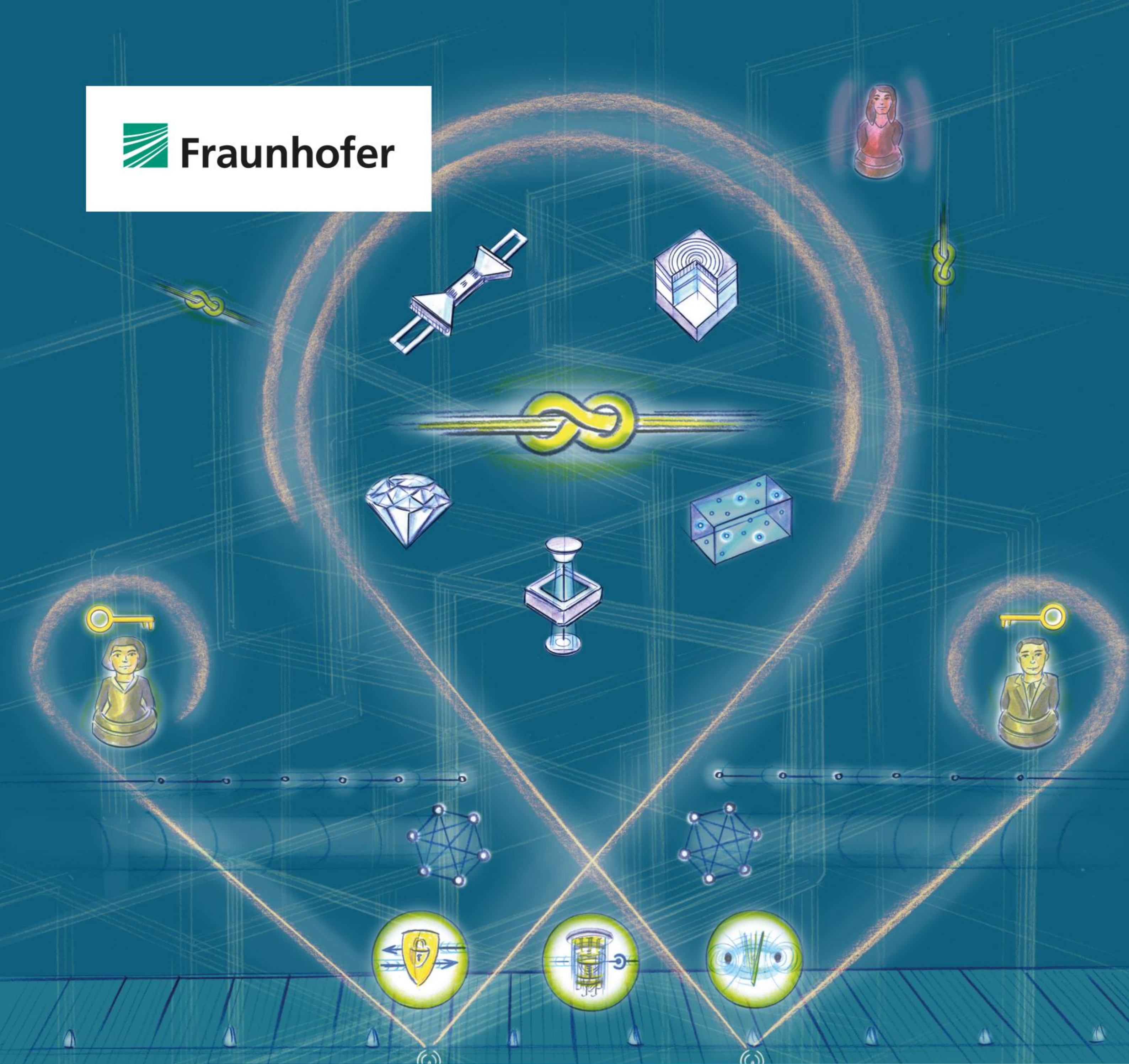

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Quantum Repeaters
A Technology Roadmap

Publishing Notes

Quantum Repeaters – A Technology Roadmap

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Notes

Contents

List of abbreviations

AFC	Atomic Frequency Combs
Alice / Bob	Notions for start (A) and end (B) node of a communication link
EG	Entanglement Generation
EIT	Electromagnetically Induced Transparency
ES	Entanglement Swapping
FWM	Four Wave Mixing
HEG	Heralded Entanglement Generation
HEP	Heralded Entanglement Purification
SPDC	Spontaneous Parametric Down Conversion
QEC	Quantum Error Correction
QFC	Quantum Frequency Conversion
QIS	Quantum Information Science
QKD	Quantum Key Distribution
QPU	Quantum Processing Unit
QR	Quantum Repeaters
YSO	Yttrium Orthosilicate

In this report, the following abbreviations are introduced for the different hardware platforms.

CC	Color centers (e.g., in diamond)
sA / sI	Trapped single atoms / trapped single ions
wAE / cAE	Warm atomic ensembles / cold atomic ensembles
RE	Rare earth ions
QD	Quantum dots

Zusammenfassung und Kernergebnisse (German)

Technologische Entwicklungen waren schon immer von verfügbaren Ressourcen abhängig, von Materialien und Energie bis hin zu Information. Mit dem **Aufkommen von Quantentechnologien** könnten Quanteninformation und verteilte Verschränkung – das Phänomen, bei dem zwei oder mehr Teilchen so korreliert sind, dass, unabhängig von der Entfernung, die Messung des einen unmittelbar den Zustand des anderen bestimmt – als komplementäre Ressourcen an Bedeutung gewinnen und völlig neuartige Anwendungen ermöglichen.

Die Kontrolle, Speicherung und Verteilung von Quanteninformation und Verschränkung stellt jedoch eine tiefgreifende wissenschaftliche und ingenieurtechnische Herausforderung dar. Anders als klassische Telekommunikationssignale kann Quanteninformation nicht einfach verstärkt werden – eine grundlegende Einschränkung durch das No-Cloning-Theorem, das das Kopieren unbekannter Quantenzustände verbietet. Daher sind neue Lösungen für die Quantenkommunikation über große Distanzen erforderlich, und einer der vielversprechendsten Ansätze ist der **Quantenrepeater**. Obwohl Forschungsgruppen weltweit bereits beeindruckende Fortschritte bei zentralen Repeater-Funktionen erzielt haben, befindet sich das Feld noch in einem frühen Entwicklungsstadium, und ein kommerziell nutzbarer Quantenrepeater, der Verschränkung mit geringeren Verlusten als bei direkter Übertragung verteilen kann, ist noch mehrere Jahre entfernt.

In diesem Bericht stellen wir den aktuellen Stand der Forschung und das zukünftige Potenzial von Quantenrepeatern dar. Grundlage sind eine umfassende Auswertung der wissenschaftlichen Literatur sowie die Einschätzungen von 22 Expertinnen und Experten aus Wissenschaft und Industrie, die in Einzelinterviews und einem Online-Roadmapping-Workshop konsultiert wurden.

Anwendungen

Die Entwicklung von Quantenrepeatern wird durch eine Reihe vielversprechender zukünftiger Anwendungen vorangetrieben. Am unmittelbarsten könnten Quantenrepeater die Reichweite der **Quanten-Schlüsselverteilung** (Quantum Key Distribution, QKD) erweitern – eines Verfahrens zur sicheren Bereitstellung kryptografischer Schlüssel für kommunizierende Parteien. Gegenwärtige faserbasierte QKD ist typischerweise auf etwa 100 km begrenzt und erfordert vulnerable Trusted-Node-Architekturen. Quantenrepeater könnten diese durch Ende-zu-Ende-sichere Verbindungen ersetzen. Eine zweite wichtige Anwendung ist die Vernetzung räumlich getrennter Quantenprozessoren auf dem Weg zu einem sogenannten „Quanteninternet“, also einem Netzwerk, das Quanteninformation übertragen, verarbeiten und empfangen kann und damit sicheren Fernzugriff, modulares Skalieren und **verteiltes Quantencomputing** ermöglichen würde. Darüber hinaus könnten Quantenrepeater **Quantensensoren** an verschiedenen Standorten verbinden und durch Verschränkung die Messpräzision und -auflösung verbessern. Denkbare Anwendungsfälle umfassen weltweit synchronisierte Netzwerke von Atomuhren sowie optische Interferometer mit vergrößerter Basislinie für astronomische Beobachtungen.

Funktionsprinzip

Quantenrepeater beruhen auf dem Prinzip des **iterativen Entanglement Swapping**: Der Kommunikationskanal wird durch dazwischenliegende Repeater-Knoten in kürzere Segmente unterteilt. Jeder dieser Knoten ist – im derzeit prominentesten Ansatz – mit Quantenspeichern ausgestattet, also mit Vorrichtungen, die Quanteninformation speichern können. Zunächst wird zwischen benachbarten Knoten Verschränkung erzeugt, deren erfolgreicher Aufbau durch klassische Signale verkündet wird. Nach dieser Bestätigung erweitern Swapping-Operationen an den Zwischenknoten benachbarte verschränkte Teilchenpaare schrittweise zu immer längeren Verbindungen, bis schließlich Ende-zu-Ende-Verschränkung zwischen den entfernten Parteien hergestellt ist. Dieser Ansatz soll den exponentiellen Abfall der Übertragungswahrscheinlichkeit mit wachsender Entfernung infolge der Photonendämpfung überwinden – eine grundlegende Begrenzung der faserbasierten Quantenkommunikation.

Dieses Prinzip und seine Varianten werden in vielfältigen unterschiedlichen Ansätzen umgesetzt. Aufgrund des frühen Entwicklungsstands hat bislang noch keine Konsolidierung der Technologien stattgefunden, und die Rolle der verschiedenen Ansätze ist derzeit noch unklar.

Repeater-Typen

Quantenrepeater lassen sich nach mehreren unterschiedlichen Logiken klassifizieren. Entlang der Dimension der Fehlerbehandlung werden **drei Generationen** unterschieden: Repeater der ersten Generation nutzen „heraldierte" Verschränkungserzeugung und Purifikation; Repeater der zweiten Generation ersetzen die Purifikation an den Knoten durch Quantenfehlerkorrektur; und Repeater der dritten Generation wenden Fehlerkorrektur sowohl auf Verluste als auch auf operationelle Fehler an und ermöglichen so einen deterministischen Betrieb ohne Quantenspeicher oder bidirektionale klassische Kommunikation. Werden Repeater nach **Vorhandensein und Art des Speichers** unterschieden, beruhen speicherbasierte Quantenrepeater auf materiebasierten Quantenspeichern – entweder ensemblebasiert (z. B. kalte oder warme atomare Gase, mit Seltenerdionen dotierte Kristalle) oder auf Einzelemittern basierend (z. B. Farbzentren, gefangene Atome und Ionen) – während vollphotonische Quantenrepeater ohne langlebige Speicher arbeiten und entweder zeitumgekehrte Verschränkungsverteilung mittels photonischer Clusterzustände oder Vorwärtsfehler korrektur nutzen. Über diese Architekturen hinweg kommt eine große Bandbreite an **Hardware-Plattformen** zum Einsatz, darunter Farbzentren in Diamant, gefangene Atome und Ionen, warme und kalte atomare Ensembles, mit Seltenerdionen dotierte Kristalle, halbleiterbasierte Quantenpunkte sowie Verschränkungsquellen auf Basis nichtlinearer Medien.

Ein direkter Vergleich dieser Ansätze ist nicht einfach, da sich ein Großteil der Forschung noch im experimentellen Stadium befindet und Demonstrationen unter unterschiedlichen Bedingungen durchgeführt wurden. Dennoch liefert die Bewertung zentraler Leistungsindikatoren (KPIs) – darunter Verschränkungserzeugungsrate, Fidelität, Kohärenzzeit des Speichers, Effizienz, Wellenlänge und Temperatur – wichtige Einblicke in die relativen Stärken und Schwächen der einzelnen Plattformen. Keine Plattform ist derzeit bei allen KPIs zugleich überlegen, was die Notwendigkeit einer Systemperspektive und die potenzielle Relevanz hybrider Architekturen unterstreicht.

Aktueller Stand der Technologien

Der aktuelle Stand der Forschung spiegelt rasche Fortschritte über verschiedene Hardware-Plattformen hinweg wider, die jeweils eigene Vorteile und Herausforderungen mit sich bringen. Für unterschiedliche Plattformen wurden in jüngster Zeit sowohl im Labor als auch in großskaligen Feldexperimenten relevante Fähigkeiten demonstriert. Die Potenziale und Herausforderungen der wichtigsten Hardware-Plattformen sind im Folgenden zusammengefasst.

Farbzentren [NV, Group-IV, Zentren in SiC]

PROs / Potenzial (z. B.)

- Kernspins: Lange Kohärenzzeiten
- Sichtbarer, Nahinfrarot & Konversion in den Telekom-Bereich
- Pfade zur Integration

CONs / Herausforderungen (z. B.)

- NV: Große spektrale Diffusion
- NV: Schwache Null-Phonon-Linie
- Group-IV: Typischerweise Tieftemperaturbetrieb

Einzelne Atome/Ionen [Rb, Cs; Ca^{+}, Ba^{+}, Sr^{+}, Yb^{+}]

PROs / Potenzial (z. B.)
- Starke optische Übergänge
- Lange Kohärenzzeiten (bes. Ionen)
- Reproduzierbarkeit

CONs / Herausforderungen (z. B.)
- Komplexe Aufbauten / Skalierung
- Herausfordernde hybride Chip Integration
- Verschränkungserzeugungsraten

Atomare Ensembles (kalte / warme) [Rb, Cs]

PROs / Potenzial (z. B.)
- Raumtemperatur (warme)
- Starke Licht-Materie-Kopplung
- Einfache Herstellung und Integration

CONs / Herausforderungen (z. B.)
- Dephasing durch thermische Bewegung (warm)
- Weitere Miniaturisierung
- Implementierung von Gatter-Operationen

Seltene Erd-Ionen [Eu, Pr, Tm, Nd, Yb, Er]

PROs / Potenzial (z. B.)
- Lange Kohärenzzeiten
- Telekom und sichtbare Wellenlängen
- Koppeln unterschiedlicher Ionen-Spezies

CONs / Herausforderungen (z. B.)
- Kryogene Temperaturen
- Schwache Wechselwirkung mit Licht
- Meist hochqualitative Resonatoren benötigt

Quantum Dots

PROs / Potenzial (z. B.)
- Einzelphotonenemission
- Hohe Wiederholungsraten
- Integrationsfähigkeit und Skalierung

CONs / Herausforderungen (z. B.)
- Kohärenzzeiten
- Spektrale Diffusion und Stabilität
- Reproduzierbarkeit

