creating, maintaining, and controlling entanglement for distribution beyond a single quantum module. Furthermore, for the universal network described above, one will need both transmission quantum bits (qubits) to send the information between the nodes and stationary (likely matter-based) qubits to perform operations at the nodes and have the ability to seamlessly transfer information between the two. Unlike classical communication that uses millions of photons to transmit signals, quantum networking requires users to send and receive single photons. These single photons encode quantum states that must be coherently maintained during the networking or communication protocol. As we will discuss below, this need for quantum-encoded single photons makes quantum networking a much more challenging task than classical communication, as many of the tools and frequency ranges available for classical communication cannot be used. For example, room-temperature quantum communication is not possible in the radio-frequency or microwave part of the electromagnetic spectrum because the single-photon states will be overwhelmed by background blackbody radiation. Therefore, quantum networking experiments primarily use visible or infrared frequencies and researchers have made substantial progress in sending single and entangled photons encoded with quantum information over long distances [7, 8] and performing preliminary networking operations over short distances [9]. Since most matter-based qubits do not operate at common telecommunication frequencies, this necessitates a way to transduce, or frequency convert, the quantum information between the qubits at the nodes with the communication channel. Transduction is one of the biggest challenges in quantum networking, and though progress is being made in getting information in and out of the nodes using the intrinsic matter-based qubit frequencies [10, 11, 12, 13, 14, 15, 16, 17], researchers have yet to demonstrate an efficient and effective transduction mechanism.

Another challenge in quantum networks is the fragility of entanglement which leads to a simultaneous need to shield the quantum systems from unwanted noise while maintaining a connection to the environment to send the information between the nodes. In classical networks, repeaters amplify the signals during transmission. Unfortunately, one cannot directly replicate this in a quantum network as one cannot copy or amplify quantum particles due to the no-cloning theorem in quantum mechanics [1]. Therefore, one must operate repeaters differently in a quantum network, incorporating ancillary qubits and error correction methods to restore the targeted quantum state before transmitting the information to another node [18, 19]. Realizing a quantum repeater is another current outstanding experimental challenge for quantum networking.

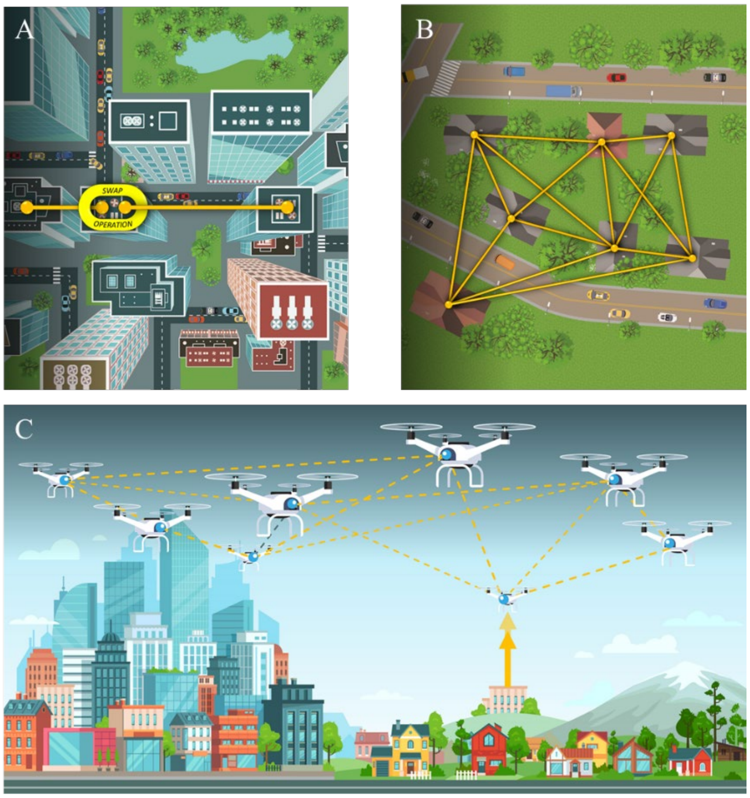

Figure 1. Different types of quantum network configurations including a (1A) linear point-to-point network, (1B) non-linear quantum network configuration, and (1C) a quantum mobile network. This image is a work of the U.S. government and in the public domain on the United States.

Figure 1 illustrates three possible quantum network configurations. Figure 1A is a point-to-point network that illustrates two end-points within a city connected by a series of quantum repeaters (only one shown in the figure).

Here, quantum repeaters between the end nodes reduce the effect of loss, allowing one to transmit the information over longer distances [18]. Point-to-point networks are the most common quantum networking system developed to date and repeater-enhanced networks are in the early stages of development. Figure 1B is a multi-user network connecting points within a small cluster. This type of topology could connect nodes for distributed quantum computing or other local networking protocols. The figure shows a "partial mesh" architecture in which each node is connected to several (but not all) others[**], but ultimately the end application will dictate how the modules are connected and what types of qubits reside within each node. Figure 1C illustrates a network of unmanned aerial systems (UAS) connected by distributed entanglement. Here the entanglement is transferred to a UAS from a central ground node and then distributed between the other UASs. One can envision replacing any of the aerial nodes with a fixed (building) or mobile ground-level node (car, truck, train, ship, etc.). The multi-user networks shown in Figs. 1B and C are still largely conceptual.

Quantum networks may enable novel networking schemes, such as the ability to teleport quantum information between quantum nodes. Early laboratory demonstrations have teleported an unknown quantum state between two nodes [9, 20, 21], and there have been numerous proof-of-principle quantum network demonstrations from city [22, 23] to intercity [24] to satellite scales [25]. In the very long term, quantum networks may provide theoretically secure communication protocols that would make eavesdropping nearly impossible. Important for some adversarial scenarios, direct optical links can be much more resilient to "jamming" than rf-communications, which can be thwarted without an adversary knowing the path of the signal. However, for the same reason, direct optical channels are *more* susceptible to a different denial-of-service attack if they rely on a single-link implementation – blocking that optical link; expanding to multi-user networks reduces this denial-of-service vulnerability. A quantum network can also provide benefits to the fields of quantum sensing and quantum computing. For example, connecting quantum sensors through an entangled network may provide improved timing for clock synchronization, or better resolution telescopy through protocols like quantum-enabled very long-baseline interferometry [2]; a network can also connect

---

[**] Other common networking topologies are a ring (each node connected to exactly two other nodes), star (all nodes but one connected to that one), and mesh (all-to-all connectivity); there are obviously many hybrid variants to these base topologies.

modules of quantum processors, and allow distributed quantum computing with greatly enhanced processing power [26].

This introduction offers far-reaching applications that future quantum networks may enable. However, there are still many challenges to extend entanglement beyond a few nodes due to the intricate nature of the quantum systems and the difficulties in connecting disparate qubit technologies. The remaining sections offer a realistic view of what is currently possible, describes the outstanding challenges to realizing full (universal) quantum network capability, highlights recent initiatives, and highlights two use cases of interest to the Aerospace community. Section II introduces quantum networking and defines important terms, Section III discusses the current status of quantum networks and outstanding challenges, Section IV provides case studies on quantum systems on an unmanned aerial system and a recent experiment entangling two atomic clocks, and Section V concludes with a summary.

II. Primer on quantum information science and quantum networking

Quantum information science merges the established fields of quantum mechanics and information science in unique ways that bring novel fundamental insights to both disciplines while providing a foundation for entirely new theories and technologies. It exploits the laws of physics to realize unique physical systems that outperform their classical counterparts for select quantum networking and quantum computing use-cases [1]. This section provides a brief introduction to quantum networking and discusses the basic quantum information processing building blocks that serve as the foundation for these networks [27].

A. Quantum versus Classical Networking

A fundamental difference between classical and quantum networking is the use of single photons encoded with quantum information to transmit messages. Due to the extreme difficulty of operating at the single-photon level while maintaining quantum coherence, the frequency ranges and tool sets are limited as compared to what can be done in classical communication; for example, the "no-cloning" theorem of QIS prevents the use of in-line amplifiers to combat signal loss. Quantum networking protocols often use optical wavelengths, typically 800 nm and 1550 nm, where there may be less loss (e.g., loss in optical fibers has a minimum of ~0.15dB/km around 1550 nm), as well as tolerable background, such as from blackbody radiation, in the environment at these wavelengths. Also, for communication in the Earth's atmosphere, there are spectral windows with lower loss from molecular absorption. Finally, the wavelength choice is often driven by the availability of high-efficiency, low-noise single-photon counting detectors, such as silicon avalanche photodiodes that operate in the visible part of the spectrum, or classical communication equipment operating around 1550 nm that can be adapted for quantum networking systems. The blackbody radiation background, on the other hand, makes using microwave (or terahertz or radiofrequency) signals at room temperature very difficult, if not impossible, as there is no way to distinguish the signal from the large background or prevent interference from this large background. The qubit technologies that do use microwaves for communication protocols are limited to operating entirely within in a cryogenic environment with temperatures typically around 10 mK to reduce the background so that one can distinguish between the qubit signals of interest and the background microwave environment.

Classical repeaters amplify signals between nodes to prevent information loss over long distances. Trying to use the same technique in a quantum network results in the amplification process destroying the quantum information and so instead, one must use a much more complicated "quantum repeater", which will be discussed later in the article. A feature of quantum mechanics that further complicates operations is that measurement destroys the quantum properties encoded in a qubit and effectively "collapses" the encoded quantum information into a single (classical) outcome. It is not possible to re-encode the resulting classical signal back into the (unknown) quantum signal and complete the protocol. Once the system is measured, the protocol is over, and one needs to start again[††]. It is important to note that an operator can measure a system intentionally, but the environment can also effectively make a measurement of the system – the environment itself becoming entangled with the system – with or without the operator's knowledge. Therefore, care must be taken to adequately shield or monitor the quantum channel to ensure that only intentional measurements are made.

Finally, as alluded to earlier, quantum mechanics does not allow one to make copies of an unknown quantum state [1]. These unique quantum mechanical properties make operating quantum systems for real-world applications

---

[††] Note that for quantum computing, one *does* make measurements on *some* of the qubits throughout a quantum calculation, in order to detect and correct errors; however, these must then be replaced with "fresh" ancilla qubits. Similar methods occur for error correction and entanglement distillation in quantum repeaters.

challenging. However, they are also at the heart of the promising advances quantum information science has to offer, e.g., the no-cloning limitation is critical for the security of quantum cryptography.

B. Qubits

A qubit is the fundamental unit in quantum information and can be nearly any well-controlled, two-level quantum system. Some common qubit technologies include trapped ions, superconducting qubits, nitrogen vacancy centers in diamond, quantum dots, neutral atoms, and photons [28]. Unlike classical bits that can store only a "0" *or* a "1", a qubit can store any arbitrary superposition of "0" *and* "1" at the same time. The ability to store and act on superposition states is a powerful feature in quantum information processing that allows one to simultaneously store and process 2^n states, where n is the number of qubits. When combined with the quantum mechanical phenomena of entanglement discussed below, these two properties allow one to fully harness quantum systems and provide unique capabilities compared to their classical counterparts. In some cases, it allows one to outperform classical systems, such as quantum computers factoring large numbers exponentially faster than any known classical algorithm [4] or using quantum communication to generate random keys for theoretically secure protocols that are, in principal, secure against any attacks allowed by physical laws [3, 29].