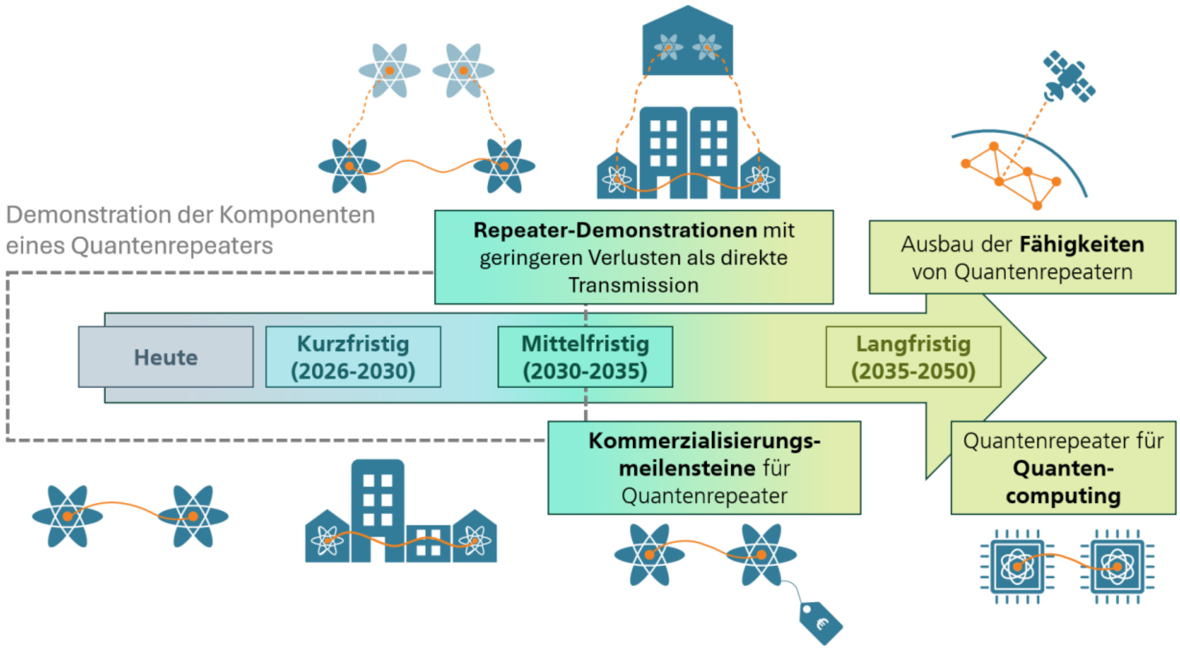
Quelle: Fraunhofer ISI

Zukünftige Entwicklung

Die weitere Entwicklung von Quantenrepeatern erfordert in den kommenden Jahren die Bewältigung mehrerer miteinander verknüpfter Herausforderungen. Dazu gehören:

- Erreichen **hoher Speichereffizienz** bei zugleich **langen Kohärenzzeiten**, sowie die Verbesserung der Raten bei Erzeugung und Verteilung von Verschränkung durch Multiplexing und andere Strategien,
- die Sicherstellung eines **robusten** Langzeitbetriebs,
- die Integration der Hardware in **telekompatible Systeme**, gegebenenfalls durch Quantenfrequenzkonversion oder bichromatische Photonenpaarquellen,
- Fortschritte in der **Nanofabrikation**, insbesondere bei optischen Kavitäten,
- die Überbrückung der Lücke zwischen den **Zeitskalen** akademischer Forschung und den Anforderungen der Kommerzialisierung an Engineering und Standardisierung,
- sowie die Senkung der **Kosten** zentraler Komponenten wie Laser, Kryostate und Magnete.

Die meisten dieser Herausforderungen werden von Expertinnen und Experten als hochrelevant eingestuft, auch wenn sich ihre Lösbarkeit je nach Plattform deutlich unterscheidet. Die Zusammenarbeit zwischen Wissenschaft und Industrie, die Etablierung von Standards und die Entwicklung integrierter photonischer Systeme werden wesentliche Treiber des Fortschritts sein.



Quelle: Fraunhofer ISI

Kurzfristig wird die **Demonstration einzelner Komponenten von Quantenrepeatern** weiterhin eine zentrale Priorität bleiben – darunter die Verteilung von Verschränkung aus einer einzelnen Quelle auf zwei entfernte Speicher sowie Dreiknoten-Netzwerkdemonstrationen, die Speicher-Speicher-Verschränkung mit Entanglement Swapping an unterschiedlichen Standorten kombinieren. Feldtests, einschließlich Quantenteleportation in realen Netzwerkumgebungen, laufen bereits und dürften an Umfang zunehmen. Mittelfristig werden die ersten Demonstrationen von Quantenrepeatern erwartet, die **direkte Übertragung hinsichtlich der Verluste übertreffen**. Hybridsysteme, die die Stärken verschiedener Hardware-Plattformen kombinieren, sind dabei ein vielversprechender Ansatz. Diese Demonstrationen dürften die Integration von Quantenrepeater-Knoten in rack-kompatible Systeme vorantreiben und die ersten anwendungsnahen Szenarien zwischen Städten in Forschungs- und **kommerziellen Kontexten** einleiten. Langfristig werden Fortschritte bei Robustheit, Geschwindigkeit und Netzwerkkomplexität angestrebt, darunter Demonstrationen von Repeater-Konzepten der zweiten und dritten Generation, die Verteilung von Verschränkung zwischen Satelliten und Bodenstationen sowie – als zentrales langfristiges Ziel – die ersten Demonstrationen der **Verbindung und des Betriebs entfernter Quantencomputer**. Dies umfasst entfernte Gatteroperationen zwischen Quantenprozessoren und die Realisierung delokalisierter logischer Qubits über physisch getrennte Systeme hinweg.

Der Weg von heutigen Laborprototypen zu kommerziell eingesetzten Quantenrepeatern wird lang und nichtlinear verlaufen. Er erfordert nachhaltige Investitionen in Forschung und Entwicklung, eine enge Abstimmung zwischen Wissenschaft, Industrie und Politik sowie das Bekenntnis, ein breites technologisches Portfolio aufrechtzuerhalten. Angesichts des hohen Tempos der jüngsten Fortschritte und der intensiven weltweiten Forschungsaktivitäten gibt es jedoch gute Gründe für Optimismus, dass die in dieser Roadmap skizzierten Meilensteine in den kommenden Jahrzehnten erreicht werden können – und dass verteilte Verschränkung tatsächlich zu einer transformativen neuen Ressource in der technologischen Landschaft der Zukunft werden könnte.

Executive Summary

Technological development has always been dependent on the resources available, from materials and energy through to information. With the **rise of quantum technologies**, quantum information and distributed entanglement—the phenomenon in which two or more particles become correlated such that measuring one instantly determines the state of the other, regardless of the distance—could emerge as complementary resources, enabling entirely novel applications.

However, controlling, storing, and distributing quantum information and entanglement represents a profound scientific and engineering challenge. Unlike classical telecommunication signals, quantum information cannot simply be amplified, a result of a fundamental constraint imposed by the no-cloning theorem, which forbids copying unknown quantum states. New solutions are therefore required to achieve long-distance quantum communication, and one of the most promising approaches is the **quantum repeater**. Although research groups worldwide have demonstrated impressive progress in key repeater functions, this field is still in its early stages, and a commercially viable quantum repeater capable of distributing entanglement with lower losses than direct transmission remains several years away.

In this report, we present the current state of research and future potential of quantum repeaters, drawing on an extensive review of scientific literature and input from 22 experts in science and industry, who were interviewed individually and/or consulted at an online roadmapping workshop.

Applications

The development of quantum repeaters is driven by a set of compelling future applications. Most immediately, quantum repeaters could extend the range of **quantum key distribution** (QKD)—an approach which securely provides cryptographic keys to communicating parties. Current fiber-based QKD is typically limited to around 100 km, requiring vulnerable trusted-node architectures. Quantum repeaters could replace these with end-to-end secure links. A second key application is the interconnection of spatially separated quantum processors, advancing toward a so-called "quantum internet", i.e., a network capable of transmitting, processing, and receiving quantum information, which would enable secure remote access, modular scaling, and **distributed quantum computing**. Furthermore, quantum repeaters could link **quantum sensors** across locations, enhancing measurement precision and resolution through entanglement. Envisioned use cases include globally synchronized atomic clock networks and extended-baseline optical interferometers for astronomical observation.

Principle of Operation

Quantum repeaters operate on the principle of **iterative entanglement swapping**: the communication channel is divided into shorter segments by intermediate repeater nodes, each equipped, in the most prominent approach, with quantum memories, i.e., devices that can store quantum information. Entanglement is first generated between neighboring nodes, heralded by classical signals confirming successful entanglement. Once confirmed, entanglement between adjacent pairs is then extended into progressively longer links through swapping operations at these intermediate nodes, ultimately establishing end-to-end entanglement between the distant parties. This approach aims to overcome the exponential decay of transmission probability with distance due to photon attenuation, which is a fundamental limitation of fiber-based quantum communication.

This principle, and variations of it, are realized across a diverse and complex landscape of approaches. Given the early stage of development, no consolidation of technologies has taken place to date and the role of different approaches presently remains unclear.

Repeater Types

Quantum repeaters can be classified according to several distinct criteria. With respect to error handling, **three generations** can be distinguished: first-generation repeaters use heralded entanglement generation and heralded purification; second-generation repeaters replace purification with quantum error correction at the nodes; and third-generation repeaters apply error correction to both loss and operational errors, enabling deterministic operation without quantum memories or two-way classical communication. According to the **presence and type of memory**: memory-based quantum repeaters rely on matter-based quantum memories—either ensemble-based (e.g., cold or warm atomic gases, rare-earth-ion-doped crystals) or single-emitter-based (e.g., color centers, trapped atoms and ions)—while all-photonic quantum repeaters operate without long-lived memories, using either time-reversed entanglement distribution via photonic cluster states or one-way forward-error-corrected schemes. Across these architectures, diverse **hardware platforms** are utilized, including color centers in diamond, trapped atoms and ions, warm and cold atomic ensembles, rare-earth-ion-doped crystals, semiconductor quantum dots, and entanglement sources based on nonlinear media.

A direct comparison of these approaches is not straightforward, as much of the research remains at the experimental stage and demonstrations have been conducted under varying conditions. Nevertheless, evaluating key performance indicators (KPIs), including entanglement generation rate, fidelity, memory coherence time, efficiency, operational wavelength, and temperature, provides essential insight into the relative strengths and limitations of each platform. No single platform currently excels across all KPIs concurrently, underscoring the need for a system-level perspective and the potential relevance of hybrid architectures.

Current State of Technologies

The current state of research reflects rapid progress across different hardware platforms, which offer distinct advantages and challenges. Relevant capabilities have recently been demonstrated on different platforms both in lab settings and in large-scale field experiments. The potential and challenges facing the most widely adopted hardware platforms are summarized in the following:

Color Centers [NV, group-IV, centers in SiC]

PROs / Potential (e.g.)

- Nuclear spins: long lifetimes
- Visible to near IR + telecom conversion
- Pathways towards integration

CONs / Challenges (e.g.)

- NV: Large spectral diffusion
- NV: Weak zero-phonon emission line
- Group-IV: Typically low temp. operation

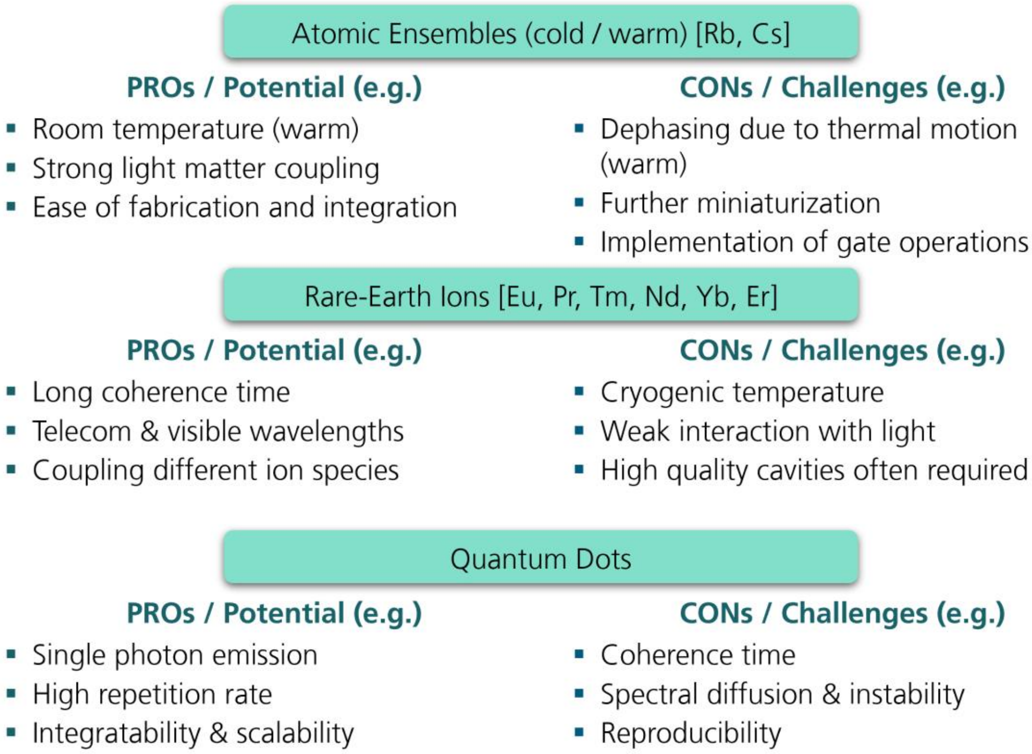
Single Atoms/Ions [Rb, Cs; Ca^+, Ba^+, Sr^+, Yb^+]

PROs / Potential (e.g.)

- Strong optical readout transitions
- Long coherence times (esp. ions)
- Reproducibility

CONs / Challenges (e.g.)

- Complex setups / challenging scalability
- Challenging hybrid chip integration
- Entanglement generation rates



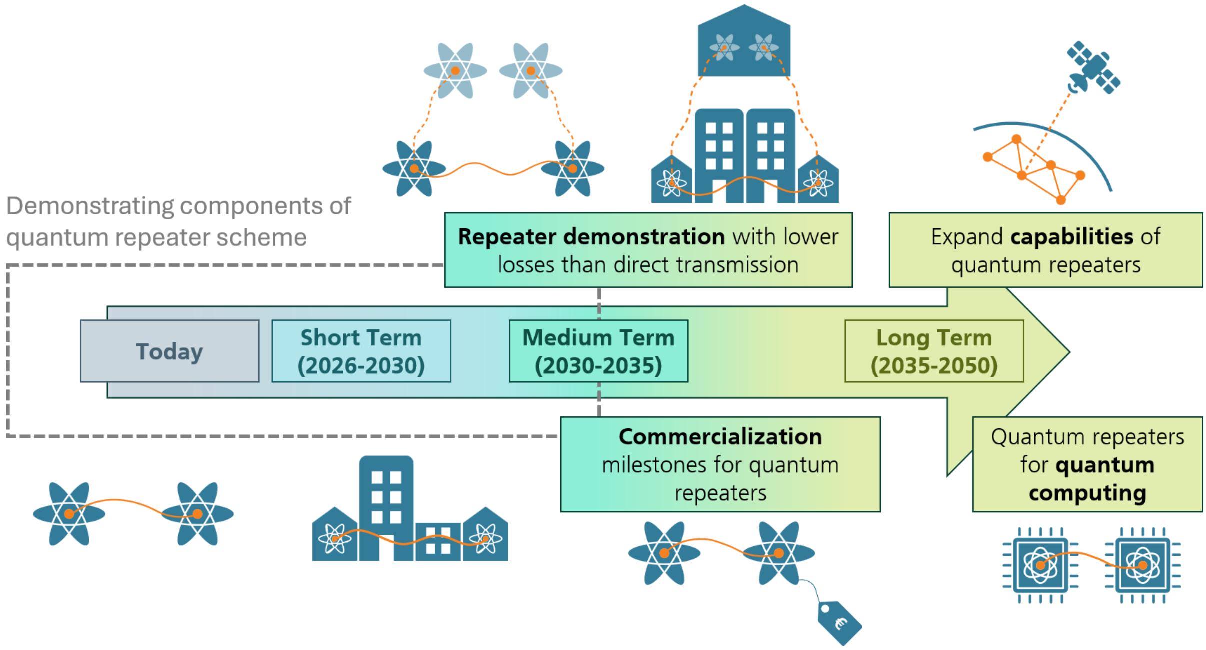
Source: Fraunhofer ISI

Future Development

The further development of quantum repeaters will require addressing several interconnected challenges in coming years. These include:

- simultaneously achieving high **memory efficiency** and long **coherence times**, improving entanglement generation and distribution rates through multiplexing and other strategies
- ensuring **robust** long-term operation
- integrating hardware into **telecom-compatible systems** via quantum frequency conversion or bichromatic photon pair sources where necessary
- advancing **nanofabrication**, particularly of optical cavities
- bridging the gap between academic research **timescales** and the engineering and standardization demands of commercialization
- and reducing the **cost** of key components such as lasers, cryostats, and magnets

Most of these challenges are rated as highly critical by experts, though the difficulty of solving these challenges varies significantly across platforms. Collaboration between academia and industry, the establishment of standards, and the development of integrated photonic systems will be essential drivers of progress.



Source: Fraunhofer ISI

In the near term, **demonstrating individual quantum repeater components** will remain a central priority, including entanglement distribution from a single source onto two distant memories, and three-node network demonstrations, combining memory–memory entanglement with entanglement swapping at distinct locations. In-field demonstrations, including quantum teleportation in deployed network environments, are already underway and expected to expand in scope. In the medium term, the first demonstrations of **quantum repeaters outperforming direct transmission** in terms of loss are anticipated, with hybrid systems, combining the strengths of different hardware platforms, considered promising candidates. These demonstrations are expected to drive the integration of quantum repeater nodes into rack-compatible systems and to initiate the first inter-city use cases in research and **commercial contexts**. In the long term, efforts will focus on improving robustness, speed, and network complexity, including demonstrations of second- and third-generation repeater concepts and satellite-to-ground entanglement distribution. In addition, **connecting and operating distant quantum computers** is a key long-term goal, encompassing remote gate operations between quantum processing units and the realization of delocalized logical qubits across physically separated systems.

The path from today's laboratory prototypes to commercially deployed quantum repeaters will be long and nonlinear, requiring sustained investment in research and development, close coordination across academia, industry, and policy, and the commitment to maintaining a broad technological portfolio. Given the rapid pace of recent progress and the depth of global research engagement, however, there is strong reason for optimism that the milestones outlined in this roadmap can be achieved in the coming decades and that distributed entanglement may indeed emerge as a transformative new resource in the technological landscape of the future.

1 Introduction

The scientific research on entanglement is about to turn 100 years (Einstein et al. 1935). Entanglement is a quantum phenomenon in which two or more particles become correlated in such a way that they cannot be described separately from each other. Measuring the state of one particle instantly determines the state of the other, no matter how far apart they are.

The experimental proofs that validated the effects predicted by theory took a few decades and were conducted by John Clauser, Stuart Freedman in 1972 (Freedman and Clauser 1972) and Alain Aspect in the early '80s (Aspect et al. 1981; Aspect et al. 1982a; Aspect et al. 1982b). Around this time, Stephen Wiesner worked on the concepts (Wiesner 1983) that were further extended by Charles Bennett and Gilles Brassard (Charles H. Bennett and Gilles Brassard 1984), building the fundamental framework of the quantum communication technologies developed today. However, utilizing entanglement in technologies proved to be tedious work, as carefully prepared quantum states tend to dissipate quickly in our noisy world. Accessing entanglement as a long-term and long-distance resource for useful applications could be coined as the "holy grail" of quantum communication.

The application potential of distributed entanglement, i.e., entangled particles or systems at different locations, is intriguing. It would enable us to expand the potential of quantum key distribution (QKD) (Schmaltz et al. 2025), an approach to create random keys for securing communication between distant parties, as well as enhance the potential of quantum computers and quantum sensors by utilizing networks of such quantum systems. Distributing entanglement over long distances, however, is technically demanding, as quantum states are fragile and the basic repeating concepts of classical communication cannot be applied due to the no-cloning theorem, stating that single quantum states in an unknown basis cannot be copied and multiplied (Wootters and Zurek 1982).

Quantum repeaters promise to overcome this limitation: they are considered the core technology for long-distance entanglement distribution in the future. By taking advantage of the quantum mechanical properties of entanglement and single-photon states, a distribution of entangled quantum states over distances with losses lower than in direct point-to-point links is anticipated. Even though a demonstration of a usable quantum repeater link superior to direct transmission has not yet been achieved, the research is picking up speed. A large number of research groups are committed to further developing the potential of the various technological platforms that are candidates for building capable quantum repeaters. In some countries, policy is supporting this acceleration. For example, in Germany, the country's Hightech Agenda states that a technology demonstration of the first quantum repeater in 2028 is one of the objectives of a key flagship measure, and currently, the QR.N project[1] funded with around 20 million euros for three years by the BMFTR is pushing forward toward the goal (BMFTR 2025). The next years and decades will show what challenges and breakthroughs the future holds for this research topic.

In this study, we will give an overview of the relevant technologies, their technical profiles today, as well as the challenges that need to be overcome to leverage their future potential. The findings are based on extensive literature research, expert interviews, and a roadmapping workshop (section 2). Quantum repeaters are introduced by providing an overview of the potential future applications, a summary of the general principle of the repeating schemes, a classification of different repeater types, and the underlying key performance indicators and hardware platforms (section 3). Finally, a roadmap is presented, which outlines the current state of the art, the challenges for further development, and potential future milestones (section 4).

[1] https://quantenrepeater.net/en/

2 Methods

A combination of methods was used to gather information on different quantum repeater technologies, underlying material platforms, their key performance indicators (KPIs), and technological challenges. Based on the analysis outlined below, relevant milestones for future developments were defined, forming a technology roadmap for quantum repeaters.

Desk research

As a first step, information on the technologies studied in this report was collected from scientific literature. The desk research initially focused on investigating general principles of quantum repeaters and the most relevant protocols and hardware platforms. The identified hardware platforms were studied further with respect to current research and demonstrations, achieved KPIs, as well as advantages and challenges. The review of relevant literature and technical reports was continued throughout the study to keep track of the latest research results.

Expert interviews

Alongside the desk research, interviews were conducted with technological experts working on different hardware platforms and theories to validate and further elaborate on the results of the desk research. The interview questionnaire focused on identifying the most important hardware platforms and protocols, categorizing different repeater types, validating the KPIs, discussing advantages and disadvantages of different platforms, assessing their technology profiles, as well as highlighting the major challenges and milestones for future development.

19 experts from the global scientific and industrial quantum repeater community were interviewed. A strong focus was placed on experts from universities and research organizations in Germany and Europe.

The interview results were used to prepare the content for the discussion workshop. By aligning the interviews with the workshop, the target stakeholders could become familiar with the study objectives, and the depth of the workshop could be optimized.

Workshop

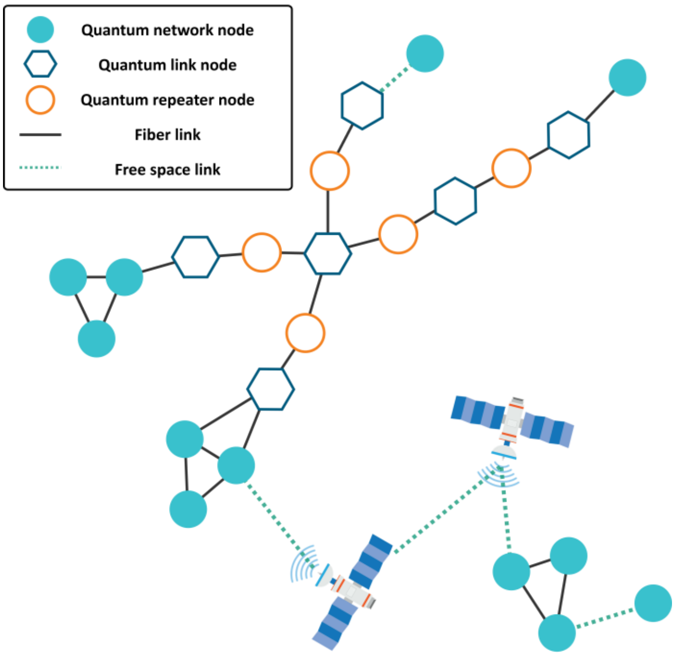
A discussion workshop was held with 12 quantum repeater experts, not only from Germany but from across Europe. In the online workshop, the experts were asked to validate the technology profiles of different platforms that had been created based on the desk research and interviews. In the second part of the workshop, the remaining challenges for quantum repeaters in the coming years were discussed. The workshop was concluded by identifying future milestones for quantum repeaters and placing them on a timeline. The workshop results verified and complemented the information gathered in the previous steps of this methodology.

3 Technology Overview

Advancements in Quantum Information Science (QIS) have laid the foundation for a new generation of technologies, including ultra-secure quantum communication systems, quantum computers, and high-precision quantum sensors. One of the long-term goals of QIS is the realization of a so-called "quantum internet"—a proposed network of quantum nodes capable of transmitting, processing, and receiving quantum information using quantum technologies (Kimble 2008; Wehner et al. 2018)[2]. Such a network relies on fundamental principles of quantum mechanics, particularly superposition and entanglement. Entanglement-based communication enables intrinsically secure information transfer, as any attempt at eavesdropping or external interference inevitably disturbs the quantum correlations, thereby revealing the presence of an adversary and enhancing communication security. In the EU, the Quantum Internet Alliance (QIA) initiative is working toward building the world's first full-stack quantum internet prototype network[3].

The quantum internet promises a range of applications (introduced in section 3.1) that extend far beyond the capabilities of classical networks. These include secure communication, secure access to remote quantum computers, enabling distributed quantum computing architectures, high-precision synchronization of clocks, and advanced scientific applications such as interferometric combination of light from distant telescopes to improve astronomical observations. As research in quantum networking continues to advance, additional transformative applications are expected to emerge in the coming decade.

Figure 1: Schematic of a quantum information network ("The Quantum Internet")



Source: Adapted from W. Tittel, M. Afzelius, A. Kinos, L. Rippe, and A. Walther, "Quantum networks using rare-earth ions," (Tittel et al. 2025) Licensed under CC BY 4.0

[2] The term quantum internet is sometimes controversially discussed in the German quantum communication community, as it can create associations that are not in-line with the actual technology and its potential capabilities.

[3] https://quantuminternetalliance.org/

In the simplest representation, as illustrated in Figure 1, a quantum internet consists of quantum network nodes where quantum information, or qubits, are generated, processed, and stored locally. These nodes are interconnected via photonic quantum links that enable the exchange of information and are realized through fiber-based or free-space quantum channels. However, such channels are inherently affected by photon loss and decoherence, which limit both communication rates and the achievable transmission distance.

While quantum link nodes can establish entanglement between neighboring nodes, they cannot extend entanglement indefinitely over long distances due to fundamental constraints such as the no-cloning theorem. One promising approach to overcome this limitation is the introduction of quantum repeater nodes. These nodes employ quantum memories, which can store the quantum state of a photon for later retrieval, and entanglement swapping protocols to distribute entanglement over extended distances, thereby enabling scalable quantum communication networks and, ultimately, the realization of a global quantum internet.

3.1 Applications for Quantum Repeaters

The realization of large and complex quantum information networks relies critically on the development of quantum repeaters, which enable the long-distance distribution of entanglement beyond the limits imposed by loss and decoherence in direct photonic links. The strong research interest in quantum repeaters is largely driven by a range of compelling application scenarios that benefit from scalable, long-range quantum connectivity. In the following, we briefly outline several key applications that motivate ongoing efforts toward the development of quantum repeater technologies.

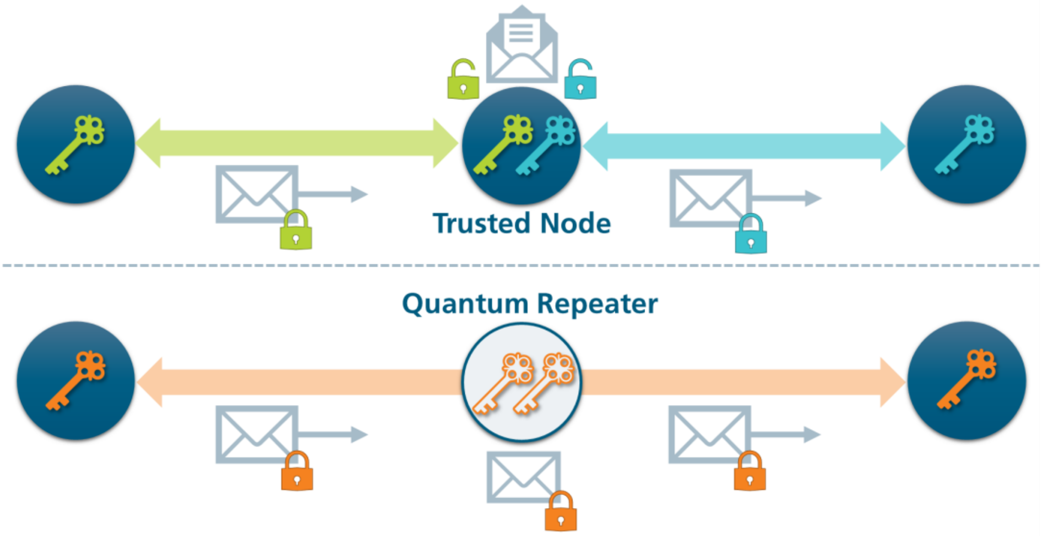
3.1.1 Quantum Repeaters for Quantum Key Distribution (QKD)

Quantum Key Distribution is a key-exchange method relying on quantum-mechanical principles, promising "unconditional security" on the transmission path—in the theoretical case of a perfect implementation. QKD encompasses several protocols, broadly divided into prepare-and-measure QKD and entanglement-based QKD. In discrete-variable operation[4], prepare-and-measure QKD encodes information onto single photons, and entanglement-based QKD leverages entangled photon pairs to distribute information between communication nodes. However, both approaches rely on photons as photonic (“flying”) qubits, which are attenuated in the optical fiber over distance. As the no-cloning theorem forbids amplifying or copying a quantum signal, the achievable end-to-end distance is largely limited by photon attenuation. For example, currently, commercially available fiber-based QKD typically enables communication over distances of around 100 km (Schmaltz et al. 2025).

One approach is to increase the node-to-node distance through **novel protocols** (e.g., twin-field QKD (Lucamarini et al. 2018), though it currently offers limited key rates). In today’s deployed systems, however, longer links are realized by concatenating several QKD segments via **trusted nodes**. These nodes run QKD with their neighboring nodes to establish two (or more) separate links. At the node itself, the information about the generated keys must be available to enable an end-to-end connection. The overall link is therefore only secure as long as each intermediate node is trustworthy—hence the term “trusted node.”

[4] QKD approaches can also be divided according to the type of variable used to encode information: discrete-variable QKD (DV-QKD) and continuous-variable QKD (CV-QKD). CV-QKD encodes the quantum information in the continuous state of light, such as amplitude and phase, rather than in discrete properties of single photons, like polarization or time-bin. CV-QKD is usually implemented in prepare-and-measure schemes, but there are approaches towards entanglement-based CV-QKD as well.

Figure 2: Comparison of trusted node and quantum repeater in a QKD link



Source: Fraunhofer ISI

This represents a fundamental vulnerability for end-to-end security. While strengthening the security of trusted nodes is the most direct way to improve overall link protection, **quantum repeaters** offer an alternative "untrusted" architecture (see Figure 2), in which no node gains access to a critical amount of key information. Therefore, trusting the provider of the network infrastructure is not required to enable end-to-end security. Replacing trusted nodes in QKD networks is thus regarded as one of the main drivers for the development of quantum repeaters.