Entanglement is a special property shared between multiple quantum systems such that each subsystem does not have a definite value for one or more properties (like energy, or polarization) on its own – all the information is stored in the joint state of the particles, no matter their separation. This leads to correlations between the outcomes of measurements on the particles, and these correlations exceed that possible with any non-quantum theory. It is important to note, this does not allow faster than light communication, as the protocols always require a classical (and therefore causal/non-superluminal) signal to facilitate the quantum information transfer. For quantum networking applications, this classical information does not reveal information about the message itself, but is auxiliary information about how to process the qubit to ensure the quantum protocol proceeds as expected; therefore, the sender can broadcast this classical information openly as it does not provide insight or access to the message transmitting over the quantum channel.

C. Single and Multi-qubit Operations

Another necessity for quantum information processing and quantum networking is a set of universal logic gates. In classical computing, a single-bit gate performs a complete bit flip ("0" ←→ "1"); in contrast, a quantum single-qubit gate can also perform a full bit flip or can prepare any arbitrary superposition of "0" and "1", with an infinite number of possibilities. Two-qubit gates can be used to create entanglement, for example, a "target" qubit is flipped from 0→1 if and only if the "control" qubit is a "1". Operating this "controlled not" gate with the control in a 0- and 1-superposition will entangle the two qubits). For qubits within the same node (intra-node), one implements these gates by coupling qubits in a specific way and the physical implementation is different for each qubit technology. For example, one can entangle trapped ions by coupling the spins of two ions through the phonon (or shared motional modes) of the trapped ion crystal [30, 31]. For photons, entangled pairs can be created directly using nonlinear optical crystals, which convert one high-energy photon into two daughter photons entangled in some (or multiple) property.

Entanglement is commonly benchmarked using the metric of fidelity. Fidelity is a measure of the overlap between the targeted end state and the state actually created [1]. Single- and two-qubit gates are now routine laboratory operations, but the control of large quantum systems (>50 qubits) remains challenging, due to the unavoidable coupling to the environment. Coherence is a measure of how long a quantum state can maintain a superposition before a user intentionally acts on it (to make a measurement) or the environment perturbs it. Decoherence is anything that disturbs the quantum state and causes the system to lose coherence. Decoherence can take various forms that depend on the qubit technology and its surrounding environment; these include photons impinging on atoms, fluctuating magnetic fields altering the precession rates of spin qubits, dispersive birefringence in fiber dephasing polarization qubits, and many other effects.

Finally, quantum networking requires faithful quantum information transfer between distant nodes. Photon-mediated interactions are the main mechanism to realize connections between remote nodes, cf. recent examples using trapped ions [32] and NV centers in diamond [33], though multiple qubit technologies have demonstrated this type of operation as discussed in this review article and the references therein [34]. Both fiber and free-space channels ("wired" and "wireless" communication) are likely to be necessary for a longer-term quantum network because of loss considerations. Optical fiber has loss scaling exponentially with distance (e.g., -0.2 dB/km at 1550nm), whereas long distance free-space channels suffer loss from diffraction (transmission falls as $1/L^2$), and from turbulence if operating in the Earth's atmosphere. Fully global quantum networking will likely require a space-based communication link, and this may be the lowest loss solution.

III. Quantum Networking

A quantum network is a set of interconnected nodes linked via entanglement distribution and protocols consist of applying quantum logic gates (single- and multi-qubit), transmitting photons between the nodes, and making measurements. In principle, these networks can range from chip-scale to global-sized networks. The very long-term vision is a universal network with plug-and-play components that can operate over both short and long distances. However, until researchers overcome the challenges needed to realize these longer-term networks, one must optimize current networking efforts for the specific end goals, as that will determine the number, the type of qubits, and the topology of the network. As we will discuss, most current network demonstrations are limited to chip-scale and local area networks due to outstanding challenges impeding progress toward long range (wide-area and global-scale) quantum networks. We primarily focus the remaining discussion on networks using photons to transmit information over short and long distances.

A quantum network will allow novel networking schemes such as teleportation of quantum states [35]. Here, through the distribution of entanglement, single-qubit operations, and two-qubit measurements, quantum information can be teleported between remote parties. The allure of this protocol is that the information transfers over a theoretically secure quantum channel that is both tamper resistant and tamper evident. Though one always needs an associated classical channel to perform the quantum protocols, no pertinent information regarding the quantum message is ever sent over these channels, *i.e.*, classical information can be widely broadcast without revealing the quantum message that is the state being teleported.

Beyond communications, quantum networks will also advance the other quantum information science areas of metrology, sensing, and computing. For example, global-scale distributed entanglement that connects remote atomic clock nodes will allow more precise timing [5]. Similarly, the ability to connect a network of telescopes via optical-spectrum entangled photons will allow higher resolution sensor protocols such as quantum-enabled very long-baseline interferometry [2], that have a baseline that greatly exceeds what is currently possible using classical optical methods.[‡‡] In quantum computing, there is a practical limit to how many qubits can be controlled and operated within a single module, so the ability to connect remote modules will allow researchers to scale quantum computers beyond these limits [26, 34, 36]. Distributed quantum states will also allow researchers to securely send computational problems to and from quantum computers while maintaining information security and integrity through protocols such as “blind” quantum computing [37]. Realizing large-scale entanglement distribution will almost certainly unlock other yet-to-be-determined disruptive information sharing and networking capabilities.

A. Quantum Key Distribution

Many early quantum communication experiments focused on Quantum Key Distribution (QKD) and related quantum communication protocols. QKD allows remote users to securely generate a random key, a critical resource in various cryptography schemes like one-time pad encryption, by transmitting single or entangled photons [3, 29]. Using quantum superpositions, e.g., of photon polarization or time bin, provides a physical layer of security since any information-revealing intrusions by a potential eavesdropper will necessarily lead to unavoidable and detectable errors, so that an insecure key is never used. However, making these QKD systems in practice is challenging, and demonstrations have suffered from imperfect implementations [38]; QKD thus serves as an interesting initial proving ground for a more general quantum network, as the protocol execution requires many of the essential networking ingredients discussed earlier. It should be noted that QKD is not currently recommended by the United States Government for deployment [39], though there are currently large QKD efforts elsewhere, e.g., China, Europe, Japan and South Korea.

B. Quantum Matter-based Qubit Nodes and Quantum Interconnects

Photons are a mature qubit technology for quantum information science especially when transferring quantum information at distances longer than a chip-scale device. Researchers have made remarkable progress in sending single photons over long distances, but these are largely proof-of-concept demonstrations that are not yet mature enough for deployment in critical systems. Examples of recent long-distance proof-of-concept quantum networks include transmitting entangled photons over 143 kilometers between the Canary islands in a free-space demonstration [7],

---

[‡‡] It is true that there are existing VLBI systems, e.g., the CHARA array [119], but channel loss limits the separations to 100’s of meters.

transmitting single photons over 600 kilometers in a fiber demonstration [8], and achieving conditional teleportation using telecommunication time-bin photonic qubits that were teleported over 22 km and then transmitted over an additional 22-km link to show future network viability [40]. The 2022 Nobel Prize in Physics was awarded to John Clauser, Alain Aspect, and Anton Zeilinger for entangled photon experiments. Photonic systems have also achieved the highest degrees of entanglement including hyper-entangled states – where one can store quantum information in multiple, simultaneous degrees of freedom [41, 42] – and are a potentially competitive technology toward building a quantum computer [9]. Space-based demonstrations include China's 2016 Micius satellite launch [25] (as part of the Quantum Experiments at Space Scale Mission), which was used to demonstrate ground-to-satellite QKD [43], a long-distance QKD experiment between China and Austria via a satellite relay [44], teleportation [45], and distributed entanglement between two ground stations separated by 1,200 kilometers [46] (see ref [47] for a review of other recent satellite quantum communication and networking demonstrations). One collaboration opportunity between the Aerospace and quantum information communities is to mature these technologies, keeping in mind the lessons learned over the past decades in developing classical networks.

The challenge now lies in adding matter-based qubits to the network nodes. The National Science Foundation recently held a workshop on "Quantum Interconnects" and the resulting report, "Development of Quantum Interconnects (QuICS) for Next-Generation Information Technologies" discusses the challenges towards developing these photon-matter qubit interconnects [48]. As the report highlights, quantum interconnects are paramount as they will be a key component for nearly all future quantum information science technologies, from quantum sensors to full-scale quantum computers. For networks, the challenge is to convert the quantum information leaving the network nodes to a wavelength optimized for the specific network channel, and this will depend on whether that segment of the network is operating over fiber or free space. For example, even though many atomic systems naturally emit photons, these are rarely at the correct wavelength for common communication channels – 1550 nm for fiber optic channels and typically between 750 nm to 1550 nm for free space (shorter wavelengths experience less diffraction, but background levels may be higher) – so one must quantum frequency convert -or "transduce"- the signal to the proper frequency range [49]. Though research is promising, many open questions remain, such as how to incorporate the memory components into an existing fiber infrastructure, e.g., most quantum memory options are relatively narrowband (10-100 MHz), not directly compatible with broadband entangled photons that may be spectrally multiplexed over 10s or 100s of nanometers, i.e., many terahertz.

Extending these concepts, a universal network will likely require many different types of matter-based qubits (optimized for computing, sensing, etc.) interfaced to each other and photons to achieve the long-term objectives discussed in this article. Such heterogeneity is likely to be a requirement because each system has different strengths and weaknesses, such as long coherence time but slow operation or the opposite. A critical challenge is to interface these disparate qubit technologies to seamlessly transfer quantum information and entanglement across the network. Researchers have made tremendous progress understanding, creating, and manipulating entanglement within various matter-based qubits (intra-node connections) [28] and preliminary two-node demonstrations [50, 13, 51] paved the way for entanglement distribution between three network nodes [33]. These proof-of-concept demonstrations provide the foundation to extend this work to larger networks; however, several outstanding obstacles stand in the way of increasing network sizes beyond a few nodes and realizing full quantum networking capability [52].

Full network operation also requires two-way communication at the nodes so that information can be read in and out. Most atom-based demonstrations to date have focused on sending a photon from the atom because inducing absorption in an atom from an incoming photon [53, 54] is much more challenging than reading the photon out of the atom [55]. This problem becomes even more difficult for qubit technologies with no natural optical photonic output, such as superconducting qubits. There is much on-going research for microwave-to-optical transduction [56] to connect remote superconducting qubit systems. Another active research area focuses on trying to connect matter-based qubits directly to each other, such as superconducting qubits to trapped ions or neutral atoms [57, 58].

C. Quantum Repeaters

One area of intense research activity is realizing a quantum repeater [19]. There is a fundamental limit to how far a single photon can be transmitted before the signal is significantly attenuated. For example, a typical optical fiber has a minimum attenuation of -0.2db/km around 1550nm, corresponding to only 1% transmission after 100 km and 10^{-20} after 1000 km! Free-space losses can be much less, but are limited by telescope diameters, atmospheric turbulence, and direct line-of-sight constraints. To enable quantum networking at practical rates over longer distances, one can use a repeater to break a long segment up into shorter ones, using quantum error correction and entanglement distillation techniques to restore the targeted quantum state before sending the information to a subsequent network node. Reference [18] presents three different repeater generations (1G, 2G, and 3G) and discusses how to overcome loss and operation errors for each generation. The authors provide a cost coefficient as an optimization parameter, as there is a trade space depending on operational parameters such as gate speed, gate fidelity, and coupling efficiency. To summarize, 3G quantum repeater architectures can achieve much higher speeds, but require much more complex quantum processing at the nodes and can tolerate less loss (at most 50%) between them than 2G or 1G. At present researchers are still working toward a first demonstration of a 1G quantum network.