3.1.2 Distributed Quantum Computing via Quantum Networks

Another motivation for the development of quantum repeaters is the ability to interconnect spatially separated quantum processors into a distributed quantum computing network. Early theoretical work by Broadbent, Fitzsimons, and Kashefi (Broadbent et al. 2009) proposed blind quantum computation, showing that a client could delegate a quantum computation to a remote quantum server while keeping the input, algorithm, and output private. In their protocol, a user with minimal quantum capabilities prepares and sends simple quantum states, while the remote processor performs the computation, demonstrating the feasibility of secure quantum cloud computing. This idea highlights a broader vision in which quantum computers operate not as isolated devices but as nodes in a larger network that can share resources and perform tasks cooperatively.

A connected quantum network could enable secure remote access to powerful quantum processors, modular scaling by combining smaller devices, and collaborative quantum algorithms executed across multiple locations. In this context, quantum repeaters act as the enabling infrastructure that allows distant quantum systems to be linked into a unified network. In the long term, such interconnected architectures are expected to overcome the scaling limits of standalone quantum hardware and form the basis of large-scale networked quantum computing platforms.

3.1.3 Distributed Quantum Sensing

Quantum repeaters could be used to connect quantum sensors over a distance. Analogous to classical sensor networks, where sensors are linked via classical information channels, quantum sensors can be interconnected via quantum communication to combine the quantum information obtained at the individual sensor nodes. This promises, first, a more efficient integration of measurement data than is possible with classical sensor networks and, second, an improved signal-to-noise ratio through entanglement of the quantum sensors. In principle, this approach is applicable to all types of quantum sensors. However, no specific use case has emerged yet that has gained broad prominence beyond the research community. Two examples of promising use cases currently discussed in the community are presented below.

Quantum network of clocks

The development of highly precise atomic clocks is becoming increasingly important for modern technological infrastructure. Many critical systems, such as global navigation and positioning networks, rely on accurate timing, where improvements in timekeeping directly translate into enhanced precision and reliability. By integrating precision metrology with quantum networking, it has been proposed that geographically separated optical atomic clocks could be interconnected using quantum communication protocols (Kómár et al. 2014). In such architectures, nonlocal entangled states shared between distant clocks allow them to operate cooperatively (Jozsa et al. 2000; Shi and Shen 2022), effectively forming a distributed quantum sensor. This approach enables optimal use of global resources and allows the network to approach the fundamental precision limits imposed by quantum mechanics. Moreover, the use of quantum communication techniques can provide intrinsic security against both internal and external tampering. In the long term, such quantum-linked clock networks could enable the realization of a globally synchronized "world clock" with unprecedented stability and accuracy. Realizing such globally distributed quantum clock networks requires the transmission of high-fidelity entanglement over long distances, thereby motivating the development of quantum repeaters to overcome loss and enable scalable interconnection.

Longer-baseline telescopes using quantum repeaters

Current optical interferometers achieve high angular resolution by combining light collected at multiple telescopes separated by large distances. However, their performance is fundamentally limited by the need to physically transmit photons between telescope sites. Over long baselines, optical signals suffer from transmission loss and phase noise in fibers or free-space links, which degrades the interference visibility and restricts the achievable resolution. As a result, extending interferometric arrays to very large distances becomes impractical with conventional techniques. Quantum-repeater-based approaches have been proposed to overcome this limitation. In particular, as proposed by Gottesman, Jennewein, and Croke (Gottesman et al. 2012) and demonstrated by Stas et al. (Stas et al. 2026), incoming starlight can be stored locally in quantum memories while entanglement is distributed between distant telescopes using quantum repeaters. This enables non-local interference measurements without long-distance photon transmission, potentially allowing interferometric arrays with much larger baselines and significantly improved imaging resolution.

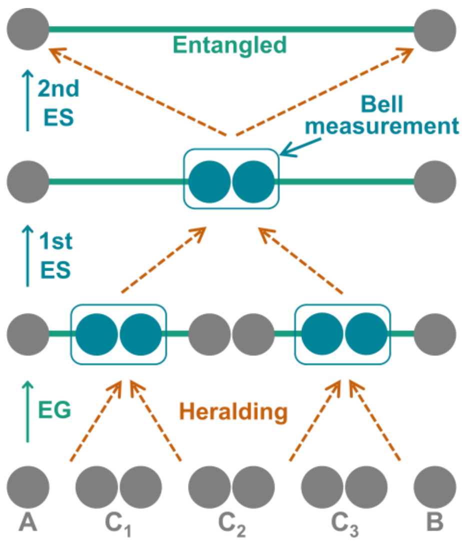
3.2 General Principle

In practical implementations of quantum networks, quantum information is transmitted via photonic channels, with optical fibers forming the backbone of long-distance communication. However, photon loss—being the dominant noise mechanism in optical fibers—causes the transmission probability to decay exponentially with distance. Consequently, the efficiency of direct quantum communication rapidly diminishes, restricting practical transmission ranges to around 100 km. In classical communication systems, such losses are mitigated using repeaters that measure, amplify, and retransmit signals. This strategy cannot be directly extended to quantum systems, as the no-cloning theorem forbids the creation of identical copies of unknown quantum states. The resulting inability to amplify quantum signals imposes a fundamental limit on direct quantum communication, thereby motivating the development of quantum repeaters.

It is important to note that quantum repeaters do not eliminate photon loss but instead mitigate its impact by dividing a long communication channel into shorter elementary links. Entanglement is first established over these shorter segments and subsequently connected through entanglement swapping. However, entanglement swapping alone is insufficient for scalable long-distance communication, since channel attenuation, imperfect quantum operations, and finite quantum memories degrade the fidelity of the distributed entanglement after successive swapping operations. Consequently, practical quantum repeater protocols incorporate additional mechanisms, such as entanglement purification or quantum error correction (see section 3.3.1), to maintain high-fidelity entanglement over long distances. Depending on the implementation, these functionalities may be realized using quantum memories at intermediate nodes (memory-based repeaters) or photonic encoding strategies that improve loss tolerance (all-photonic repeaters). A more detailed discussion of these repeater architectures is provided in sections 3.3.2 and 3.3.3.

Entanglement swapping forms the fundamental primitive of quantum repeater protocols. In this process, two distant parties (Alice and Bob) each share an entangled pair with an intermediate node (Charlie). The intermediate node performs a joint Bell-state measurement[5] on its two qubits, projecting the two distant particles onto an entangled state, even though these particles have never directly interacted. The resulting entangled state depends on the measurement outcome, but appropriate local corrections can be applied if required. By repeatedly applying this procedure, entanglement can be extended across **multiple segments**, enabling long-distance quantum correlations. Together with entanglement purification or quantum error correction, this forms the basis of conventional quantum repeater protocols. To provide a clearer picture, the standard repeater scheme, in which entanglement swapping is performed after successful entanglement generation, is illustrated in Figure 3.

Figure 3: Conventional quantum repeater protocol (nested entanglement swapping)



Source: Adapted from K. Azuma, K. Tamaki, and H.-K. Lo, "All-photonic quantum repeaters," (Azuma et al. 2015)

5 A joint Bell-state measurement is a special kind of simultaneous measurement on two particles which projects them into one of the Bell states (maximally entangled states), while revealing only limited information about their individual properties, and can therefore be used for tasks such as entanglement swapping: previously not-entangled particles of two different Bell-pairs are measured, creating entanglement between the two remaining quantum states.

The communication channel between Alice (A) and Bob (B) is divided into shorter segments using repeater nodes C_1, C_2, and C_3. Long-distance entanglement is established through a sequence of entanglement generation (EG) and entanglement swapping (ES) steps at these intermediate nodes. Each repeater node is equipped with two matter-based quantum memories, one for each adjacent link. The protocol begins with the generation of entanglement between neighboring nodes, usually via photonic Bell-state measurement: for example, between Alice and the left memory of C_1, between the right memory of C_1 and the left memory of C_2, and so on until the final node connects to Bob. Since entanglement generation is probabilistic, a heralding signal—a classical message sent between nodes—confirms which quantum memories have successfully formed entangled pairs.

Once the heralding signals indicate successful entanglement, the first stage of entanglement swapping is performed. At each repeater node, a Bell-state measurement on its two memories connects the neighboring entangled pairs into a longer pair. For instance, C_1 connects the A-C_1 and C_1-C_2 pairs into a longer A-C_2 pair in the first step. In the second step, C_2 connects A-C_2 and C_2-B to create a long-distance entangled pair between Alice and Bob. At every stage, the heralding signals ensure that only successfully prepared pairs are used for swapping, enabling the protocol to systematically extend entanglement across the entire communication distance. A major drawback of this protocol is the reliance on heralding signals, which must propagate between repeater nodes before entanglement swapping can be performed. The resulting latency is at least the classical communication time between adjacent nodes, imposing stringent requirements on long-lived quantum memories —which is a challenge, because qubits interact easily with the external environment and the stored quantum state loses its coherence and becomes a mixed state (decoherence). Thus, the operation often necessitates cryogenic or tightly controlled environmental conditions. Furthermore, since entanglement generation is inherently probabilistic, additional delays arise while waiting for successful entangled links to be established.

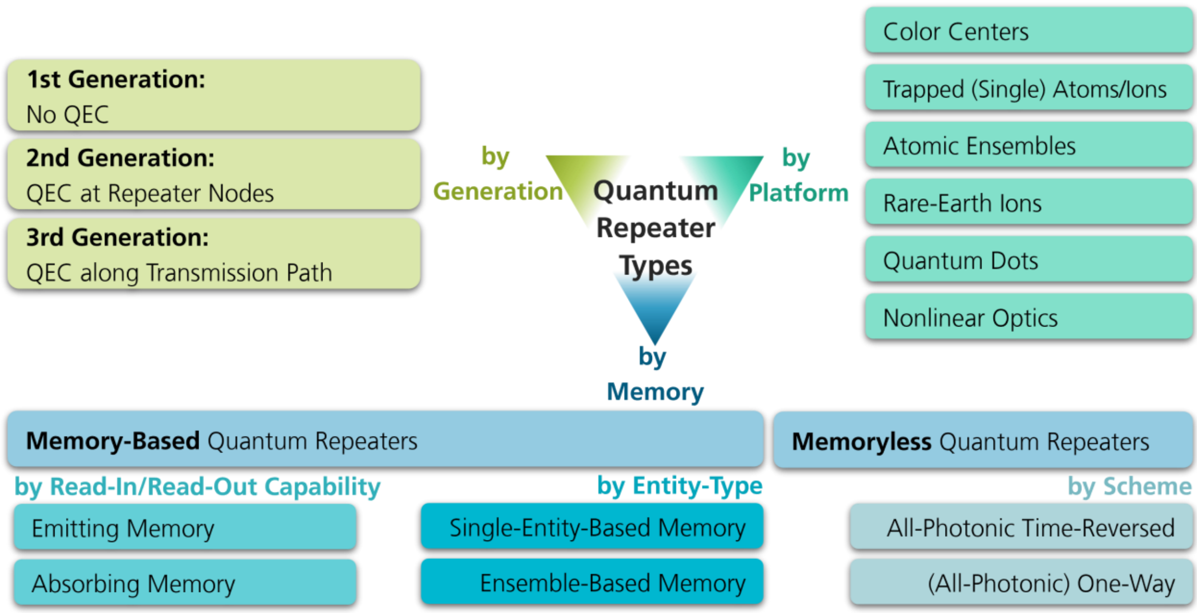
To overcome these limitations, alternative architectures based on all-photonic quantum repeaters have been proposed. In such schemes, linear-optical Bell-state measurements (Calsamiglia and Lütkenhaus 2001) using beam splitters and polarization-resolving detectors are employed to identify photonic entanglement, enabling repeater operation without long-lived quantum memories. However, waiting-time issues can still persist, as extended processing times increase the probability of photon loss. A path toward eliminating waiting times is found in approaches that implement forward error correction with the goal of minimizing the required round-trip time and enabling faster long-distance quantum communication (Munro et al. 2015).

3.3 Repeater Types

As described in the previous section, quantum repeaters can be broadly divided into two technologically distinct approaches—memory-based and all-photonic—whose key difference lies in whether quantum information is stored in matter-based memories. Quantum repeaters can also be classified by other characteristics, such as their approach to addressing errors and the utilized hardware platform (Figure 4).

This section describes various classifications of quantum repeaters. Section 3.3.1 explains three generations of quantum repeaters, based on how they address loss errors and operational errors. Memory-based repeaters (section 3.3.2) can be distinguished by the read-in/read-out capabilities (absorbing and emitting) and by the entity type (single-entity-based and ensemble-based) of the underlying memory. Memoryless repeaters (section 3.3.3) are separated into two approaches: all-photonic time-reversed and all-photonic one-way repeaters. The different hardware platforms proposed to realize these quantum repeater architectures (section 3.3.4) are discussed, and key performance indicators to compare these platforms are introduced (section 3.4).

Figure 4: Overview of different classifications of quantum repeaters



Source: Fraunhofer ISI

3.3.1 Generations of Quantum Repeaters

A general challenge in quantum communication is the presence of errors arising from intrinsic channel attenuation, referred to as *loss errors*, as well as errors due to imperfections in the channel, measurements, and gate operations, referred to as *operation errors*. To establish a reliable communication line, active mechanisms are required to correct for these errors. Depending on the methods used to suppress loss and operation errors—a combination of heralded protocols and quantum error correction (QEC) (Jiang et al. 2009)—quantum repeater schemes can be classified into three generations (Muralidharan et al. 2016; Wei et al. 2022).

Loss errors are commonly addressed through heralded entanglement generation (HEG) (Briegel et al. 1998), where entanglement between neighboring nodes is probabilistically established using, for example, two-photon interference conditioned on specific detection patterns[6] at intermediate stations. The presence of loss is overcome by repeating this process until successful entanglement is confirmed via two-way classical signaling. Alternatively, loss can be mitigated by encoding a logical qubit into a block of physical qubits and transmitting it through the channel, where QEC is used to recover the encoded information using only one-way signaling (see section 3.3.3).

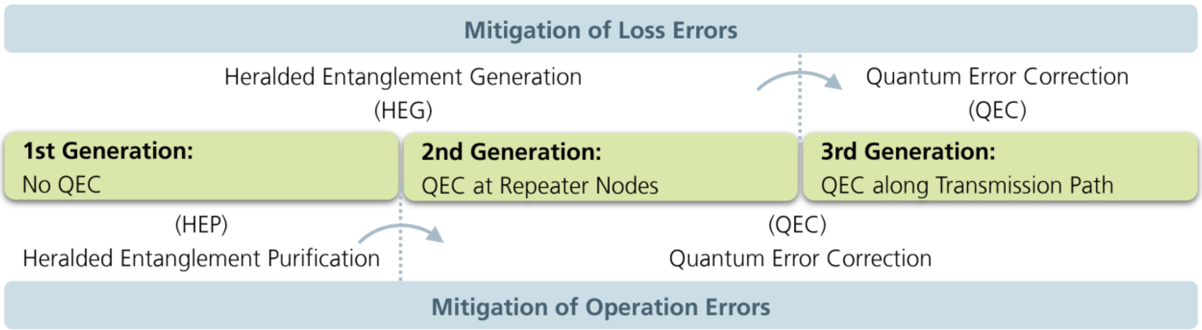
Operation errors, on the other hand, can be suppressed either by heralded entanglement purification (HEP) (Deutsch et al. 1996) or by QEC. In HEP, multiple low-fidelity Bell pairs, i.e., photons entangled in an imperfect way, are consumed to probabilistically generate a smaller number of higher-fidelity pairs, again requiring two-way classical communication to verify successful purification. In contrast, QEC enables deterministic correction of operation errors using only one-way signaling, provided local quantum gates[7] with sufficiently high fidelity are available. Based on how these techniques—HEG, HEP, and QEC—are combined to address loss and operation errors,

[6] Which detectors along the node measure a detection ("click") event depends on loss, probabilistic emission, detection efficiency and quantum interference. Depending on the specific combinations of detector clicks (which detectors clicks and when) the two-photon interference has occurred in the right way to herald entanglement between the nodes.

[7] Quantum gates are controlled operations applied to qubits – analogous to how logic gates process bits in classical computing.

quantum repeater protocols are broadly classified into three generations (Figure 5), each offering different trade-offs in communication rate, resource overhead, and experimental requirements.

Figure 5: Generations of quantum repeaters



Source: inspired by (Muralidharan et al. 2016) / adapted by Fraunhofer ISI

The **first generation of QRs** uses HEG to address loss errors and HEP to suppress operation errors. Since it relies on classical heralding signals, entanglement swapping can only proceed once these signals have been received. This introduces delays that increase with the distance between repeater nodes. This method reduces the exponential scaling of losses to a polynomial overhead. However, it remains limited for global-scale applications and often requires temporal, spatial, and frequency multiplexing to boost communication rates. Representative protocols of this generation include the seminal proposal by Hans Briegel, Wolfgang Dür, Juan Ignacio Cirac, and Peter Zoller (BDCZ) (Briegel et al. 1998), which introduced the nested entanglement swapping and purification strategy as a conceptual framework for quantum repeaters. However, its practical implementation has been hindered by the lack of efficient and long-lived quantum memories required to store entangled states during the protocol. To address these challenges, the Duan–Lukin–Cirac–Zoller (DLCZ) protocol proposed a more explicitly specified, experimentally implementable approach based on atomic ensembles and linear optics, where entanglement generation, storage, and connection are incorporated within a single physical system (Duan et al. 2001). The Sean D. Barrett–Pieter Kok (Kok–Barrett) scheme presents a distinct approach by entangling *individual matter qubits*, rather than atomic ensembles as in DLCZ or relying on an abstract framework as in BDCZ (Barrett and Kok 2005). It is designed to be robust against photon loss and other sources of errors, using optical transitions of the qubit system together with linear optics and photodetection to generate entanglement between spatially separated qubits in a probabilistic but heralded manner. Unlike DLCZ, which stores entanglement in collective excitations, this protocol directly creates entanglement between single, addressable qubits, making it well-suited for distributed quantum computing. Although the entangling operation is non-deterministic, repeated attempts enable scalable generation of large, entangled states such as cluster states.

The **second-generation QR** uses HEG to suppress loss errors and QEC to correct operation errors. While HEG is still employed locally between adjacent nodes, the use of long-distance two-way classical heralding signals is avoided, as QEC replaces heralded entanglement purification. This approach, explicitly proposed by Liang Jiang et al. (Jiang et al. 2009), shifts the paradigm toward *local error correction at repeater nodes*, while the transmission channel itself remains unchanged. In this scheme, quantum information is encoded into *logical qubits at each node*, typically using small Calderbank–Shor–Steane (CSS) codes (Nielsen and Chuang 2000), enabling errors to be actively corrected rather than merely detected, thereby maintaining high efficiency without discarding states. Entanglement swapping is performed at the encoded level, and classical error correction is used to improve fidelity, eliminating the need for long-distance entanglement purification and reducing resource overhead compared to full QEC-based approaches. As a result, entanglement distribution can proceed continuously with only local classical communication between neighboring stations, and the communication rate is primarily limited by local signaling delays and gate operation times. Such protocols can, in principle, enable long-distance communication over scales of 10^3–10^6 km while maintaining efficient key generation rates using finite local resources that scale only logarithmically with distance.

On the other hand, the **third-generation QR** uses QEC to correct both loss and operation errors (Munro et al. 2015; Muralidharan et al. 2016). In this scheme, the quantum information is directly encoded into a block of physical qubits and transmitted through the lossy channel, where errors are corrected not only at the repeater nodes but effectively also during transmission. If the loss and operation errors remain below the fault-tolerance threshold, the received physical qubits can be used to fully restore the encoded logical state, which is then retransmitted to the next repeater station. In contrast to earlier generations, this approach enables *deterministic entanglement distribution*, eliminating the need for probabilistic heralding and synchronization between segments. As a result, quantum memories and two-way classical communication become unnecessary, and the communication rate is limited primarily by local operation times, closely resembling the performance of classical repeaters.

3.3.2 Memory-Based Quantum Repeaters

As discussed in the previous section, the success of memory-based quantum repeaters relies heavily on the availability of reliable quantum memories capable of storing the state of flying qubits for either predefined or flexible durations. In this sense, quantum memories have a function that goes beyond simple storage. They act as interfaces between photons, which carry quantum information across a network, and stationary matter qubits, which can store and process that information locally. Their key function is to coherently map a photonic quantum state onto a material system and retrieve it later, on demand, while preserving the encoded information.

Distinction by entity type

Quantum memories can be broadly classified according to the physical systems used to realize this light–matter interface, with a natural distinction between **ensemble-based** and **single-emitter** approaches. Ensemble-based memories, such as cold and warm atomic gases or rare-earth-ion-doped crystals (RE, often also REIDs), store quantum information in collective excitations shared among many atoms. Rather than addressing each atom individually, these systems exploit the cooperative interaction of the entire ensemble with light, which can lead to strong and efficient light–matter coupling. One of their major strengths is their ability to support **multimode storage**, meaning several quantum states can be stored simultaneously—an important advantage for boosting the rates of quantum communication.

A different approach is offered by **single-emitter quantum memories**, based on individual quantum systems such as trapped atoms, ions, molecules, quantum dots, or solid-state defects like nitrogen-vacancy (NV) centers in diamond. Here, quantum information is stored and manipulated at the level of a single qubit, often with the help of optical cavities to enhance coupling to photons. Although these systems can be experimentally more demanding, they offer highly precise and often deterministic control over individual qubits. This makes them particularly appealing, not only as memories, but also as building blocks for quantum network nodes. In many cases, they can additionally function as sources of high-quality single photons, an essential resource for quantum communication and distributed quantum computing.

Distinction by read-in/read-out capability

To establish entanglement between distant nodes, a key prerequisite is generating entanglement between flying photonic qubits and stationary matter qubits stored in quantum memories. This can be realized through two conceptually distinct approaches: **emissive** and **absorptive** quantum memories (Duan et al. 2001; Liu et al. 2021; Choi et al. 2008). **Emissive quantum memories** generate light–matter entanglement through photon emission. A weak write pulse probabilistically creates a collective spin-wave excitation in an ensemble, heralded by the spontaneous emission and detection of an idler photon entangled with the stored excitation. This excitation can later be retrieved as a signal photon using a read pulse. This principle underlies the **Duan–Lukin–Cirac–Zoller (DLCZ)** protocol (Duan et al. 2001), where idler photons emitted from two distant memories interfere at a 50:50 beam splitter; a joint detection erases which-path information and projects the remote memories into an entangled state.

In **absorptive memories**, in contrast, an incoming photonic qubit is coherently mapped onto a long-lived collective excitation in an atomic or solid-state medium and later retrieved as a photon on demand. Their defining role is therefore the storage and retrieval of flying qubits, making them natural quantum buffers for synchronization in repeater architectures. This approach is realized in protocols such as electromagnetically induced transparency (EIT), Raman memories, and atomic frequency combs, where the quantum state of an externally generated photon is preserved within the memory until needed for further network operations (see below for details). In this way, absorptive memories primarily serve as storage elements for photonic qubits, while emissive memories naturally function as entanglement-generating nodes for long-distance quantum communication.

Protocols for memory-based repeaters

A variety of protocols exist to implement quantum storage across different platforms. Each platform may support more than one protocol, and therefore, depending on the intended memory application, an appropriate choice must be made. There are clear trade-offs between high efficiencies, long storage times, temporal and spatial multimode capacity, large bandwidths, and high fidelities. As a result, no single solution satisfies all requirements simultaneously, and these trade-offs must be carefully balanced with respect to the targeted application.

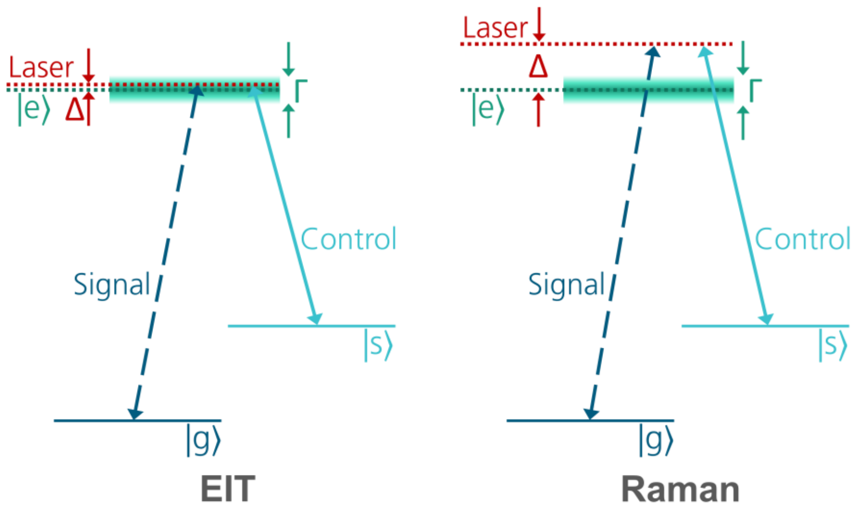
Heshami et al. used the terms optically-controlled memories and engineered absorption to categorize ensemble-based quantum memory protocols according to their photon-storage mechanisms (Heshami et al. 2016). In optically controlled quantum memories, strong control fields are employed to drive and regulate the processes of photon storage and retrieval. In contrast, memories based on engineered absorption make use of broad inhomogeneously broadened optical transitions, where the absorption profile is deliberately tailored—either in a static or dynamic manner—to achieve the required storage and controlled re-emission behavior.

To describe **optically controlled quantum memories**, consider a three-level Λ*-type system* consisting of a ground state $|g\rangle$, an excited state $|e\rangle$, and a long-lived metastable state $|s\rangle$. Dipole-allowed transitions exist between $|g\rangle\leftrightarrow|e\rangle$ and $|s\rangle\leftrightarrow|e\rangle$, while the direct transition between $|g\rangle$ and $|s\rangle$ is typically forbidden. This makes $|s\rangle$ a suitable storage state with a long coherence time. In many physical systems, such as atoms or solid-state platforms, these levels can be realized using hyperfine ground states and an optically excited state.

The storage and retrieval of an optical signal are controlled by an external laser field. When the detuning Δ, i.e., the difference of laser and transition frequency, is small compared to the excited-state linewidth Γ, the application of the control field induces a narrow transparency window for the signal field—an effect known as EIT. Under these conditions, the signal pulse experiences slow light propagation, where its group velocity is significantly reduced. By dynamically varying the control field, the optical pulse can be mapped into a collective excitation of the medium and stored. In contrast, when the detuning is large ($\Delta \gg \Gamma$), the interaction is off-resonant, and storage and retrieval occur via *Raman processes* rather than through EIT (see Figure 6).

To retrieve the stored photon, the control field is reapplied, converting the stored excitation back into a propagating optical mode. This process can be performed on demand, provided retrieval occurs within the coherence time of the storage medium. EIT memories offer excellent controllability and have demonstrated exceptionally high storage fidelities (>99.5% (Mamann et al. 2025)). Nevertheless, practical implementations require careful suppression of noise arising from control-field leakage and other nonlinear optical processes. Furthermore, the multimode storage capacity of EIT memories is typically limited by their relatively small time-bandwidth product, so efficient storage of many temporal modes generally requires additional multiplexing techniques, such as spatial multiplexing.

Figure 6: Schematic of optically controlled memories in Λ-type system



Source: Fraunhofer ISI

Engineered absorption memories exploit the naturally broad inhomogeneous linewidth present in materials such as rare-earth-ion-doped crystals by actively tailoring their spectral properties. In protocols like *controlled reversible inhomogeneous broadening (CRIB)* (Sangouard et al. 2007), a narrow and well-defined absorption feature is first created within the broader line, typically by optically pumping most of the population into auxiliary states. This engineered line is then artificially broadened in a controlled and reversible way using an external electric or magnetic field gradient, enabling efficient absorption of an incoming photon. After absorption, the excitation can be transferred to a long-lived ground or metastable state to extend the storage time. Retrieval is achieved by reversing the process: the excitation is brought back to the optical transition, and the sign of the applied field gradient is inverted, causing the atomic ensemble to rephase and emit the photon as an echo. When the probe field propagates along the direction of the applied gradient, the scheme is known as *gradient echo memory (GEM)* (Hétet et al. 2008), a longitudinal variant of CRIB that supports on-demand readout. GEM is particularly attractive due to its high efficiency, reduced re-absorption losses, and its ability to provide flexible and coherent control over the stored optical information.

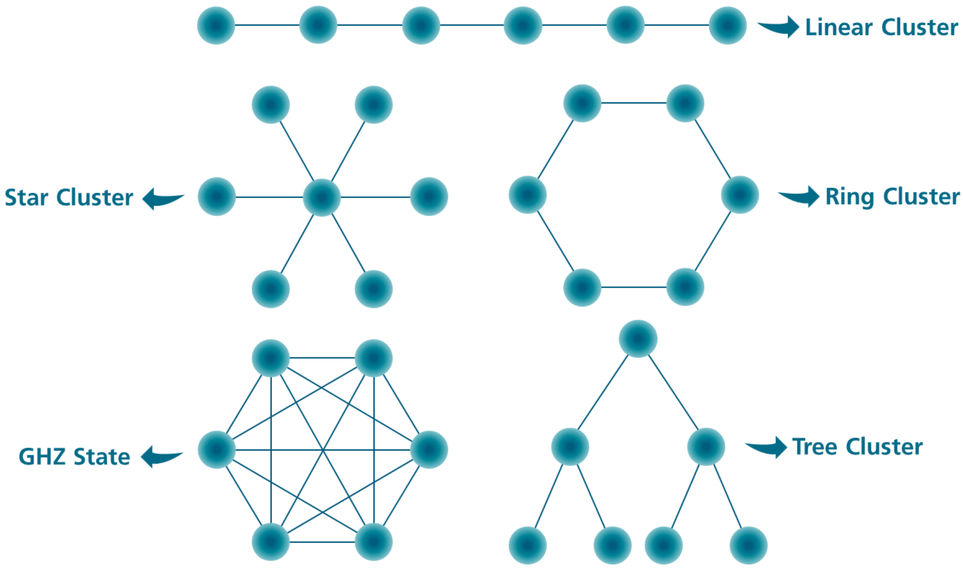
Another important class of engineered absorption quantum memories is based on the atomic frequency comb (AFC) protocol. In this approach, the broad inhomogeneous absorption profile of the material is shaped into a series of equally spaced narrow absorption peaks through optical pumping. When an incoming light pulse is absorbed across several of these peaks, the different frequency components of the collective optical excitation evolve in time and naturally rephase after a fixed delay determined by the comb spacing, resulting in the re-emission of the stored photon. By itself, this AFC echo provides only a predetermined storage time. To achieve on-demand retrieval and realize a true quantum memory, the collective optical excitation is transferred to a long-lived **spin-wave excitation** using a control pulse before the AFC echo occurs. A second control pulse later transfers the spin-wave excitation back to the optical transition, allowing retrieval of the stored photon at a user-defined time. Compared to optically controlled memories, AFC-based memories offer the important advantage of supporting efficient multimode storage. In addition to the widely used memory protocols discussed above, several **alternative approaches** have been proposed and explored in recent years, each aiming to overcome specific limitations of conventional schemes. For instance, traditional two-pulse photon echo techniques have been extended to *four level photon-echo schemes* (Beavan et al. 2011), in order to suppress population inversion and thereby reduce noise arising from spontaneous emission. Another notable development is the revival of rephasing-based methods like *revival of silenced echoes (ROSE)* (Damon et al. 2011), which enable echo generation while minimizing unwanted emissions. Further progress includes protocols such as *Stark echo modulation memory (SEMM)* (Arcangeli et al. 2016), which takes advantage of symmetry properties in the linear Stark effect to control rephasing dynamics in solid-state systems. Additionally, *off-resonant cascaded absorption (ORCA)* (Kaczmarek et al. 2018) has been introduced as a scheme capable of achieving near noise-free storage by operating far from resonance. More recently, the *fast ladder memory (FLAME)* (Finkelstein et al. 2018) approach has demonstrated the storage of optical information in higher electronic states of systems like rubidium vapor, offering fast operation at the expense of shorter storage times due to the limited lifetime of these excited states.