Ultimately, which repeater generation works best for a specific outcome depends on the desired networking protocol one wants to implement, along with the qubit technologies and topologies available in the network. A quantum repeater has not yet been achieved; however, researchers are making progress. Using a single solid-state spin memory integrated in a nanophotonic diamond resonator, researchers were able to demonstrate entanglement distribution at rates higher than would be possible with direct transmission [59]. Other researchers recently demonstrated the first telecom-heralded entanglement between remote multimode solid-state quantum memories [60]; the entanglement was heralded by detection of a telecommunication photon at a rate up to 1.4 kHz and stored for up to 25 microseconds. In another recent paper [61], researchers demonstrated heralded entanglement distribution between two absorptive memories, generating atom-photon entanglement asynchronously and then performing an entanglement swap between two repeater segments once each atom-photon event was registered. An atomic rubidium ensemble served as a short-term memory while waiting for each atom-photon entanglement event to occur, resulting in a linear dependence on the entanglement generation rate versus a quadratic dependence when there is no memory present. Each of these results and their predecessors pave the way for a future long-distance quantum repeater demonstration; however, it should be stressed that the achieved communication rates in these tour-de-force proof-of-principle experiments are far below what would be necessary for any practical/useful applications. For example, the QKD 600-km fiber record of [8] achieved secret key rates of only 1 bit/sec; in contrast, continuous one-time pad encoding of an audio signal, or blind remote quantum programming, might require >1-1000 kbit/sec.

D. Other Challenges

An outstanding nontrivial challenge is operating quantum networks in conjunction with classical network infrastructure. Many research groups have successfully operated quantum channels in parallel with classical channels, such as in reference [62], where researchers performed a fiber-based QKD experiment at 1550 nm with two simultaneous 200 GHz-spaced classical channels in the same fiber. More recently, classical coexistence experiments have investigated the deleterious noise created by strong classical signals at 1550 nm on entangled photons at ~1310 nm, over a 45-km optical fiber link [63]; having the classical signal at longer wavelength (lower energy) reduces the noise from Raman-process photons. Another solution to the noise added by classical signals is to reduce those signals themselves, by using quantum receivers to detect them [64].

Another difficulty is operating quantum information science apparatuses outside of a well-controlled laboratory environment. Though many photon-based experiments have been successfully fielded, fewer matter-based qubits have been proven outside of a laboratory, and this is currently an active area of investigation. A promising example is the NASA Deep Space Atomic Clock that launched in 2019. This mission is testing the accuracy of a mercury-ion atomic clock in space; a recent publication detailing the clock performance since its launch [65] reports an order-of-magnitude performance improvement over space clocks currently in use. Another recent experiment demonstrated an elementary quantum link that connected two room-temperature quantum memories in nodes at Stony Brook University and Brookhaven National Laboratory, separated by 158 km [66]. Experiments like these pave the way for future fieldable distributed entanglement networks.

The final challenge we will discuss here is how to distribute quantum information and entanglement across more than two nodes. Only recently have researchers moved beyond two nodes and used pairwise entanglement to build up a three-node entangled state [33]. An active research area in quantum computing is how to create multi-partite entanglement, how to operate experiments with high levels of entanglement, and how to verify and validate the entanglement. Quantum networking faces similar challenges but with the added complication of distributing this entanglement across remote nodes [67]. In reference [18], the authors compare three different protocols for connecting two quantum repeater nodes and discuss how one can combine these protocols to realize a larger network connectivity. Reference [68] presents a case where a global distributed entangled state is the starting point and targeted operations are performed within the network to generate a specific end state; the paper also examines multi-partite versus bi-partite entangled states and offers a quantum network configuration protocol to dynamically extend the network.

E. Quantum Network Initiatives

In much the same way that the release of IBM's 5-qubit "quantum computer" to the cloud revolutionized the field of quantum computing [69], a distributed entanglement testing ground offers promise for quantum networking. The IBM 5-qubit cloud device offered researchers a platform to test concepts and develop a better understanding for how quantum computers operate; since then, multiple companies have made their own small-scale quantum processors accessible to the public. Quantum network testbeds, where one can investigate entanglement distribution and get a "hands-on" grasp of the challenges around large-scale entanglement distribution, will likely propel the field forward in a similar manner, and inspire new applications as more people learn what advantages quantum networks offer, and discover new capabilities (e.g., this is a major goal in the recent establishment of a permanent public access quantum network node [70]). In addition, given the overwhelming amount of research still necessary to realize a quantum network, no one group can do it alone; therefore, we must strengthen ties across the many research groups working on quantum networking and come together. Such efforts are starting to take shape in many forms. For example, in 2013, the United Kingdom established several quantum hubs, one of which focuses on Communications and another on Networked Quantum Information Technologies [71], and in the European Union initiated a Quantum Flagship with one focus area on Quantum Communication [72]. As mentioned previously, China has an effort to explore Quantum Experiments at Space Scale [73] and is working toward hybrid networks combining space-and fiber-based links [24]. The US recently released the report, "A Coordinated Approach to Quantum Networking Research" [74], which details the on-going activities within the US government agencies that includes multiple quantum networking testbeds currently under development.

IV. Case Studies

This section will present two quantum-networking case studies of interest to the Aerospace community. The first will focus on entanglement distribution using an unmanned aerial system (UAS) and the challenges associated with operating outside of a laboratory environment. The second will present an experimental demonstration of two entangled quantum clocks and discuss the potential applications this new tool could enable.

A. Case Study 1: Quantum networks on mobile platforms

In future quantum-enabled systems, quantum information processors and sensors will be interconnected via a quantum network; at present, with few exceptions [24] the network nodes are at fixed stations and photons are exchanged over dedicated optical fibers or over free-space channels with fixed optical systems such as telescopes. On the other hand, there are many advantages to developing quantum networks on mobile platforms, such as those shown in Figure 2, to realize flexible and easily reconfigurable quantum networking or sensor systems. For example, there are scenarios where fiber links are simply impossible (ships, planes, etc.), or where a fixed telescope is undesirable, e.g., direct line-of-sight over distances exceeding 10-100 km requires transmitter/receiver heights greater than 100 m to avoid occlusion by the (curved) earth and to minimize the deleterious effects of turbulence (which drops off rapidly with altitude). As a second example, quantum-enhanced sensors will likely be optimally deployed *relative to some region/object of interest*, so being able to readily adjust their location is critical. Such platforms could also be useful for addressing the "last mile" problem that often plagues classical communication systems; as an extreme example, soldiers on a battlefield accessing quantum information resources will need small SWaP solutions. This case study discusses applications of a mobile quantum network, technical challenges for its realization, and a brief review of current progress.

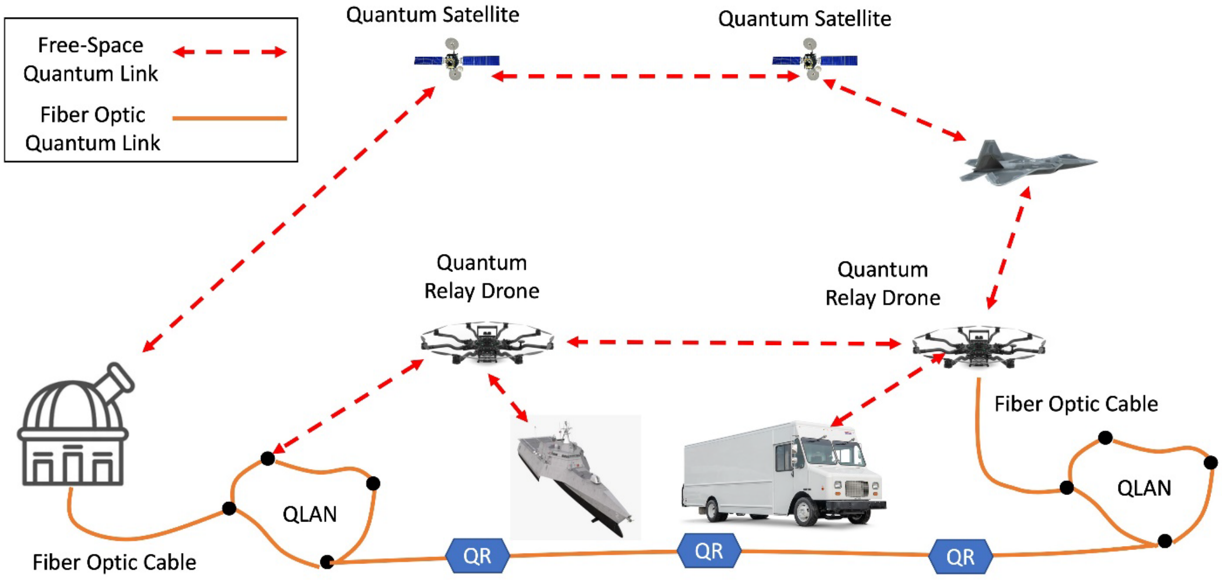

Figure 2 An eventual quantum network will connect across a variety of stationary and mobile platforms using fiber and free-space channels.

As discussed above, quantum networks may enable new applications that go beyond quantum key distribution (QKD) and include blind quantum computing, distributed quantum computing, and distributed quantum sensing. In these applications, there are use cases requiring links beyond a fiber-based network. For example, to establish a secure quantum link across transcontinental or even transoceanic distances, we will either need a fiber link with many robust quantum repeater nodes, or a satellite entanglement "bridge", which will enable higher rates by many orders-of-magnitude, because the transmission for a satellite bridge falls off at worst with distance squared, compared to exponential drop-offs in fiber.

One exciting area of quantum information science is distributed quantum sensing, which we discuss by contrasting with classical sensor networks. In a classical sensor network, multiple devices are used to transduce information from the world around us, such as the presence and location of people, local magnetic fields, or local weather conditions. Data from each sensor is combined to improve the signal-to-noise ratio (SNR) and to create a spatially distributed map. In contrast, a quantum sensor network will use distributed devices that have a shared quantum state via distributed entanglement to greatly improve the SNR. In rough terms, the SNR of a classical sensor network scales as the square-root of the number of devices, whereas it can scale linearly for a quantum sensor network [75].

For many envisioned applications, having a quantum sensor network on mobile systems will be important for several practical reasons. For example, mapping the Earth's anomaly magnetic and gravitational fields, or searching for tunnels and caves will make the most sense using airborne or space-based quantum assets. Furthermore, we can envision having a small quantum computer on a satellite orbiting a distant planet that is integrated with a sensor network on the surface of the planet.

There are many applications where it is important for the sensors to be placed on mobile devices to form a reconfigurable network so that it can focus on areas of interest or adapt to a changing environment. The case of quantum-enhanced clocks, e.g., for geodesy, is discussed below in Case Study 2. Another example is optical quantum telescopy [2], where quantum links between separate telescopes could enable them to act coherently as one large sensor with an angular resolution set by the separation of the telescopes (rather than their individual sizes); varying the baseline separation of the telescopes yields source information in the observed interference (a quantum version of classical stellar very long baseline interferometry) (VLBI). The advantage of the quantum VLBI is that it does not require directly interfering the light received by the individual telescopes. Classical systems must interfere the received light (e.g., starlight). Because transmission loss from the telescope to the point of interference can be high for long baselines, the signal-to-noise of the interfered signal is degraded. In the quantum approach, entangled photons from a central station are sent to the individual telescope, where local interference with the received light and the entangled photon occurs, thus preserving the precious resource – the received light. One challenge is creating quantum light that can interfere with the *asynchronous* stellar photons. Though originally envisioned as an observational technique for astronomy, the same methods could find other applications, *e.g.*, looking downward instead of upward; in this case, entanglement-linked mobile optical sensors would be required.