3.3.3 All-Photonic Quantum Repeaters

Memory-based quantum repeater schemes require matter-based quantum memories at every repeater node, as well as a two-way communication between the repeater nodes for exchanging the relevant information about the successful completion of photon receiving, storing and quantum gates. The third generation of quantum repeaters aims for memoryless realizations, which could overcome some of the inherent limitations of memory-based approaches, however at the cost of addressing demanding technical challenges. Even though these approaches are often called "all-photonic quantum repeaters" they still require hardware platforms for the generation of the photonic states and optical setups for performing operations at the repeater nodes.

One approach toward memoryless quantum repeaters is based on **graph or cluster states** of photons, i.e., multi-photon states whose photons are entangled according to a predefined graph. Examples of cluster states are given in Figure 7: the nodes of the graph are the photons, and the connections between the nodes present the entanglement between two photons. Quantum repeaters can use cluster states to realize loss tolerance along the transmission path by exploiting the inherent redundancy in suitably encoded photon clusters.

Figure 7: Overview of different types of cluster-states



Source: Fraunhofer ISI

All-photonic time-reversed quantum repeater

The *first proposal of an all-photonic quantum repeater* by Azuma et al. (Azuma et al. 2015) is based on source nodes that create complex photonic cluster states and adjacent receiver nodes that perform appropriate single-photon measurements. The structure of the cluster state and its measurement pattern at the receiver nodes effectively implements the entanglement-swapping operations that in memory-based repeaters are carried out via explicit Bell measurements on stored qubits. This is the key advantage of this concept: due to the entanglement established within the cluster state prior to the photons' arrival at the receiver nodes, no storage of the photons is required to perform a Bell measurement on a two-qubit state (one photon of each neighboring node). Instead, the individual photons can be measured directly upon arrival, with the choice of measurement bases determining the effective logical Bell-type measurement.

The successful measurements at the intermediate nodes and the (classical) communication of their outcomes propagate the entanglement along the chain, ultimately generating entanglement between the two end nodes, Alice and Bob. As the chronological order of the conceptual steps "sending photons through the channel" and "creating long-distance entanglement via entanglement swapping" is effectively inverted, this scheme is often referred to as an all-photonic **time-reversed** quantum repeater.

Only a small part of the photons sent out by the source nodes have to arrive at the receiver node and need to be successfully measured in the single-photon measurements realizing the logical Bell-type measurement. Alice and Bob, the two end nodes, send out photons that are entangled to their local qubit to the closest receiver node, which connects them to the next source node and so on. In recent years, variations or specifications of this scheme have been proposed (Benchasattabuse et al. 2024; Buterakos et al. 2017; Rozpędek et al. 2023), and first proof-of-principle experiments have been conducted (Hasegawa et al. 2019; Li et al. 2019).

One-way quantum repeater

All repeater schemes introduced above are based on distributing entanglement, which can then be used for various applications. One approach toward all-photonic quantum repeaters breaks with this convention: *One-way or forward-error-corrected quantum repeaters* can be used for directly transferring a logical qubit from Alice to Bob. In the original proposal of Muralidharan et al. (Muralidharan et al. 2014), light–matter systems are included for the error correction at the repeater node, hence, while being a memoryless concept, the term "all-photonic" would be misleading. Variations of that proposal suggest schemes that only require linear optics at the repeater nodes (Ewert et al. 2016).

In this concept, Alice prepares a logical qubit spread over multiple physical qubits (photons). This logical qubit is sent to the first repeater node, which forwards it to the next until it arrives at Bob. To account for photon losses, in each repeater node an error correction is performed. The stabilizer codes required for this error correction can be implemented, for example, by the initial generation of a cluster state, which can be reconstructed if more than half of the photons of the cluster arrive at the repeater node. The photon loss allowed for in-between repeater nodes in this scheme has to be below 50% of the photons to prevent a potential eavesdropper from reconstructing the information of the qubit. Therefore, the repeater nodes have to be closer together than in other schemes, which can tolerate larger photon losses, marking a key disadvantage of this approach. However, as this approach only requires one-way communication the speed of this protocol can be, in theory, faster than other proposed repeater protocols. Due to this advantage, it is the focus of many research activities (Borregaard et al. 2020; Niu et al. 2023).

3.3.4 Hardware Platforms

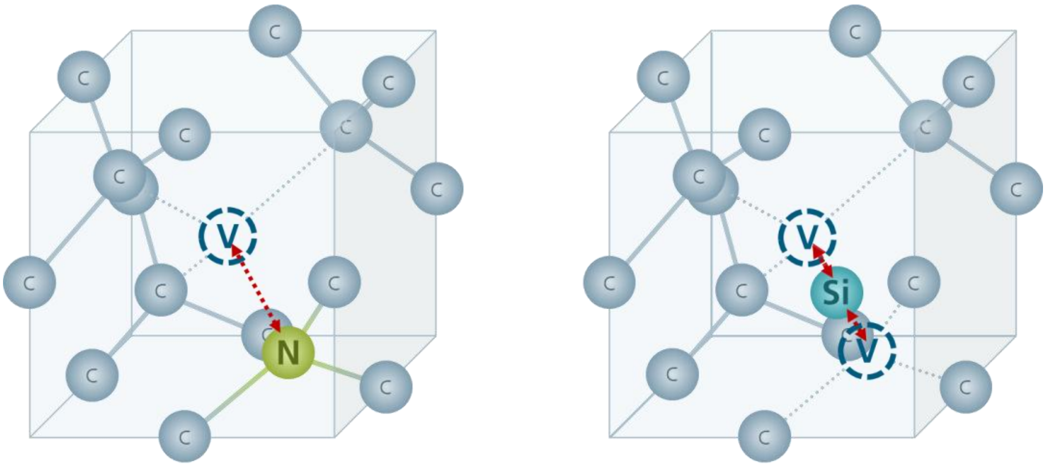
Different hardware platforms have been proposed for use in quantum repeaters. This section describes the mechanisms of the materials/technology platforms most frequently mentioned during the conducted desk research and expert interviews, namely color centers, trapped single atoms/ions, atomic ensembles (including cold atoms and warm atoms in vapor cells), rare-earth systems, semiconductor quantum dots, and entanglement generation in nonlinear media. More detailed descriptions of the characteristics of the memory types based on these hardware platforms will be given in section 4.1.

While the platforms introduced in the following paragraphs cover the most important approaches with respect to distributing entanglement over longer distances, strictly speaking this list is not exhaustive. One example not discussed in detail is approaches based on **superconducting qubits**, which play a role in quantum computing applications, but have limited value for long-range quantum information networks, as they naturally interact via microwave photons (hard to distribute over long distances) (Caleffi et al. 2026) and have relatively short coherence times (hard to store long enough to account for the time required for photons to travel between repeater nodes) (Lisenfeld et al. 2023).

Color centers (CC)

Color centers in diamond and other wide-bandgap materials are promising candidates for the implementation of a scalable quantum network. Impurity atoms are embedded into the diamond crystal lattice to introduce electronic states into the bandgap of diamond in order to add transitions which can be used for absorbing and emitting light. The most famous and widely used color center in diamond is the nitrogen-vacancy (NV) center (see Figure 8, left side), in which two carbon atoms of the diamond crystal lattice are replaced by one nitrogen atom (N), leaving one lattice position empty (vacancy, V).

Figure 8: Schematic of nitrogen-vacancy and silicon-vacancy in diamond



Source: Fraunhofer ISI

Color centers have an optically active, individually controllable spin that serves as the communication qubit and can be accessed via photons to establish communication with other nodes, as well as long-lived nuclear spins in their surroundings that serve as memory qubits. They also have spin-selective optical transitions that can efficiently entangle the color center's spin state with a photonic state (number, polarization, or frequency basis).

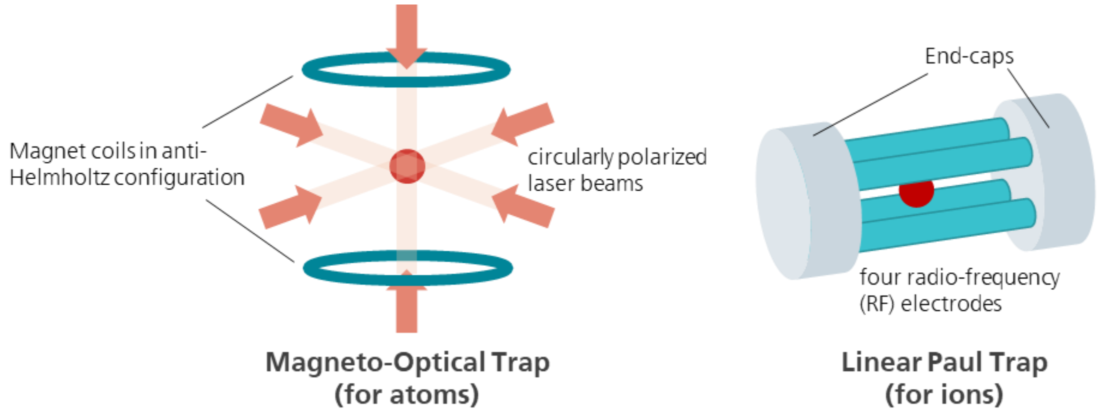
Research has succeeded in establishing efficient methods for the fabrication of high-quality bulk crystals as well as nanodiamonds, with fine control over the composition of introduced defects, which commonly include silicon, germanium, tin, nickel, nitrogen, and others. Besides NV centers, Group-IV vacancy centers, particularly silicon-vacancy centers (SiV), are most commonly used for demonstrations of quantum network protocols and components.

Trapped single atoms (sA) / trapped single ions (sI)

Atoms or ions confined in optical or electromagnetic traps can serve as single-entity-based quantum memories. In these systems, quantum information is typically encoded in long-lived internal states, such as hyperfine ground states. Since atoms and ions of the same species and isotopes are inherently identical, they can offer excellent spectral indistinguishability, enabling high-fidelity quantum operations and a natural uniformity across different setups. Owing to these properties, trapped atoms and ions have attracted significant attention in both quantum computing and quantum networking. Commonly used atomic species include rubidium (Rb) and cesium (Cs) for trapped atoms, and calcium (Ca^+), barium (Ba^+), strontium (Sr^+), and ytterbium (Yb^+) for trapped ions.

Individually addressable neutral atoms can be trapped and arranged using optical tweezers created by lasers, enabling the arrangement of single-atom qubits in array structures. Beyond their use as quantum memories, trapped neutral atoms are also known for their capability to generate photonic graph states, which can be utilized for all-photonic quantum repeaters. In contrast, trapped ions are confined using electromagnetic traps (e.g., Paul Traps), with an effectively deeper trapping potential compared to optical traps used for neutral atoms. While neutral atoms may escape optical traps and threfore require reloading, electromagnetic traps can confine ions over longer time scales.

Figure 9: Schematic figures of typical traps used to confine single atoms/ions

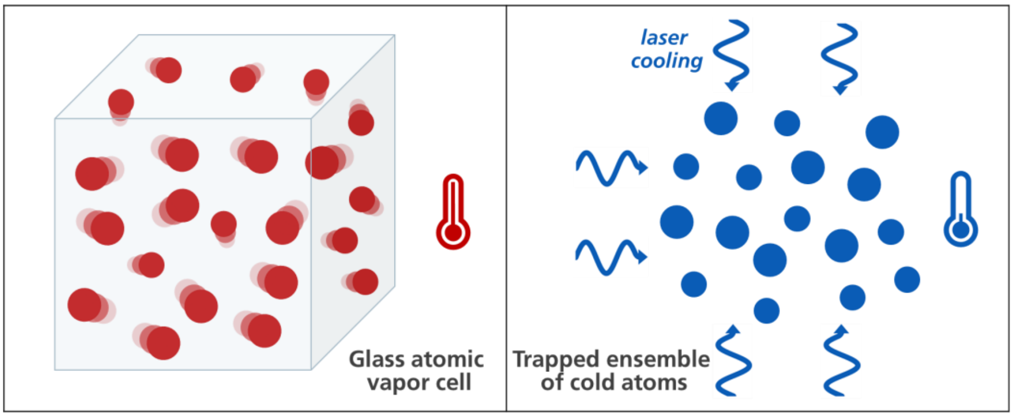


Source: Fraunhofer ISI

Atomic ensembles: cold atoms (cAE) / warm atoms in vapor cell (wAE)

Atoms can also be used as ensemble-based quantum memories. They offer high storage-and-retrieval efficiency due to their large optical depth and are progressing toward commercialization, making them attractive particularly for use in communication backbone networks. One approach to realizing ensemble-based memories is to trap atoms using laser-cooling techniques, while the other approach is to use a vapor cell, which is a glass cell filled with warm atomic gas. Both systems rely on the same underlying physical principle: quantum states are stored as collective excitations shared among many atoms. The quantum information is mapped onto a collective spin-wave mode of the atomic ensemble. A key distinction between these two approaches lies in the operating temperature. Laser-cooled atomic ensembles are usually trapped at temperatures in the microkelvin regime, whereas vapor cells operate at room temperature or above; hence, they are being referred to as "warm atoms."

Figure 10: Schematic of confined warm and cold atomic ensembles



Source: Fraunhofer ISI

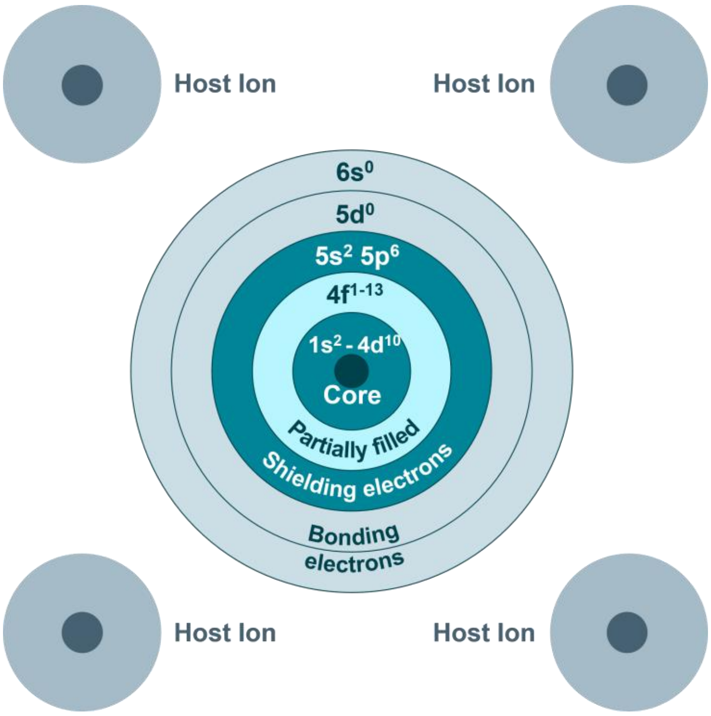
Atomic ensembles became a prominent platform, particularly following the proposal of the DLCZ protocol in 2001, which uses atomic ensembles as quantum memories (Duan et al. 2001). Rubidium (Rb) and cesium (Cs) are the most commonly used atomic species for this type of quantum memory.

Rare-earth-ion-doped crystal (RE)

Due to the combination of long-lived hyperfine levels (for storage), large inhomogeneous broadening (enabling high-bandwidth multiplexing), promising optical and spin coherence properties, and their effectiveness as light–matter interfaces, ensembles of rare-earth ions doped into inorganic crystals have high potential to serve as quantum memories for quantum repeaters.

The rare-earth elements include lanthanum to lutetium (atomic numbers 57–71), along with the two additional elements scandium and yttrium. They are characterized by their electronic configuration (see Figure 11): the partially filled 4f shells are shielded from external perturbations by the outer 5s and 5p shells, leading to long-lived and narrow-linewidth transitions. When doped into inorganic crystals, rare-earth elements generally form trivalent ions[8] and exhibit inhomogeneously broadened 4f–4f transitions in the visible and near-infrared regions. The hyperfine interactions give rise to spin states whose lifetimes can reach minutes and, in some cases, even days and weeks (as demonstrated in europium), offering an attractive key feature for potential quantum memory applications. Common host crystals include inorganic materials such as yttrium orthosilicate (Y_2SiO_5, also YSO) and yttrium orthovanadate (YVO_4), though many other materials, such as $CaWO_4$, $LiNbO_3$ and SiO_2 fiber, have also shown potential.

Figure 11: Rare-earth ion – 4f electrons are shielded by the outer 5s and 5p shells



Source: Fraunhofer ISI

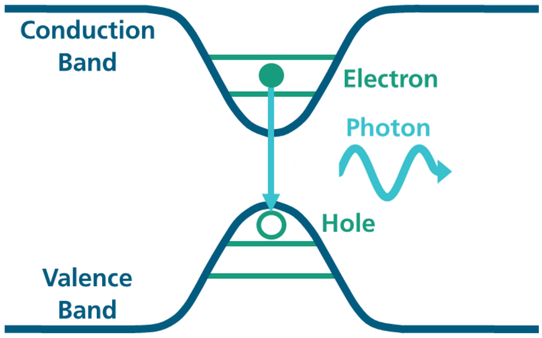
In parallel, single rare-earth ions are being explored as individually addressable quantum emitters and qubits for quantum applications. Unlike ensembles, single-ion systems enable single-qubit control, spin–photon interfaces, and the possibility of multi-qubit gate operations. Although detecting single rare-earth ions is challenging because of their weak photoluminescence, advances in nanophotonics and cavity-enhanced detection have significantly improved feasibility and enabled the multiplexed entanglement of single emitters in distant devices.

8 Ions with a 3+ charge, such as Eu^{3+}, Pr^{3+}, Er^{3+}, Nd^{3+}, Tm^{3+}, Yb^{3+}

Semiconductor quantum dots (QD)

A semiconductor quantum dot is a nanometer-scale semiconductor structure that confines electrons and holes in all three spatial dimensions. Owing to this strong quantum confinement, quantum dots exhibit discrete energy levels and therefore behave similarly to "artificial atoms." Various material platforms can host quantum dots; however, III–V and II–VI compound semiconductors are most commonly employed for quantum photonic applications.

Figure 12: Potential diagram for semiconductor quantum dots



Source: Fraunhofer ISI

Recently, quantum dots have attracted attention in quantum communication as novel deterministic single-photon sources that can reach repetition rates up to the GHz range (Endo et al. 2026). Quantum dots can also generate entangled photon pairs via the biexciton–exciton cascade, exhibiting attractive optical properties as deterministic entangled-photon sources (EPSs) and are therefore expected to be used in hybrid repeater systems, combined with absorbing memories implemented on other hardware platforms.

Beyond their application as EPSs, quantum dots have also been shown to generate multi-qubit photonic graph states, which are essential resources for all-photonic quantum repeaters. On the other hand, the application of quantum dots as quantum memories is currently limited by their relatively short coherence times. However, some recent studies suggest that longer coherence times could be achievable by leveraging nuclear spins (for details, see section 4.1).

Entanglement generation in nonlinear media

Entangled photon pairs can be generated in nonlinear media via spontaneous parametric down conversion (SPDC) or four-wave mixing (FWM). Commercial entangled-photon-pair sources (EPSs) generally use SPDC, especially the ones used in commercially available QKD systems. The use of SPDC for entangled photon pair generation is well-established, due to the achievable large conversion rates at short interaction lengths (Zhang et al. 2021), however, requiring a non-zero second-order electric susceptibility only present in materials that lack a center of inversion symmetry. FWM, even though less mature in general, could be promising for future applications due to the wide range of material availability (requires only a non-zero third-order electric susceptibility) and pathways toward photonic integration (Endo et al. 2026).

For all-photonic quantum repeaters, EPSs based on nonlinear media can be used in combination with optical setups to generate complex photonic cluster states (Zhong et al. 2018; Malik et al. 2016). While EPSs based on nonlinear media generate entanglement, they are not built to store entanglement and therefore cannot be used as quantum memories.

However, these types of sources can be used in quantum repeaters in combination with quantum memories as a source for entanglement. For example, warm atomic ensembles in vapor cells are usually coupled with SPDC-based EPSs (Buser et al. 2022). This approach can be used for quantum repeaters: one of the generated photons is sent toward the next node, while the other is stored directly within the vapor cell and can be read out after successful entanglement distribution.

3.4 Key Performance Indicators (KPIs)

Comparing different types of quantum repeaters commonly follows the same set of key characteristics, which are introduced in the following. These characteristics are often interdependent and, therefore, in general, should not be used isolated from each other. Not all of the characteristics introduced here are applicable to every type of quantum repeater.

One of the most relevant KPIs for quantum repeaters is the **distance** over which end-to-end entanglement can be distributed, since the primary goal of a quantum repeater is to extend entanglement beyond the limits of direct transmission. In current experimental studies, reported distances typically refer to the spacing between nodes, i.e., the length of an elementary link, rather than to the total end-to-end distance of a full repeater chain. The achievable distance strongly depends on the target entanglement distribution rate.

Therefore, distance alone is not a sufficient performance metric and must be considered together with other key parameters, such as error rate and entanglement generation rate. **Error rate** is a key indicator of how much the distributed quantum state deviates from the ideal target state due to, e.g., photon loss, decoherence, and imperfect operations.

Fidelity measures the closeness between an actually generated state and an ideal target state, ranging from 0 to 1, and can be defined for different processes in a quantum repeater. Fidelity is related to the error rate of a process: higher fidelity means a lower probability of errors (1 – error rate). In this report, the focus lies on retrieval fidelity for emitting memories and storage-and-retrieval fidelity for absorbing memories.

The **Entanglement generation rate** corresponds to the speed of entanglement distribution and is therefore, in combination with fidelity, directly related to the potentially achievable secret key rate, in the context of quantum key distribution. Note that the term "entanglement generation rate" can be defined either at the component level (e.g., entangled-photon-pair generation rate in SPDC), or at the repeater-link level as the rate of generating useful heralded entanglement shared between communication partners. This report presents the available figures for each platform, specifying the definition used in each referenced research paper.

The **memory coherence time** indicates the duration over which a quantum memory can store information while preserving its quantum properties. It must be sufficiently long to cover the entire repeater protocol in order to achieve long-distance and high-fidelity quantum repeaters. When benchmarking different hardware platforms, the transverse coherence time T_2 is often considered a physical parameter that characterizes the timescale of dephasing in storage materials.

Efficiency in quantum repeaters can be defined for different processes. In general, it is the ratio of the number of output photons to input photons for a certain process. Building on that, Peter van Loock et al. (van Loock et al. 2020) introduced the concept of **link (coupling) efficiency**[9] (P_{link}) to assess the performance of quantum repeater segments within a simplified model. This indicator characterizes the optical interface and includes all relevant efficiency parameters except channel

[9] The term "link efficiency" is defined differently across studies. In this report, this term is used to describe the efficiency in a repeater segment, excluding the channel transmission efficiency.

transmission, such as photon creation efficiency, fiber-channel in- and outcoupling efficiencies, and, depending on the protocol, a detector efficiency or a memory write-in efficiency.

The **operational wavelength** plays a key role, particularly in the context of building quantum communication networks. The telecom C-band (around 1550 nm) is the most desirable for fiber-based long-distance communication, as it corresponds to the lowest loss in state-of-the-art optical fibers (Endo et al. 2026). The emission and absorption wavelengths of photons are determined primarily by the material system and the selected transition. Therefore, the exploration of new materials capable of emitting and absorbing at telecom wavelengths is an active area of research in several platforms, such as quantum dots and color centers. When hardware systems are not directly compatible with the telecom band, efficient frequency conversion or a bichromatic photon-pair source becomes a key technology for achieving low-loss entanglement distribution.

The **operational temperature** of quantum repeater platforms can be connected to noise and robustness of the operation. Depending on the technological platform used, it ranges from above room temperature down to a few microkelvins, requiring different experimental setups (e.g., liquid-helium cryostats, dilution refrigerators, and laser-cooling systems). The size and cost of these setups can affect the scalability and industrial viability of each hardware system.

There are also important aspects when comparing different platforms that cannot be experimentally quantified. For example, some material platforms offer advantages in **manufacturing** due to their relatively low material costs and mature production processes. Single-entity platforms typically excel in **their ability to implement local gate operations**, making them well suited for use at end nodes. In contrast, ensemble-based memories tend to exhibit high **multiplexing potential**, which can be leveraged to extend communication distances or connect to multiple nodes of the network simultaneously.

It should be noted that some of these KPIs can also be defined for the performance of entangled-photon-pair sources without memory functions, requiring a clear definition of the given parameter. Although the KPIs for memories and light sources should not be directly compared, relevant KPIs for entangled-photon sources are given in the following sections when specific material platforms are particularly well suited for hybrid systems, which are composed of absorbing memories and entangled-photon-pair sources.

4 Roadmap

The research and development on quantum repeaters toward commercialization and broad applications requires long-term efforts from scientific and industrial actors. So far, only parts of quantum repeater schemes have been demonstrated, mostly in lab environments. Various technological challenges have to be addressed in the next years to realize more elaborate demonstrations toward the first quantum repeater (Azuma et al. 2023). The roadmap presented in this section consists of three parts: a description of the current technological maturity, an outline of challenges for future development, and an overview over potential demonstration milestones.

4.1 Current State

Over the past decade, many research groups have advanced the performance of quantum memories and single-photon technologies. Theoretical works have created a range of repeater schemes, and experimentalists have demonstrated the evolving capability of the different technological platforms candidating for future repeater realizations and proof-of-principles of relevant elements of these schemes. Most activities are still located in academia, while first startups are getting involved (some examples will be mentioned later in this section), aiming for commercialization in the next years.

This section describes the status quo of the research on the most relevant hardware platforms introduced in section 3.3.4.—color centers, trapped single atoms/ions, atomic ensembles (including cold atoms and warm atoms in vapor cells), rare-earth systems, and semiconductor quantum dots. The technology profile for each platform was drawn based on the literature and expert assessments, focusing on advantages and disadvantages, multi-dimensional benchmarking, achieved KPIs, and usability for different types of memories and repeaters.

It is important to note that the radar charts shown in the technology profiles, as well as the classification into repeater types, are intentionally coarse and provide only a rough, heuristic overview of the hardware. They represent merely a snapshot of the state of the art at the time of publication, while the technology continues to evolve rapidly. Therefore, these schematics are not intended to support detailed comparisons or provide a deeper understanding of the technologies.

For the sake of simplicity, we will only highlight selected recent achievements in the different hardware platforms and compare the platforms in terms of their most relevant advantages and disadvantages. Not included are achievements beyond these platforms, such as the development of entangled-photon-pair sources (Endo et al. 2026) and single-photon detectors (Shirinzadeh et al. 2026) used in many repeater schemes, and theoretical works on topics such as all-photonic quantum repeaters (Azuma et al. 2023).

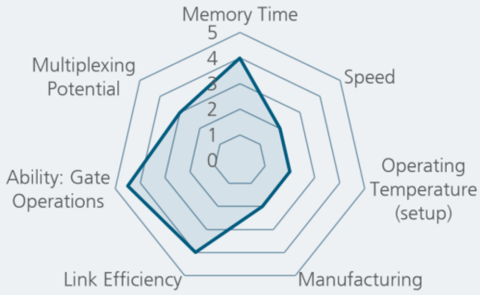
Color Centers [NV center, group-IV centers, color centers in SiC]

PROs

- Nuclear spin with long lifetimes accessible
- Visible to near IR, efficient conversion to telecom demonstrated
- Clear pathways toward integration identified

CONs

- Large scale growth of high quality, thin film diamonds is complex
- Charge instability issues
- NV: Large spectral diffusion
- NV: Weak zero-phonon emission line (restricts generation rates)
- Group-IV: Typically low temperature operation



Distance (fiber length / spatial separation)	40 km / 6 m entanglement of nuclear spin memories in lab (SiV) 25 km / 10 km heralded entanglement linked with midpoint station (NV)	[1] [2]
Fidelity	92% estimated fidelity distant electron spins (NV) 87% average spin–photon storage fidelity (SiV)	[3] [4]
Op. Wavelengths	Depending on materials/type of vacancies. NV: 637 nm, SiV: 738 nm, certain SiC-based: telecom wavelengths	[5]
Generation Rate	up to 100 Hz (NV)	[6]
Coherence Time	>1 s achievable (NV in 12C-enriched diamond)	[7]
Efficiency (retrieval or storage-and-retrieval)	NV: <1% storage / SiV: much higher	
Op. Temperature	Cryogenic operation is typically required; Subkelvin (millikelvin) temperatures are often specifically demanded.	

[1] Knaut et al., Nature 629, 573–578 (2024); [2] Stolk et al., Sci. Adv.10, eadp6442 (2024); [3] Hensen et al., Nature 526, 682–686 (2015); [4] Nguyen et al., Phys. Rev. Lett. 123, 183602 (2019); [5] Becher et al., Mater. Quantum. Technol. 3 012501 (2023).; [6] Ruf et al., Journal of Applied Physics 130, 070901 (2021); [7] Abobeih et al., Nat Commun 9, 2552 (2018).

Absorbing | Emitting | Single-Entity | Ensemble | Cluster States

The technology profiles are not intended to "rank" different hardware platforms, but rather to describe their distinct characteristics. The KPIs cited in the profiles cannot simply be compared with those of other platforms or other KPIs of the same platform from different papers, because research papers often report numbers produced under different experimental conditions.

Optical emission from **color centers (CC)** can be very bright and collected with high efficiency, enabling high entanglement generation rates. However, this strongly depends on the species of the color centers: Although NV centers have great potential to serve as workhorse for scalable quantum networks, their low fraction of optical emission into the zero-phonon line (ZPL) (~3%) restricts local entanglement generation rates to below 100 Hz (Ruf et al. 2021), with a few Hz being demonstrated (Humphreys et al. 2018). Group-IV color centers offer advantages in this regard and can achieve higher rates, especially when coupled to a cavity (Purcell enhancement).

At the same time, the storage of the qubit in nuclear spins allows for manipulation with high fidelities and achieving long coherence times. Storage of quantum states in the electronic spin for over 1 s has been established by decoupling the electronic spin from unwanted environmental fluctuations with the help of tailored microwave pulses (Abobeih et al. 2018). A recent paper even reports about 11 s of electron-spin coherence time under dynamic coupling (Yamamoto et al. 2026). Single-qubit gate operations with fidelities >99% and two-qubit gate operations with fidelities of ~98% have already been established between NV electron spins and ^{13}C nuclear spins, and spin–spin entanglement over distance has been achieved with fidelities of 92% (Hensen et al. 2015).