As another example, consider one day in the future when fault-tolerant quantum computers exist. As with classical computer systems, the efficiency of the system can be enhanced by performing *distributed* processing, with some computations performed at the "edge" where data is collected before transporting a pre-processed dataset to data centers. There will likely be a similar need for quantum computer systems. For example, small quantum computers might be found on satellites in space to pre-process observational data. To transport these calculations to a quantum data center requires that the current quantum state be teleported to the quantum data center. That is, readout of the intermediate calculation cannot be performed, as it would turn the quantum data into classical data. Performing teleportation between the ground and a satellite requires interaction with a moving target (for satellites not in a geosynchronous orbit).

One of the main challenges faced by the community is that a low-error-rate, high-transmission rate quantum network has not been realized. Compounding the problem is that most mobile platforms, such as satellite or small unmanned aerial systems, have severe constraints on the networking device's size, weight, and power ("SWaP"). The fragility of quantum states requires low-loss transport over the communication channel, and precise quantum state generation, manipulation, and measurement. For the measurement, the states are encoded on single photons, which requires high-efficiency single-photon detectors. Another challenge is that quantum teleportation-like protocols, including entanglement "swapping" and quantum telescopy, require interfering single-photon wave packets on a beam splitter and subsequent single-photon detection. These wave packets can have durations below ~ 1 ps, making it challenging to ensure their overlap on a mobile platform. Also, the wave packets need to have identical frequencies, which could be challenging to achieve on a rapidly moving platform due to the Doppler effect. While many of the engineering challenges have been identified through theoretical and numerical modeling studies, the best approaches for addressing these problems have not been proven. Furthermore, experimental tests in a relevant environment or in the field have not yet been undertaken. At best, these systems are at a Technology Readiness Level (TRL) of 2-3 (for a description of TRLs, see https://www.nasa.gov/general/technology-readiness-level/), which corresponds to a proof of concept experimental demonstration; collaboration between the Aerospace and quantum information science communities will accelerate the maturation of these devices and systems.

We now mention some of the recent proof-of-concept experiments for mobile communication experiments. Entanglement distribution using a small unmanned aerial system (drone) has been demonstrated [76]. Here, one drone housed the entanglement source; one photon was sent from the source to a ground station, and the other sent to a second drone, which housed an optical relay device that reshaped the wave packet wavefront to reduce diffractive losses as it passed this wave packet to a second ground station. The researchers achieved verified entanglement distribution over a 1-km-long free-space optical path using this approach. This work developed key components for the entangled source and classical optical tracking, with high performance and light weight, which should be scalable to realize larger networks.

Another project is to develop a mobile network for securely sharing a key between two parties via QKD [77]. QKD relies on transmitting single-photon states between the parties in non-orthogonal bases (*e.g.*, horizontal/vertical and left/right circular polarization) and does not require entanglement-based sources (though such sources have some security advantages). For example, a light-emitting diode coupled into single-mode fiber and attenuated to the single-photon level suffices if extra assumptions are made. Single-photon detectors are required on the quantum receiver. Having achieved stable optical locking between two airborne mobile drones, this team has recently demonstrated air-to-air quantum communication, implementing decoy-state quantum cryptography [78], with the next step to distribute entangled photon states to/from the drone platform.

Developing broader applications of mobile quantum networks requires distributing entangled photonic states, in turn requiring the development of low-SWaP sources; these will likely require optical-waveguide devices integrated with micro-optical systems that can tolerate large temperature variations and mechanical vibration to go beyond what has already been demonstrated [76]. Photonic integrated circuits are being developed to meet these needs, but the requirements of extremely low photon loss and pure quantum state generation have yet to be met; also, these devices often operate in the telecommunication band of the electromagnetic spectrum, where high-quality and low-SWaP single-photon counting detectors are not available. Realizing mobile quantum networks requires substantial engineering effort to exceed the current state-of-the-art of the corresponding classical devices – for example, background noise from the classical Pointing and Tracking locking signals is much more problematic for quantum transmissions than classical, and the quantum systems generally require higher levels of temperature and vibration control – but there seem to be no in-physical limits to prevent such developments. Certainly, the field would benefit greatly from input from the Aerospace community.

B. Case Study 2: An entangled clock network demonstration

A particularly interesting quantum networking application for the Aerospace community may be a quantum network of distributed atomic clocks. Atomic clocks with optical transitions are our most precise tools to measure time and frequency [79, 80, 81]. Optical atomic clocks provide more accuracy and precision than their microwave counterparts; Ref. [79] demonstrated an aluminum-ion based optical atomic clock, which has a fractional frequency uncertainty of less than 10^{-18} - this clock will not gain or lose one second in 33 billion years! Optical clocks that are networked classically could enable time transfer of picosecond accuracy, a level that is not achievable with the Global Positioning System (GPS) or microwave atomic clocks. Further, success in the NASA Deep Space Atomic Clock experiments paves the way for future on-board clocks that may enable deep-space exploration [65] or enable more effective communication between satellite swarms. Here, we discuss the potential benefits of using atomic clocks that are linked via a quantum network and present a recent demonstration of how this remote entanglement might enhance timekeeping applications.

Frequency comparisons between atoms in separate locations can be used to probe the space-time variation of fundamental constants [82], to improve geodesy [82, 83, 84], or to study the properties of dark matter [85, 86]. However, measurements on independent clock systems are limited by the standard quantum limit (SQL). Nonclassical states, such as entangled states, enable measurements beyond the SQL [87, 88, 75] and can attain the Heisenberg limit, the ultimate precision allowed by quantum mechanics, whereby the measurement precision scales as $1/N$, where N is the number of entangled systems (a $\sqrt{N}$ enhancement over measurements with N non-entangled systems, i.e., the SQL). Such ‘quantum-enhanced’ measurements have been used for gravitational wave sensing [89, 90], searches for dark matter [91], and force sensing [92, 93].

For atomic clocks, local entangling operations have been used to demonstrate enhancements for atoms within the same device [94, 95, 96, 97, 98, 99, 100]. Quantum networks can be used for enhanced metrology by distributing entanglement between remote atomic clocks; such entanglement can enable frequency comparisons to move beyond the SQL and reach precision floors faster, leading to the detection of previously undetectable signals or the study of phenomena on shorter timescales. Using a quantum network for such applications is demanding, as it requires high-fidelity remote entanglement to generate an enhancement. Furthermore, the time to generate entanglement needs to be significantly shorter than the probe durations of the atomic clocks (typically about 500 ms [80]) to minimize the effect on the measurement duty cycle.

Recently, Ref. [101] reported the demonstration of entanglement-enhanced frequency comparisons using an elementary quantum network consisting of two $^{88}\mathrm{Sr}^{+}$ ions, separated by ~2 m, that were entangled using a photonic link [26, 15]. Entanglement reduced the measurement uncertainty for frequency comparisons by approximately $\sqrt{2}$, as predicted for the Heisenberg limit, thus halving the number of measurements required to reach a given precision compared to independent measurements on each ion. In addition, entanglement can offer insensitivity to dephasing of the probe laser, which is a limitation to the achievable probe durations, and hence the measurement uncertainty, with present optical clock technology [102, 103]. Conventional correlation spectroscopy techniques [104, 105, 106, 107], which involve simultaneous measurements of an unentangled two-atom state using a common probe laser [108], can enable interrogation times beyond the coherence time of the laser, as recently demonstrated in Ref. [109] for two macroscopically separated clocks. In this regime, compared to correlation spectroscopy, the experiment in Ref. [101] demonstrated that the use of entanglement decreased the measurement uncertainty by nearly a factor of 2, leading to a factor of 4 reduction in the number of measurements required. Thus, the use of entanglement combines insensitivity to probe laser phase noise with the maximum measurement precision permitted by quantum mechanics.

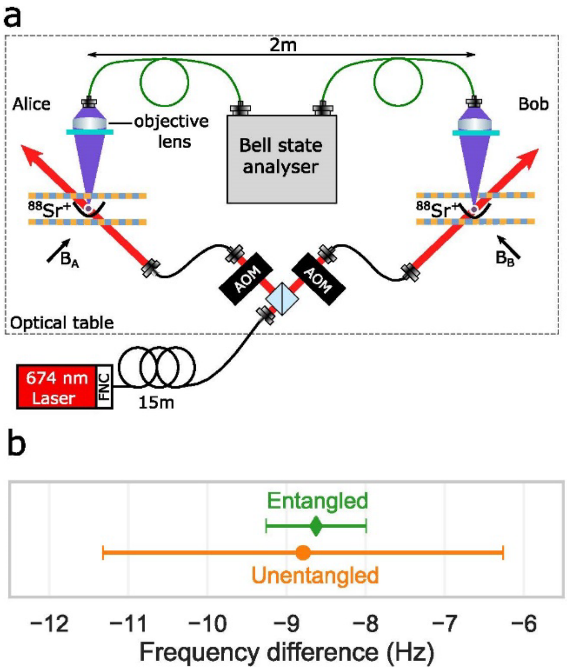

FIG. 3: a) Experimental apparatus for the initial demonstration of an elementary entangled clock network in Ref. [101] **b) Measurement of an applied frequency shift between the two clocks of −8.6±0.6 Hz with (green) and −8.8±2.5 Hz without (orange) entanglement on a 445 THz optical transition. With entanglement, they observed a much smaller uncertainty. (figure adapted from Ref.** [101]**) (Adapted with permission from B. C. Nichol, R. Srinivas, D. P. Nadliinger, P. Drmota, D. Main, G. Araneda, C. J. Ballance and D. M. Lucas, "An elementary quantum network of entangled optical atomic clocks,"** ***Nature,*** **vol. 609, pp. 689-694, 2022. https://doi.org/10.1038/s41586-022-05088-z, 2022, Springer Nature.)**

An overview of the experimental apparatus in Ref. [101] is shown in Fig. 3a. Remote entanglement is created between two ^{88}Sr^{+} ions that are separated by about 2 m. Using a photonic link, the authors achieved a remote entanglement fidelity of 0.960(2) in an average duration of 9 ms [110]. As shown in Fig. 3b, they observed a reduction in the measurement uncertainty for a frequency shift applied to one of the ions using entanglement-enhanced spectroscopy, compared to that obtained using correlation spectroscopy with unentangled atoms.

The achievable probe durations in Ref. [101] of about 10 ms were short compared to the limit set by the ^{88}Sr^{+} $4D_{5/2}$ lifetime [111] of ≈ 400 ms, due to qubit decoherence from magnetic field fluctuations. This decoherence limited the absolute measurement precision to a fractional frequency uncertainty of ~10^{-15}, approximately three orders of magnitude worse than the state of the art for optical clocks [79]. These magnetic field fluctuations could be reduced by using superconducting solenoids [112], mu-metal shielding [113], or more advanced dynamical decoupling schemes [114]. The remote entanglement could in principle be mapped to any other ion species via quantum logic operations [115], with negligible loss of fidelity or speed using local mixed-species entangling operations [116]. Longer probe durations could be achieved with a secondary ion species with a transition that has a reduced magnetic field sensitivity [79] or a narrower linewidth. The secondary ion species could also have an increased sensitivity to fundamental constants [86].

For remote sensing applications of geodesy, larger distances between the clock nodes will be required. While longer fibers with phase noise cancellation [117] could be used, the entanglement rate would be quickly reduced due to substantial fiber losses at 422 nm; this reduction could be potentially mitigated by frequency conversion to telecommunication wavelengths [118]. A larger network of atomic clocks, with more ions in each node, could reduce the measurement uncertainty further [5], either by having more ions in each node with local entangling operations, or with more nodes connected via additional photonic links.

V. Conclusion

The ability to distribute and harness quantum states will lead to exciting new capabilities for networking and communication as outlined in this article. Distributed entanglement will provide a fundamentally new way to communicate, through protocols such as teleportation, and may ultimately enable new capabilities such as entangled sensor arrays that will provide unprecedented imaging capabilities; new modalities for time transfer across networks; unparalleled accuracy for time keeping; the ability to perform distributed quantum computing, and other yet-to-be-imagined possibilities. Though researchers are making progress in understanding entanglement distribution, there are many outstanding challenges to overcome and many questions to answer. One of these is ascertaining some meaningful short-term use cases for these new networks. The Aerospace community could play a pivotal role in unlocking some of these answers through increased collaboration and multi-disciplinary opportunities. Once realized, this new tool set could provide novel solutions to current and future problems related to drone synchronization, satellite communications, and deep space exploration. Despite the difficulties ahead, the future holds great promise for this new networking paradigm.

Acknowledgments

KABS gratefully acknowledges support from the Air Force Research Laboratory and the Air Force Office of Scientific Research. The views expressed are those of the authors and do not reflect the official guidance or position of the United States Government, the Department of Defense or of the United States Air Force.

DJG and PGK gratefully acknowledge previous financial support from the Office of Naval Research Multidisciplinary University Research Initiative program on Wavelength-Agile QKD in a Marine Environment (grant N00014-13-1-0627). PGK acknowledges support from the U.S. Department of Energy Office of Science National Quantum Information Science Research Center Q-NEXT (award DE-AC02-06CH11357).

R.S. acknowledges funding from the EPSRC Fellowship EP/W028026/1 and Balliol College.

VI.References

[1] M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information, Cambridge University Press, 2000.

[2] D. Gottesman, T. Jennewein and S. Croke, "Longer-Baseline Telescopes Using Quantum Repeaters," *Phys. Rev. Lett.,* vol. 109, p. 070503, 2012. https://doi.org/10.1103/PhysRevLett.109.070503.

[3] C. H. Bennett and G. Brassard, "Quantum Cryptography: Public Key Distribution and Coin Tossing," *Proceedings of the IEEE International Conference on Computers, Systems, and Signal Processing,* pp. 175-179, 1984. https://doi.org/10.1016/j.tcs.2014.05.025.

[4] P. W. Shor, "Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer," *SIAM J. Sci. Statist. Comput.,* vol. 26, p. 1484, 1997. https://doi.org/10.1137/S0097539795293172.

[5] P. Kómár, E. M. Kessler, M. Bishof, L. Jiang, A. S. Sørensen, J. Ye and M. D. Lukin, "A quantum network of clocks," *Nature Physics,* vol. 10, pp. 582-587, 2014. https://doi.org/10.1038/nphys3000.

[6] H. J. Kimble, "The quantum internet," *Nature,* vol. 453, pp. 1023-1030, 2008. https://doi.org/10.1038/nature07127.

[7] T. Herbst, T. Scheidl, M. Fink and A. Zeilinger, "Teleportation of entanglement over 143 km," *PNAS,* vol. 112, no. 46, pp. 14202-14205, 2015. https://doi.org/10.1073/pnas.1517007112.

[8] M. Pittaluga, M. Minder, M, Lucamarini, M. Sanzaro, R. I. Woodward, M.-J. Li, Z. Yuan and A. J. Shields, "600-km repeater-like quantum communications with dual-band stabilization," *Nature Photonics,* vol. 15, pp. 530-535, 2021. https://www.nature.com/articles/s41566-021-00811-0.

[9] D. Llewellyn, Y. Ding, I. I. Faruque, S. Paesani, D. Bacco, R. Santagati, Y.-J. Qian, Y. Li, Y.-F. Xiao, M. Huber, M. Malik, G. F. Sinclair, X. Zhou, K. Rottwitt, J. L. O'Brien, J. G. Rarity, Q. Gong, L. K. Oxenlowe, J. Wang and M. G. Thompson, "Chip-to-Chip quantum teleporation and multi-photon entanglement in silicon," *Nature Physics,* vol. 16, pp. 148-153, 2020. https://doi.org/10.1038/s41567-019-0727-x.

[10] P. Kobel, M. Breyer and M. Köhl, "Deterministic spin-photon entanglment form a trapped ion in a fiber Fabry-Perot cavity," *npj Quantum Infomrmation,* vol. 7, p. 6, 2021. https://doi.org/10.1038/s41534-020-00338-2.

[11] Y. Zhong, H.-S. Chang, A. Bienfait, É. Dumur, M.-H. Chou, C. R. Connor, J. Grebel, R. G. Povey, H. Yan, D. I. Schuster and A. N. Cleland, "Deterministic multi-qubit entanglement in a quantum network," *Nature,* vol. 590, pp. 571-575, 2021. https://doi.org/10.1038/s41586-021-03288-7.

[12] A. Bienfait, K. J. Satzinger, Y. P. Zhong, H.-S. Chang, M.-H. Chou, C. R. Conner, É. Dummur, J. Grebel, G. A. Peairs, R. G. Povey and A. N. Cleland, "Phonon-mediated quantum state transfer and remote qubit entanglement," *Science,* vol. 364, no. 6438, pp. 368-371, 2019. https://doi.org/10.1126/science.aaw8415.

[13] P. Kurpiers, P. Magnard, T. Walter, B. Royer, M. Pechal, J. Heinsoo, Y. Salathé, A. Akin, S. Storz, J.-C. Besse, S. Gasparinetti, A. Blais and A. Wallraff, "Deterministic quantum state transfer and remote entanglement using microwave photons," *Nature,* vol. 558, pp. 264-267, 2018. https://doi.org/10.1038/s41586-018-0195-y.

[14] V. Krutyanskiy, M. Meraner, J. Schupp, V. Krmarsky, H. Hainzer and B. P. Lanyon, "Light-matter entanglement over 50 km of optical fiber," *npj Quantum Information,* vol. 5, p. 72, 2019. https://doi.org/10.1038/s41534-019-0186-3.

[15] L. J. Stephenson, D. P. Nadlinger, B. C. Nichol, S. An, P. Drmota, T. G. Ballance, K. Thirumalai, J. F. Goodwin, D. M. Lucas and C. J. Ballance, "High-rate, high-fidelity entanglement of qubits across an elementary quantum netwok," *Physical Review Letters,* vol. 124, p. 110501, 2020. https://doi.org/10.1103/PhysRevLett.124.110501.

[16] L.-M. Duan, M. D. Lukin, J. I. Cirac and P. Zoller, "Long-distance quantum communication with atomic ensembles and linear optics," *Nature,* vol. 414, pp. 413-418, 2001. https://doi.org/10.1038/35106500.

[17] C. J. Axline, L. D. Burkhart, W. Pfaff, M. Zhang, K. Chou, P. Campagne-Ibarcq, P. Reinhold, L. Frunzio, S. M. Girvin, L. Jiang, M. H. Devoret and R. J. Schoelkopf, "On-demand quantum state transfer and entanglelment between remote microwave cavity memories," *Nature Physics,* vol. 14, pp. 705-710, 2018. https://doi.org/10.1038/s41567-018-0115-y.

[18] C. Jones, D. Kim, M. T. Rakher, P. G. Kwiat and T. D. Ladd, "Design and analysis of communication protocols for quantum repeater networks," *New J. Phys.,* vol. 18, p. 083015, 2016. https://doi.org/10.1088/1367-2630/18/8/083015.

[19] H.-J. Briegel, W. Dür, J. I. Cirac and a. P. Zoller, "Quantum Repeaters: The Role of Imperfect Local Operations in Quantum Communication," *Phys. Rev. Lett.,* vol. 81, p. 5932, 1998. https://link.aps.org/doi/10.1103/PhysRevLett.81.5932.

[20] S. Olmschenk, D. N. Matsukevich, P. Maunz, D. Hayes, L.-M. Duan and C. Monroe, "Quantum Teleportation Between Distant Matter Qubits," *Science,* vol. 323, no. 5913, pp. 486-489, 2009. https://doi.org/10.1126/science.1167209.

[21] D. Bouwmeester, J.-W. Pan, K. Mattle, M. Eibl, H. Weinfurter and A. Zeilinger, "Experimental quantum teleportation," *Nature,* vol. 390, pp. 575-579, 1997. https://doi.org/10.1038/37539.

[22] S. K. Joshi, D. Aktas, S. Wengerowsky, M. Lončarić, S. P. Neumann, B. Liu, T. Scheidl, G. C. Lorenzo, Ž. Samec, L. Kling, A. Qiu, M. Razavi, M. Stipčević, J. G. Rarity and R. Ursin, "A trusted node-free eight-user metropolitan quantum communication network," *Science Advances,* vol. 6, p. eaba0959, 2020. https://doi.org/10.1126/sciadv.aba0959.

[23] J. F. Dynes, A. Wonfor, W. W.-S. Tam, A. A. Sharpe, R. Takahashi, M. Lucamarini, A. Plews, Z. L. Yuan, A. R. Dixon, J. Cho, Y. Tanizawa, J.-P. Elbers, H. Greißer,, I. H. White, R. V. Penty and A. J. Shields, "Cambridge Quantum Network," *npj Quantum Information,* vol. 5, p. 101, 2019. https://doi.org/10.1038/s41534-019-0221-4.

[24] Y.-A. Chen, Q. Zhang, T.-Y. Chen, W.-Q. Cai, S.-K. Liao, J. Zhang, K. Chen, J. Yin, J.-G. Ren, Z. Chen, S.-L. Han, Q. Yu, K. Liang, F. Zhou, X. Yuan, M.-S. Zhao, T.-Y. Wang, X. Jiang, L. Zhang, W.-Y. Liu, Y. Li, Q. Shen, Y. Cao, C.-Y. Lu, R. Shu, J.-Y. Wang, L. Li, N.-L. Liu, F. Xu, X.-B. Wang, C.-Z. Peng and J.-W. Pan, "An integrated space-to-ground quantum communication network over 4,600 kilometers," *Nature,* vol. 589, pp. 214-219, 2021. https://doi.org/10.1038/s41586-020-03093-8.

[25] C.-Y. Lu, Y. Cao, C.-Z. Peng and J.-W. Pan, "Micius quantum experiments in space," *Rev. Mod. Phyis.,* vol. 94, p. 035001, 2022. https://doi.org/10.1103/RevModPhys.94.035001.

[26] C. Monroe, R. Raussendorf, A. Ruthven, K. R. Brown, P. Maunz, L.-M. Duan and J. Kim, "Large-scale modular quantum-computer architecture with atomic memory and photonic interconnects," *Phys. Rev. A,* vol. 89, p. 022317, 2014. https://doi.org/10.1103/PhysRevA.89.022317.

[27] D. P. DiVincenzo, "The Physical Implementation of Quantum Computation," *Fortschritte der Physik,* vol. 48, pp. 771-783, 2000. https://doi.org/10.1002/1521-3978(200009)48:9/11%3C771::AID-PROP771%3E3.0.CO;2-E.

[28] T. D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe and J. L. O'Brien, "Quantum Computers," *Nature,* vol. 464, p. 45, 2010. https://doi.org/10.1038/nature08812.

[29] A. K. Ekert, "Quantum cryptography based on Bell's theorem," *Phys. Rev. Lett.,* vol. 67, p. 661, 1991. https://doi.org/10.1103/PhysRevLett.67.661.

[30] K. Mølmer and A. Sørensen, "Multiparticle Entanglement of Hot Trapped Ions," *Phys. Rev. Lett.,* vol. 82, p. 1835, 1999. https://doi.org/10.1103/PhysRevLett.82.1835.

[31] J. I. Cirac and P. Zoller, "Quantum Computations with Cold Trapped Ions," *Phys. Rev. Lett.,* vol. 74, p. 4091, 1995. https://doi.org/10.1103/PhysRevLett.74.4091.

[32] D. Hucul, I. Inlek, G. Vittorini, C. Crocker, D. Debnath, S. Clark and C. Monroe, "Modular entanglement of atomic qubits using photons and phonons," *Nature Physics,* vol. 11, p. 37, 2015. https://doi.org/10.1038/nphys3150.

[33] M. Pompili, S. L. N. Hermans, S. Baier, H. K. C. Beukers, P. C. Humphreys, R. N. Schouten, R. F. L. Vermeulen, M. J. Tiggelman, L. Dos Santos Martins, B. Dirkse, S. Wehner and R. Hanson, "Realization of a multinode quantum network of remote solid-state qubits," *Science,* vol. 372, no. 6539, pp. 259-264, 2021. https://doi.org/10.1126/science.abg1919.

[34] C. Monroe, R. J. Schoelkopf and M. D. Lukin, "Quantum Connections and the Modular Quantum Computer," *Scientific American,* p. 50, 2016. https://doi.org/10.1038/scientificamerican0516-50.

[35] C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres and W. K. Wootters, "Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels," *Phys. Rev. Lett.,* vol. 70, p. 1895, 1993. https://doi.org/10.1103/PhysRevLett.70.1895.

[36] L. Jiang, J. M. Taylor, A. S. Sørensen and M. D. Lukin, "Distributed quantum computation based on small quantum registers," *Phys. Rev. A,* vol. 76, p. 062323, 2007. https://link.aps.org/doi/10.1103/PhysRevA.76.062323.

[37] J. Fitzsimons, "Private quantum computation: an introduction to blind quantum computing and related protocols," *npj Quantum Information,* vol. 23, 2017. https://doi.org/10.1038/s41534-017-0025-3.

[38] V. Scarani and C. Kurtsiefer, "The black paper of quantum cryptography: Real implementation problems," *Theoretical Computer Science,* vol. 560, pp. 27-32, 2014. https://doi.org/10.1016/j.tcs.2014.09.015.

[39] [Online]. Available: https://www.nsa.gov/Cybersecurity/Quantum-Key-Distribution-QKD-and-Quantum-Cryptography-QC/.

[40] R. Valivarthi, S. I. Davis, C. Pena, S. Xie, N. Lauk, L. Narvaez, J. P. Allmaras, A. D. Beyer, Y. Gim, M. Hussein, G. Iskander, H. L. Kim, B. Korzh, A. Mueller, M. Rominsky, M. Shaw, D. Tang, E. E. Wollman, Simon, C. Spetzouris, D. P. Oblak, N. Sinclair and M. Spiropulu, "Teleportation Systems Toward a Quantum Internet," *PRX,* vol. 1, p. 020317, 2020. https://doi.org/10.1103/PRXQuantum.1.020317.

[41] P. G. Kwiat, "Hyper-entangled states," *Journal of Modern Optics,* vol. 44, no. 11-12, pp. 2173-2184, 1997. https://doi.org/10.1080/09500349708231877.

[42] J. C. Chapman, T. M. Graham, C. K. Zeitler, H. J. Bernstein and a. P. G. Kwiat, "Time-Bin and Polarization Superdense Teleportation for Space Applications," *Phys. Rev. Applied,* vol. 14, p. 014044, 2020. https://doi.org/10.1103/PhysRevApplied.14.014044.

[43] S.-K. Liao, W.-Q. Cai, W.-Y. Liu, L. Zhang, Y. Li, J.-G. Ren, J. Yin, Q. Shen, Y. Cao, Z.-P. Li, F.-Z. Li, X.-W. Chen, L.-H. Sun, J.-J. Jia, J.-C. Wu, X.-J. Jiang, J.-F. Wang, Y.-M. Huang, Q. Wang, Y.-L. Zhou, L. Deng, T. Xi, L. Ma, T. Hu, Q. Zhang, Y.-A. Chen, N.-L. Liu, X.-B. Wang, Z.-C. Zhu, C.-Y. Lu, R. Shu, C.-Z. Peng, J.-Y. Wang and J.-W. Pan, "Satellite-to-ground quantum key distribution," *Nature,* vol. 549, pp. 43-47, 2017. https://doi.org/10.1038/nature23655.

[44] S.-K. Liao, W.-Q. Cai, J. Handsteiner, B.Liu, J. Yin, L. Zhang, D. Rauch, M. Fink, J.-G. Ren, W.-Y. Liu, Y. Li, Q. Shen, Y. Cao, F.-Z. Li, J.-F.Wang, Y.-M. Huang, L. Deng, T. Xi, L. Ma, T. Hu, L. Li, N.-L. Liu, F. Koidl, P. Wang, Y.-A. Chen, X.-B. Wang, M. Steindorfer, G. Kirchner, C.-Y. Lu, R. Shu, R. Ursin, T. Scheidl, C.-Z. Peng, J.-Y. Wang, A. Zelinger and J.-W. Pan, "Satellite-Relayed Intercontinental Quantum Network," *Phys. Rev. Lett.,* vol. 120, p. 030501, 2018. https://doi.org/10.1103/PhysRevLett.120.030501.

[45] J.-G. Ren, P. Zu, H.-L. Yong, L. Zhang, S.-K. Liao, J. Yin, W.-Y. Liu, W.-Q. Cai, M. Yang, L. Li, K.-X. Yang, X. Han, Y.-Q. Yao, J. Li, H.-Y. Wu, S. Wan, L. Liu, D.-Q. Liu, Y.-W. Kuang, Z.-P. He, P. Shang, C. Guo, R.-H. Zheng, K. Tian, Z.-C. Zhu, N.-L. Liu, C.-Y. Lu, R. Shu, Y.-A. Chen, C.-Z. Peng, J.-Y. Wang and J.-W. Pan, "Ground-to-satellite quantum teleportation," *Nature,* vol. 549, pp. 70-73, 2017. https://doi.org/10.1038/nature23675.

[46] J. Yin, Y. Cao, Y.-H. Yi, S.-L. Liao, L. Zhang, J.-G. Ren, W.-Q. Cai, W.-Y. Liu, B. Li, H. Dai, G.-B. Li, Q.-M. Lu, Y.-H. Gong, Y. Xu, S.-L. Li, F.-Z. Li, Y.-Y. Yin, Z.-Q. Jiang, M. Li, J.-J. Jia, G. Ren, D. He, Y.-L. Zhou, X.-X. Zhang, N. Wang, X. Chang, Z.-C. Zhu, N.-L. Liu, Y.-A. Chen, C.-Y. Lu, R. Shu, C.-Z. Peng, J.-Y. Wang and J.-W. Pan, "Satellite-based entanglement distribution over 1200 kilometers," *Science,* vol. 356, pp. 1140-1144, 2017. https://doi.org/10.1126/science.aan3211.

[47] J. S. Sidu, S. K. Joshi, M. Gundoğan, T. Brougham, D. Lowndes, L. Mazzarella, M. Krutzik, S. Mohapatra, D. Dequal, G. Vallone, P. Villoresi, A. Ling, T. Jeneewein, M. Mohageg, J. G. Rarity, I. Fuentes, S. Pirandola and D. K. L. Oi, "Advances in space quantum communications," *IET Quantum Communication,* vol. 2, pp. 182-217, 2021. https://doi.org/10.1049/qtc2.12015.

[48] D. Awschalom, K. K. Berggren, H. Bernien, S. Bhave, L. D. Carr, P. Davids, S. E. Economou, D. Englund, A. Faraon, M. Fejer, S. Guha, M. V. Gustafsson, E. Hu, L. Jiang, J. Kim, B. Korzh, P. Kumar, P. G. Kwiat, M. Lončar, M. D. Lukin, D. A. B. Miller, C. Monroe, S. W. Nam, P. Narang, J. S. Orcutt, M. G. Raymer, A. H. Safavi-Naeini, M. Spiropulu, K. Srinivasan, S. Sun, J. Vučković, E. Waks, R. Walsworth, A. Weiner and Z. Zhang, "Development of Quantum Interconnects (QuICs) for Next-Generation Information Technologies," *PRX Quantum,* vol. 2, p. 017002, 2021. https://doi.org/10.1103/PRXQuantum.2.017002.

[49] P. Kumar, "Quantum Frequency Conversion," *Opt. Lett.,* vol. 15, pp. 1476-1478, 1990. https://doi.org/10.1364/OL.15.001476.

[50] D. L. Moehring, P. Maunz, S. Olmschenk, K. C. Younge, D. N. Matsukevich, L.-M. Duan and C. Monroe, "Entanglement of single-atom quantum bits at a distance," *Nature,* vol. 449, p. 68, 2007. https://doi.org/10.1038/nature06118.

[51] S. Krastanov, H. Raniwala, J. Holzgrafe, K. Jacobs, M, Lončar, M. J. Reagor and a. D. R. Englund, "Optically Heralded Entanglement of Superconducting Systems in Quantum Networks," *Phys. Rev. Lett.,* vol. 127, p. 040503, 2021. https://doi.org/10.1103/PhysRevLett.127.040503.

[52] S. Wehner, D. Elkouss and R. Hanson, "Quantum internet: A vision of the road ahead," *Science,* vol. 362, no. 6412, p. eaam9288, 2018. https://doi.org/10.1126/science.aam9288.

[53] C. Kurz, M. Schug, P. Eich, J. Huwer, P. Müller and J. Eschner, "Experimental protocol for high-fidelity heralded photon-to-atom quantum state transfer," *Nature Communications,* vol. 5, p. 5527, 2014. https://doi.org/10.1038/ncomms6527.

[54] A. Lenhard, M. Bock, C. Becher, S. Kucera, J. Brito, P. Eich, P. Müller and J. Echner, "Telecom-herladed single-photon absorption by a single atom," *Phys. Rev. A,* vol. 92, p. 063827, 2015. https://doi.org/10.1103/PhysRevA.92.063827.

[55] B. B. Blinov, D. L. Moehring, L.-M. Duan and C. Monroe, "Observation of entanglement between a single trapped atom and a single photon," *Nature,* vol. 428, p. 153, 2004. https://doi.org/10.1038/nature02377.

[56] N. Lauk, N. Sinclair, S. Barzanjeh, J. P. Covey, M. Saffman, M. Spiropulu and C. Simon, "Perspectives on quantum transduction," *Quantum Sci. and Technol.,* vol. 5, p. 020501, 2020. https://doi.org/10.1088/2058-9565/ab788a.

[57] D. D. Motte, A. R. Grounds, M. Rehák, A. R. Blanco, B. Lekitsch, G. S. Giri, P. Neilinger, G. Oelsner, E. Il'ichev, M. Grajcar and W. K. Hensinger, "Experimental system design for the integration of trapped-ion and superconducting qubit systems," *Quantum Information Processing,* vol. 15, pp. 5385-5414, 2016. https://doi.org/10.1007/s11128-016-1368-y.

[58] D. Petrosyan, K. Mølmer, J. Fortágh and M. Saffman, "Microwave to optical conversion with atoms on a superconducting chip," *New Journal of Physics,* vol. 21, p. 073033, 2019. https://doi.org/10.1088/1367-2630/ab307c.

[59] M. K. Bhaskar, R. Riedinger, B. Machielse, D. S. Levonian, C. T. Nguyen, E. N. Knall, H. Park, D. Englund, M. Lončar, D. D. Sukachev and M. D. Lukin, "Experimental demonstration of memory-enhanced quantum communication," *Nature,* vol. 580, pp. 60-64, 2020. https://doi.org/10.1038/s41586-020-2103-5.

[60] D. Lago-Rivera, S. Grandi, J. V. Rakonjac, A. Seri and H. d. Riedmatten, "Telecom-heralded entanglement between multi-mode solid-state quantum memories," *Nature,* vol. 594, pp. 37-40, 2021. https://doi.org/10.1038/s41586-021-03481-8.

[61] X. Liu, J. Hu, Z.-F. Li, X. Li, P.-Y. Li, P.-J. LIang, Z.-Q. Zhou, C.-F. Li and G.-C. Guo, "Heralded entanglment distribution between two absorptive quantum memories," *Nature,* vol. 594, pp. 41-45, 2021. https://doi.org/10.1038/s41586-021-03505-3.

[62] N. Peters, P. Toliver, T. E. Chapuran, R. J. Rusner, S. R. McNown, C. G. Peterson, D. Rosenberg, N. Dallmann, R. J. Hughes, K. P. McCabe, J. E. Nordholt and K. T. Tyagi, "Dense wavelength multiplexing of 1550 nm QKD with strong classical channles in reconfigurable networking environments," *New Journal of Physics,* vol. 11, p. 045012, 2009. https://doi.org/10.1088/1367-2630/11/4/045012.

[63] J. M. Thomas, G. S. Kanter, E. M. Eastman, K. F. Lee and P. Kumar, "Entanglement Distribution in Installed Fiber with Coexisting Classical Light for Quantum Network Applications," *in Optical Fiber Communication Conference (OFC) 2022, S. Matsuo, D. Plant, J. Shan Wey, C. Fludger, R. Ryf, and D. Simeonidou, eds., Technical Digest Series,* p. paper Tu3I.3, 2022.

[64] I. A. Burenkov, A. Seminov, T. Gerrits, A. Rahmouni, D. Anand, Y.-S. Li-Baboud, O. Slattery, A. Battou and S. V. Polyakov, "Synchronization and coexistence in quantum networks," *Optics Express,* vol. 31, p. 11431, 2023. https://doi.org/10.1364/OE.480486.

[65] E. A. Burt, J. D. Prestage, R. L. Tjoelker, D. G. Enzer, D. Kuang, D. W. Murphy, D. E. Robison, J. M. Seubert, R. T. Wang and T. A. Ely, "Demonstration of a trapped-ion atomic clock in space," *Nature,* vol. 595, pp. 43-47, 2021. https://doi.org/10.1038/s41586-021-03571-7.

[66] D. Du, P. Stankus, O.-P. Saira, M. Flament, S. Sagona-Stphel, M. Namazi, D. Katramatos and E. Figueroa, "An elemantary 158-km long quantum network connecting room temperature quantum memories," *arXiv:2101.12742v1,* 2021. https://doi.org/10.48550/arxiv.2101.12742.

[67] S. Das, S. Khatri and J. P. Dowling, "Robust quantum network architectures and topologies for entanglement distribution," *Phys. Rev. A,* vol. 97, p. 012335, 2018. https://doi.org/10.1103/PhysRevA.97.012335.

[68] A. Pirker, J. Wallnöfer and W. Dür, "Modular architectures for quantum networks," *New J. Phys.,* vol. 20, p. 053054, 2018. https://doi.org/10.1088/1367-2630/aac2aa.

[69] C. Lee, "How IBM's new five-qubit universal quantum computer works," 4 May 2016. [Online]. Available: https://arstechnica.com/science/2016/05/how-ibms-new-five-qubit-universal-quantum-computer-works/.

[70] [Online]. Available: https://grainger.illinois.edu/news/stories/60290.

[71] P. Knight and I. Walmsley, "UK National Quantum Technology Programme," *Quantum Science and Technology,* vol. 4, p. 040502, 2019. https://doi.org/10.1088/2058-9565/ab4346.

[72] "Quantum Technologies Flagship Final Report," High Level Steering Committee, European Union, June 2017.

[73] E. Gibney, "Chinese satellite is one giant step for the quantum internet," *Nature,* vol. 535, pp. 478-479, 2016. https://doi.org/10.1038/535478a.

[74] "A Coordinated Approach to Quantum Networking Research," National Science and Technology Council, Washington, DC, January 2021.

[75] C. L. Degen, F. Reinhard and P. Cappellaro, "Quantum Sensing," *Rev. Mod. Phys.,* vol. 89, p. 035002, 2017. https://doi.org/10.1103/RevModPhys.89.035002.

[76] H.-Y. Liu, X.-H. Tian, C. Gu, P. Fan, X. Ni, R. Yang, J.-N. Zhang, M. Hu, J. Guo, X. Cao, Z. Hu, G. Zhao, Y.-Q. Lu, Y.-X. Gong, Z. Xie and S.-N. Zhu, "Optical-Relayed Entanglement Distribution Using Drones as Mobile Nodes," *Phys. Rev. Lett.,* vol. 126, no. 2, p. 020503, 2021. https://doi.org/10.1103/PhysRevLett.126.020503.

[77] A. Conrad, S. Isaac, R. Cochran, D. Sanchez-Rosales, B. Wilens, A. Gutha, T. Rezaei, D. J. Gauthier and P. Kwiat, "Drone-based quantum key distribution: QKD," *Proc. SPIE Free-Space Laser Communications XXXIII,* vol. 11678, p. 116780X, 2021. https://doi.org/10.1117/12.2582376.

[78] H.-K. Lo, X. Ma and K. Chen, "Decoy State Quantum Key Distribution," *Phys. Rev. Lett.,* vol. 94, p. 230504, 2005. https://doi.org/10.1103/PhysRevLett.94.230504.

[79] S. M. Brewer, J.-S. Chen, A. M. Hankin, E. R. Clements, C. W. Chou, D. J. Wineland, D. B. Hume and D. Leibrandt, "27 Al + Quantum-Logic Clock with a Systematic Uncertaintly below 10^-18," *Phys. Rev. Lett.,* vol. 123, p. 033201, 2019. https://doi.org/10.1103/PhysRevLett.123.033201.

[80] E. Oekler, R. B. Hutson, C. J. Kennedy, L. Sonderhouse, T. Bothwell, A. Goban, D. Kedar, C. Sanner, J. M. Robinson, G. E. Marti, D. G. Matei, T. Legero, M. Giunta, R. Holzwarth, F. Riehle, U. Sterr and J. Ye, "Demonstration of 4.8 x 10^-17 stability at 1 s for two independent clocks," *Nature Photonics,* vol. 13, pp. 714-719, 2019. https://doi.org/10.1038/s41566-019-0493-4.

[81] A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik and P. O. Schmidt, "Optical atomic clocks," *Rev. Mod. Phys.,* vol. 87, p. 637, 2015. https://doi.org/10.1103/RevModPhys.87.637.

[82] T. Rosenband, D. B. Hume, P. O. Schmidt, C. W. Chou, A. Brusch, L. Lorini, W. H. Oskay, R. E. Drullinger, T. M. Fortier, J. E. Stalnaker, S. A. Diddams, W. C. Swann, N. R. Newbury, W. M. Itano, D. J. Wineland and J. C. Bergquist, "Frequency Ratio of Al+ and Hg+ Single-Ion Optical Clocks; Metrology at the 17th Decimal Place," *Science,* vol. 319, no. 5871, pp. 1808-1812, 2008. https://doi.org/10.1126/science.1154622.

[83] T. E. Mehlstäubler, G. Grosche, C. Lisdat, P. O. Schmidt and H. Denker, "Atomic clocks for geodesy," *Rep. Prog. Phys.,* vol. 81, no. 6, p. 064401, 2018. https://doi.org/10.1088/1361-6633/aab409.

[84] W. F. McGrew, Z. Zhang, R. J. Fasano, S. A. Schäffer, K. Beloy, D. Nicolodi, R. C. Brown, N. Hinkley, G. Milani, M. Schioppo, T. H. Yoon and A. D. Ludlow, "Atomic clock performance enabling geodesy below the centimetre level," *Nature,* vol. 564, pp. 87-90, 2018. https://doi.org/10.1038/s41586-018-0738-2.

[85] A. Dervianko and M. Pospelov, "Hunting for topological dark matter with atomic clocks," *Nature Physics,* vol. 10, pp. 933-936, 2014. https://doi.org/10.1038/nphys3137.

[86] M. S. Safronova, D. Budker, D. DeMille, D. F. J. Kimball, A. Derevianko and C. W. Clark, "Search for new physics with atoms and molecules," *Rev. Mod. Phys.,* vol. 90, p. 025008, 2018. https://doi.org/10.1103/RevModPhys.90.025008.

[87] D. J. Wineland, J. J. Bollinger, W. M. Itano, F. L. Moore and D. J. Heinzen, "Spin squeezing and reduced quantum noise spectroscopy," *Phys. Rev. A,* vol. 46, p. R6797(R), 1992. https://doi.org/10.1103/PhysRevA.46.R6797.

[88] D. J. Wineland, J. J. Bollinger, W. M. Itano and D. J. Heinzen, "Squeezed atomic states and projection noise in spectroscopy," *Phys. Rev. A,* vol. 50, p. 67, 1994. https://doi.org/10.1103/PhysRevA.50.67.

[89] C. M. Caves, "Quantum-mechanical noise in an interferometer," *Phys. Rev. D,* vol. 23, p. 1693, 1981. https://doi.org/10.1103/PhysRevD.23.1693.

[90] M. Tse, H. Yu, N. Kijbunchoo, A. Fernandez-Galiana, P. Dupej, L. Barsotti, C. D. Blair, D. D. Brown, S. E. Dwyer, A. Effler, M. Evans, P. Fritschel, V. V. Frolov, A. C. Green, G. L. Mansell, F. Matichard, N. Mavalvala, D. E. McClelland, L. McCuller, T. McRae, J. Miller, A. Mullavey, E. Oelker, I. Y. Phinney, D. Sigg, B. J. J.

Slagmolen, T. Vo, R. L. Ward, C. Whittle, R. Abbott, C. Adams, R. X. Adhikari, A. Ananyeva, S. Appert, K. Arai, J. S. Areeda, Y. Asali, S. M. Aston, C. Austin, A. M. Baer, M. Ball, S. W. Ballmer, S. Banagiri, D. Barker, J. Bartlett, B. K. Berger, J. Betzwieser, D. Bhattacharjee, G. Billingsley, S. Biscans, R. M. Blair, n. Bode, P. Booker, R. Bork, A. Bramley, A. F. Brooks, A. Buikema, C. Cahillane, K. C. Cannon, X. Chen, A. A. Ciobanu, F. Clara, S. J. Cooper, K. R. Corley, S. T. Countryman, P. B. Covas, D. C. Coyne, E. H. Datrier, D. Davis, C. Di Fronzo, J. C. Driggers, T. Etzel, T. M. Evans, J. Feicht, P. Fulda, M. Fyffe, J. A. Giaime, K. D. Giardina, P. Godwin, E. Goetz, S. Gras, C. Gray, R. Gray, A. Gupta, E. K. Gustafson, R. Gustafson, J. Hanks, J. Hanson, T. Hardwick, R. K. Hasskew, M. C. Heintze, A. F. Helming-Cornell, N. A. Holland, J. D. Jones, S. Kandhasamy, S. Karki, M. Kasprzack, K. Kawabe, P. J. King, J. S. Kissel, R. Kumar, M. Landry, B. B. Lane, B. Lantz, M. Laxen, Y. K. Lecoeuche, J. Leviton, J. Liu, M. Lormand, A. P. Lundgren, R. Macas, M. MacInnis, D. M. Macleod, S. Márka, Z. Márka, D. V. Martynov, K. Mason, T. J. Massinger, R. McCarthy, S. McCormick, J. McIver, G. Mendell, K. Merfeld, E. L. Merilh, F. Meylahn, T. Mistry, R. Mittleman, G. Moreno, C. M. Mow-Lowry, S. Mozzon, T. J. N. Nelson, P. Nguyen, L. K. Nuttall, J. Oberling, R. J. Oram, B. O'Reilly, C. Osthelder, D. J. Ottaway, H. Overmier, J. R. Palamos, W. Parker, E. Payne, A. Pele, C. J. Perez, M. Pirello, H. Radkins, K. E. Ramirez, J. W. Richardson, K. Riles, N. A. Robertson, J. G. Rollins, C. L. Romel, J. H. Romie, M. P. Ross, K. Ryan, T. Sadecki, E. J. Sanchez, L. E. Sanchez, T. R. Saravanan, R. L. Savage, D. Schaetzl, R. Schnabel, R. M. Schofield, E. Schwartz, D. Sellers, T. J. Shaffer, J. R. Smith, S. Soni, B. Sorazu, A. P. Spencer, K. A. Strain, L. Sun, M. J. Szczepańczyk, M. Thomas, P. Thomas, K. A. Thorne, K. Toland, C. I. Torrie, G. Traylor, A. L. Urban, G. Vajnete, G. Valdes, D. C. Vander-Hyde, P. J. Veitch, K. Venkateswara, G. Venugopalan, A. D. Viets, C. Vorvick, M. Wade, J. Warner, B. Weaver, R. Weiss, B. Willke, C. C. Wipf, L. Xiao, H. Yamamoto, H. Yu, H. Yu, L. Zhang, M. E. Zucer and J. Zweizig, "Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy," *Phys. Rev. Lett.,* vol. 123, p. 231107, 2019. https://doi.org/10.1103/PhysRevLett.123.231107.

[91] M. Malnou, D. Palken, B. Brubaker, L. R. Vale, G. C. Hilton and K. Lehnert, "Squeezed Vacuum Used to Accelerate the Search for a Weak Classical Signal," *Phys. Rev. X,* vol. 9, p. 021023, 2020. https://doi.org/10.1103/PhysRevX.9.021023.

[92] S. C. Burd, R. Srinvas, J. J. Bollinger, A. C. Wilson, D. J. Wineland, D. Leifried, D. H. Slichter and D. T. C. Allcock, "Quantum amplification of mechanical oscillator motion," *Science,* vol. 364, pp. 1163-1165, 2019. https://doi.org/10.1126/science.aaw2884.

[93] K. A. Gilmore, M. Affolter, R. J. Lewis-Swan, D. Barberena, E. Jordan, A. M. Rey and J. J. Bollinger, "Quantum-enhanced sensing of displacements and electric fields with two-dimensional trapped-ion crystals," *Science,* vol. 373, pp. 673-678, 2021. https://doi.org/10.1126/science.abi5226.

[94] V. Meyer, M. A. Rowe, D. Kielpinski, C. A. Sackett, W. M. Itano, C. Monroe and D. J. Wineland, "Experimental Demonstration of Entanglement-Enhanced Rotation Angle Estimation Using Trapped Ions," *Phys. Rev. Lett,* vol. 86, p. 5870, 2001. https://doi.org/10.1103/PhysRevLett.86.5870.

[95] D. Leibfried, M. D. Barrett, T. Schaetz, J. Britton, J. Chiaverini, W. M. Itano, J. D. Jost, C. Langer and a. D. J. Wineland, "Toward Heisenberg-Limited Spectroscopy with Multiparticle Entangled States," *Science,* vol. 304, pp. 1476-1478, 2004. https://doi.org/10.1126/science.1097576.

[96] C. F. Roos, M. Chwalla, K. Kim, M. Riebe and R. Blatt, "‘Designer atoms’ for quantum metrology," *Nature,* vol. 443, pp. 316-319, 2006. https://doi.org/10.1038/nature05101.

[97] E. Megidish, J. Broz, N. Greene and H.Häffner, "Improved Test of Local Lorentz Invariance from a Deterministic Preparation of Entangled States," *Phys. Rev. Lett.,* vol. 122, p. 123605, 2019. https://doi.org/10.1103/PhysRevLett.122.123605.

[98] T. Manovitz, R. Sahniv, Y. Sharpira, R. Ozeri and N. Akerman, "Precision Measurement of Atomic Isotope Shifts Using a Two-Isotope Entangled State," *Phys. Rev. Lett.,* vol. 123, p. 203001, 2019. https://doi.org/10.1103/PhysRevLett.123.203001.

[99] E. Pedrozo-Peñafiel, S. Colombo, C. Shu, A. F. Adiyatullin, Z. Li, E. Mendez, B. Braverman, A. Kawasaki, D.Akamatsu, Y. Xiao and V. Vuletić, "Entanglement on an optical atomic-clock transition," *Nature,* vol. 588, pp. 414-418, 2020. https://doi.org/10.1038/s41586-020-3006-1.

[100] B. K. Malia, Y. Wu, J. Martínez-Rincón and M. A. Kasevich, "Distributed quantum sensing with mode-entangled spin-squeezed atomic states," *Nature,* vol. 612, pp. 661-665, 2022. https://doi.org/10.1038/s41586-022-05363-z.

[101] B. C. Nichol, R. Srinivas, D. P. Nadliinger, P. Drmota, D. Main, G. Araneda, C. J. Ballance and D. M. Lucas, "An elementary quantum network of entangled optical atomic clocks," *Nature,* vol. 609, pp. 689-694, 2022. https://doi.org/10.1038/s41586-022-05088-z.

[102] E. Riis and A. G. Sinclair, "Optimum measurement strategies for trapped ion optical frequency standards," *J. Phys. B: At. Mol. Opt. Phys.,* vol. 37, p. 4719, 2004. https://doi.org/10.1088/0953-4075/37/24/001.

[103] I. D. Leroux, N. Scharnhorst, S. Hanning, J. Kramer, L. Pelzer, M. Stepanova and P. O. Schmidt, "On-line estimation of local oscillator noise and optimisation of servo parameters in atomic clocks," *Metrologia,* vol. 54, p. 307, 2017. https://doi.org/10.1088/1681-7575/aa66e9.

[104] S. Bize, Y. Sortais, P. Lemonde, S. Zhang, P. Laurent, G. Santarelli, C. Salomon and A. Clairon, "Interrogation oscillator noise rejection in the comparison of atomic fountains," *IEEE Transactions of Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 47, pp. 1253-1255, 2000. https://doi.org/10.1109/58.869073.

[105] M. Chwalla, J. Benhelm, K. Kim, G. Kirchmair, T. Monz, M. Riebe, P. Schindler, A. S. Villar, W. Hänsel, C. F. Roos, R. Blatt, M. Abgrall, G. Santarelli, G. D. Rovera and P. Laurent, "Absolute Frequency Measurement of the ^(40) Ca^(+) 4s^(2)S(1/2) - 3d^(2)D(5/2) Clock Transition," *Phys. Rev. Lett.,* vol. 102, p. 023002, 2009. https://doi.org/10.1103/PhysRevLett.102.023002.

[106] G. E. Marti, R. B. Hutson, A. Goban, S. L. Campbell, N. Poli and J. Ye, "Imaging Optical Frequencies with 100 μHz Precision and 1.1 μm Resolution," *Phys. Rev. Lett.,* vol. 120, p. 103201, 2018. https://doi.org/10.1103/PhysRevLett.120.103201.

[107] A. W. Young, W. J. Eckner, W. R. Milner, D. Kedar, M. A. Norcia, E. Oelker, N. Schine, J. Ye and A. M. Kaufman, "Half-minute-scale atomic coherence and high relative stability in a tweezer clock," *Nature,* vol. 588, pp. 408-413, 2020. https://doi.org/10.1038/s41586-020-3009-y.

[108] D. B. Hume and D. R. Leibrandt, "Probing beyond the laser coherence time in optical clock comparisons," *Phys. Rev. A,* vol. 93, p. 032138, 2016. https://doi.org/10.1103/PhysRevA.93.032138.

[109] E. R. Clements, M. E. Kim, K. Cui, A. M. Hankin, S. M. Brewer, J. Valencia, J.-S. Chen, C.-W. Chou, D. R. Leibrandt and D. B. Hume, "Lifetime-Limited Interrogation of Two Independent 27Al+ Clocks Using

Correlation Spectrscopy," *Phys. Rev. Lett.,* vol. 125, p. 243602, 2020. https://doi.org/10.1103/PhysRevLett.125.243602.

[110] D. P. Nadlinger, P. Drmota, B. C. Nichol, G. Araneda, D. Main, R. Srinivas, D. M. Lucas, C. J. Ballance, K. Ivanov, E. Y.-Z. Tan, P. Sekatski, R. L. Urbanke, R. Renner, N. Sangouard and J.-D. Bancal, "Experimental quantum key distribution certified by Bell's theorem," *Nature,* vol. 607, pp. 682-686, 2022. https://doi.org/10.1038/s41586-022-04941-5.

[111] B. K. Sahoo, M. R. Islam, B. P. Das, R. K. Chaudhuri and D. Mukherjee, "Lifetimes of the metastable 2D3/2,5/2 states in Ca+, Sr+, and Ba+," *Phys. Rev. A,* vol. 74, p. 062504, 2006. https://doi.org/10.1103/PhysRevA.74.062504.

[112] G. Gabrielse and J. Tan, "Self-shielding superconducting solenoid systems," *Journal of Applied Physics,* vol. 63, p. 5143, 1988. https://doi.org/10.1063/1.340416.

[113] T. Ruster, C. T. Schmiegelow, H. Kaufmann, C. Warschburger, F. Schmidt-Kaler and U. G. Poschinger, "A long-lived Zeeman trapped-ion qubit," *Applied Physics B,* vol. 122, p. 254, 2016. https://doi.org/10.1007/s00340-016-6527-4.

[114] N. Aharon, N. Spethmann, D. Leroux, P. O. Schmidt and A. Retzker, "Robust optical clock transitions in trapped ions using dynamical decoupling," *New Journal of Physics,* vol. 21, p. 083040, 2019. https://doi.org/10.1088/1367-2630/ab3871.

[115] P. O. Schmidt, T. Rosenband, C. Langer, W. M. Itano, J. C. Berquist and D. J. Wineland, "Spectroscopy Using Quantum Logic," *Science,* vol. 309, pp. 749-752, 2005. https://doi.org/10.1126/science.1114375.

[116] A. Hughes, V. Schäfer, K. Thirumalai, D. Nadlinger, S. Woodrow, D. Lucas and C. Ballance, "Benchmarking a High-Fidelity Mixed-Species Entangling Gate," *Phys. Rev. Lett.,* vol. 125, p. 080504, 2020. https://doi.org/10.1103/PhysRevLett.125.080504.

[117] Boulder Atomic Clock Optical Network Collaboration, "Frequency ratio measurements at 18-digit accuracy using an optical clock network," *Nature,* vol. 591, pp. 564-569, 2021. https://doi.org/10.1038/s41586-021-03253-4.

[118] T. A. Wright, R. J. A. Francis-Jones, C. B. E. Gawith, J. N. Becker, P. M. Ledingham, P. G. R. Smith, J. Nunn, P. J. Mosley, B. Brecht and I. A. Walmsley, "Two-Way Photonic Interface for Linking the Sr+ Transition at 422 nm to the Telecommunication C Band," *Phys. Rev. Applied,* vol. 10, p. 044012, 2018. https://doi.org/10.1103/PhysRevApplied.10.044012.

[119] E. Pedretti, J. D. Monnier, T. t. Brummelaar and N. D. Thureau, "Imaging with the CHARA interferometer," *New Astronomy Reviews,* vol. 53, no. 11-12, pp. 353-362, 2009. https://doi.org/10.1016/j.newar.2010.07.008.