In addition, due to their permanent electric dipole moment, NV centers experience charge fluctuations, which lead to spectral shifts on short timescales, thereby limiting their performance. As a result, group-IV color centers, which exhibit first-order insensitivity to electric fields, have emerged as a promising alternative, enabling the demonstration of close-to-lifetime-limited optical transitions even in heavily fabricated nanophotonic structures. High-fidelity single-shot spin-state readout has already been demonstrated in such systems, with fidelities exceeding 99.9%.

Most color centers operate in the near-infrared spectrum and have been shown, using efficient techniques, to be convertible to telecom wavelengths while maintaining quantum correlations. Certain SiC-based systems can be operated at telecom wavelengths directly (Babin et al. 2022). Color centers are typically operated at cryogenic temperatures, often even in the millikelvin range. The effect of strain on the energy levels of group-IV-based color centers can enable higher operating temperatures. Diamond is a solid-state material, potentially enabling nanophotonic device fabrication at large scale. Such devices can also be integrated with photonic circuits, and efficient interfacing of color centers embedded in such systems has been demonstrated.

These properties make color centers promising candidates for future quantum networks. In recent demonstrations, entanglement distribution has been shown for electron spins (Hensen et al. 2015) and nuclear spins (Knaut et al. 2024) over fiber lengths of several kilometers. One example is the demonstration of Knaut et al. with nuclear-spin memories of SiV centers separated by 6 m in the lab and connected by a) fiber spools with a length of 40 km in a lab environment and b) deployed fiber with a length of 35 km in an urban environment (17 dB loss) (Knaut et al. 2024). Highlights are the demonstrations of Ronald Hanson's group demonstrating entanglement distribution in a metropolitan-scale quantum link and entanglement distribution demonstrations including three nodes in two labs separated by 30 m (Pompili et al. 2021; Hanson 2023; Stolk et al. 2024). These demonstrations are the most advanced in terms of connecting multiple nodes over distance from all platforms discussed herein. Furthermore, memory-enhanced quantum communication was demonstrated with a single SiV center integrated into a cavity (Bhaskar et al. 2020). Recently, in addition to NV and SiV centers, tin-vacancy (SnV) centers in diamond have emerged as promising candidates due to their bright optical transitions and ability to retain long spin coherence times at relatively high temperatures (above 1 K) (Parker et al. 2024; Codreanu et al. 2026; Resch et al. 2026).

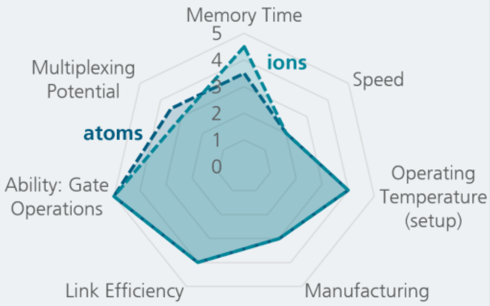
Trapped single atoms/ions [Rb, Cs; Ca^{+}, Ba^{+}, Sr^{+}, Yb^{+}]

PROs

- Low level of perturbations in system due to surrounding vacuum
- Strong optical readout transitions
- Long coherence times (esp. ions)
- Reproducibility: identical for given species/isotope
- High fidelity operations (single- and two-qubit-gates)

CONs

- Complex setups / challenging scalability
- Hybrid integration on chip is challenging
- Low entanglement generation rates
- Atoms get lost (max ~minutes); but efficient replacement possible



Distance (fiber length / spatial separation)	33 km/400 m atom–atom entanglement with QFC (Rb) >101 km atom–photon entanglement with QFC (Rb) 520 m/230 m ion–ion entanglement (Ca^{+})	[1] [2] [3]
Fidelity	97% Bell state fidelity for ion-ion entanglement (Ba^{+}) 93% average fidelity (Rb-based memory)	[4] [5]
Op. Wavelengths	Depends on transition. Cs D1/D2: 894/852 nm; Rb D1/D2: 795/780 nm Ca^{+}: 854 nm, Ba^{+}: 493 nm, Sr^{+}: 422 nm, Yb^{+}: 369 nm	
Generation Rate	250/s spin-spin entanglement	
Coherence Time	ms-s. >1 h observed for $^{171}Yb^{+}$	[6]
Efficiency (retrieval or storage-and-retrieval)	~25% (retrieval only)	
Op. Temperature	µK-scale achievable by laser cooling, but without a cryostat	

[1] van Leent et al., Nature 607, 69–73 (2022). ; [2] Zhou et al., PRX Quantum 5, 020307 (2024).; [3] Krutyanskiy et al., Phys. Rev. Lett. 130, 050803 (2023).; [4] Saha et al., Nat Commun 16, 2533 (2025); [5] Specht et al., Nature 473, 190–193 (2011); [6] Wang et al., Nat Commun 12, 233 (2021).

Absorbing | Emitting | Single-Entity | Ensemble | Cluster States

The technology profiles are not intended to "rank" different hardware platforms, but rather to describe their distinct characteristics. The KPIs cited in the profiles cannot simply be compared with those of other platforms or other KPIs of the same platform from different papers, because research papers often report numbers produced under different experimental conditions.

A quantum memory based on a **single atom (sA)** trapped inside an optical cavity was already reported in 2011, with an average fidelity of 93% and a qubit coherence time exceeding 180 µs (Specht et al. 2011). A repeater node with two memory atoms in an optical cavity was also demonstrated, achieving improved rate-versus-distance scaling and a fidelity sufficient for secure key communication for the BB84 protocol (Langenfeld et al. 2021). With optical-tweezer technology, multiple atoms, up to six in (Hartung et al. 2024), can be loaded and assemble an array in an optical cavity in a deterministic manner, indicating the potential for scalability toward multi-qubit operations.

Compared with trapped ions, neutral atoms can be relatively easily lost from their traps due to the comparatively shallow optical potential, posing a challenge for maintaining long-lived qubits. Optical-tweezer technologies also allow arrays to be refilled from a spatially separated reservoir, which helps mitigate atomic loss and maintain large-scale arrays (Pause et al. 2023).

Neutral atoms are also known for their capability to generate complex multi-photon entangled states. Based on this platform, experiments have demonstrated Greenberger–Horne–Zeilinger states of up to 14 photons and linear cluster states of up to 12 photons, with fidelities lower-bounded by 76% and 56%, respectively (Thomas et al. 2022). In addition, the generation of ring and tree graph states with up to eight qubits through the fusion from the photonic states emitted by individually addressable atoms has been reported (Thomas et al. 2024). Due to their ability to generate large clusters, neutral atoms are an attractive platform for one-way quantum repeaters.

Trapped **single ions (sI)** tend to show longer coherence times, which can exceed one hour (Wang et al. 2021), due to their deep trapping potential. With the long coherence times as well as their ability for deterministic gate operations, single trapped ions are expected to play an important role particularly at the end nodes of quantum networks.

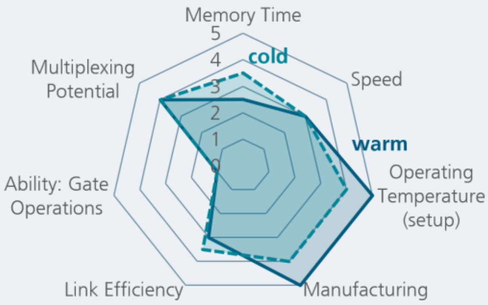
As a common drawback of these systems, the interaction between a single atom or ion and a photon is intrinsically weak, which can limit the efficiency of photon emission and absorption. To enhance light–matter coupling, experiments often employ optical cavities or other photonic interfaces; however, these introduce additional engineering complexity. Furthermore, the atomic species used for this platform usually emit in the ultraviolet or visible spectral range for their commonly used transitions, which require frequency conversion to interface with telecom-band optical fibers. To address this issue, the Quantum Frequency Conversion (QFC) techniques have been well established and employed for long-distance communication.

In recent years, several important milestones have been achieved. In 2022, a German research group reported heralded entanglement between two remote single Rb atoms over fiber links up to 33 km in length, with the atoms located in buildings 400 m apart, using QFC (van Leent et al. 2022). The same group also observed high-fidelity (>70%) entanglement between an Rb-based memory and emitted photons transmitted over a distance of 101 km of telecom fiber spools (Zhou et al. 2024). Regarding trapped-ion systems, entanglement of trapped-ion qubits separated in buildings 230 m apart and connected with around 520 m of optical fibers was reported in 2023, representing the longest reported distance for entanglement distribution in this system (Krutyanskiy et al. 2023b).

Atomic ensembles (cold atoms/vapor cells) [Rb, Cs]

PROs
- Operation at room temperature (warm atoms)
- Strong light matter coupling with high bandwidth
- Ease of fabrication (deterministic) and integration
- Multi-qubit capability

CONs
- Dephasing due to thermal motion (warm atoms)
- Order of 10–100 mm^3 per qubits - further miniaturization is challenging
- Implementation of gate operation not straight-forwardly possible



Distance (fiber length / spatial separation)	22 km fibers in field via two-photon interference and 50 km fibers in lab via single-photon interference (cold Rb) Not yet demonstrated over distance for two warm vapor cells	[1]
Fidelity	99.5% polarization fidelity after storage (cold Cs)	[2]
Op. Wavelengths	Depends on transition. Cs D1/D2: 894/852 nm, Rb D1/D2: 795/780 nm	
Generation Rate	Up to 1,200 pairs/s photon-memory entanglement with 80% fidelity (Rb)	[3]
Coherence Time	Typical µs–ms for memories; Record is light storage for 1s with Cs vapor at RT	[4]
Efficiency (retrieval or storage-and-retrieval)	Warm atoms: 20–40% storage-and-retrieval efficiency (typical) Cold atoms: 70–90% storage-and-retrieval efficiency (typical)	
Op. Temperature	Warm atoms: RT or above; Cold atoms: µK regime (laser-cooled without a cryostat)	

[1] Yu et al., Nature 578, 240–245 (2020); [2] Mamann et al., Sci. Adv.11,eadx3223(2025) [3] Wang et al., (2025). https://arxiv.org/abs/2503.11564; [4] Katz and Firstenberg, Nat Commun 9, 2074 (2018).;

Absorbing | Emitting (cold) | Single-Entity | Ensemble | Cluster States

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Although ensemble-based memories often exhibit shorter coherence times than single trapped atoms and are more limited in their ability to perform gate operations, they can offer important advantages for quantum networks. In particular, their ability to support multiplexing and their high optical depth, leading to high storage-and-retrieval efficiency, make them promising candidates for long-distance quantum communication and for serving as a quantum repeater backbone.

As the name suggests, **warm atomic ensembles (wAE)** can operate at or above room temperature, making the system more compact and simpler. **Cold atomic ensembles (cAE)** require laser cooling to bring the atoms to extremely low temperature, although they do not require an external cryostat, as the cooling is achieved optically. At the operating temperature of vapor cells, atomic kinetic motion is not strongly suppressed, which leads to dephasing of the spin wave and typically limits the coherence time compared to cold-atom systems, although there are some exceptions—for example, a storage time of 1s in room-temperature Cs vapor was already reported (Katz and Firstenberg 2018). On the other hand, Doppler broadening caused by atomic motion increases the bandwidth, which can be advantageous for broadband operation and frequency multiplexing. The broader bandwidth of warm atoms also improves their compatibility with broadband photon sources, such as spontaneous parametric down-conversion (SPDC) sources and quantum dots, enabling their use in hybrid quantum repeater architectures as absorptive memories.

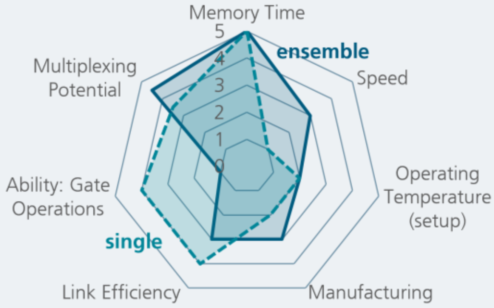
Owing to their relative ease of fabrication and integration, compact system size, and the possibility of room-temperature operation, warm atomic vapor memories have attracted attention from several start-up companies aiming to commercialize this technology. For example, the U.S.-based company Qunnect has demonstrated entanglement between a telecom photon and a warm-rubidium-vapor quantum memory with a fidelity of up to 90.2%, albeit at a low internal storage efficiency of below 10% (Wang et al. 2025b). In addition, the Berlin-based company Advanced Quantum Light Sources (AQLS) is working on integrating its SPDC-based photon sources with warm-atom (Rb) quantum memories (Jutisz et al. 2025). There is also a startup focusing on cold Rb atoms, Welinq based in France, commercially offering high memory efficiencies (over 90% on-demand storage-and-retrieval efficiency for single photons) as a key advantage of its approach (Welinq 2025).

In 2020, the entanglement of two atomic ensembles of cold Rb atoms in one laboratory was demonstrated using QFC, over 22 km of field-deployed fibers and 50 km of coiled fibers, via two-photon and single-photon interference, respectively (Yu et al. 2020). Furthermore, memory–memory entanglement between the nodes separated apart for 12.5 km in a metropolitan area was also achieved with cold atomic ensembles (Liu et al. 2024). On the other hand, such a large-scale demonstration of entanglement distribution with vapor cells has not been reported, to our best knowledge.

Rare-earth-doped crystals [Eu, Pr, Tm, Nd, Yb, Er]

PROs
- Long coherence time
- Telecom & visible wavelengths
- Crystal allows integration into chips: small crystals/films for optical interfacing
- Large number of spectral channels
- Different ion species can be coupled in one crystal

CONs
- Cryogenic temperature
- Weak interaction with light
- High quality cavities often required



Distance (fiber length / spatial separation)	50 km light-matter entanglement distribution (Pr:YSO)	[1]
Fidelity	99.8% storage-and-retrieval achieved in an AFC memory (Nd:YVO_4) For single emitter control, typically well-above 90% readout fidelity	[2] [3]
Op. Wavelengths	Broad range depending on element and transition. Eu: 580 nm, Pr: 606 nm, Tm: 794 nm, Nd: 883 nm, Yb: 980 nm, Er: 1530 nm	[4]
Generation Rate	230 Hz with cavity enhancement (Yb:YVO_4)	[5]
Coherence Time	~ ms–s for repeater systems record for preserving quantum coherence: 18 hours (Eu:YSO)	[6]
Efficiency (retrieval or storage-and-retrieval)	Typically low ~10% storage-and-retrieval (up to 70% demonstrated)	[7]
Op. Temperature	Cryogenic temperature (up to 8 K) ; mK-level for some set-ups	

[1] Rakonjac et al., Optica Quantum 1, 94-102 (2023).; [2] Zhou et al., Phys. Rev. Lett. 108, 190505 (2012).; [3] Ulanowski et al. (2026) https://doi.org/10.48550/arXiv.2603.01987 [4] Tittel et al., Quantum Sci. Technol. 10 033002 (2025).; [5] Ruskuc et al., Nature 639, 54–59 (2025).; [6] Wang et al., PRX Quantum 6, 010302 (2025).; [7] Merkel et al., Phys. Rev. X 10, 041025 (2020).

Absorbing | Emitting | Single-Entity | Ensemble | Cluster States

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Rare-earth-ion-doped crystals (RE) have emerged as promising solid-state platforms for quantum information processing due to the exceptionally long coherence times of their optical and spin transitions within the shielded 4f electronic levels. These transitions can be further split into Zeeman and hyperfine sublevels, which enable coherent control in the optical, microwave, and radio-frequency regimes.

RE systems combine narrow optical linewidths, large inhomogeneous broadening suitable for multiplexing, and long optical and spin coherence times. A prominent example is Eu:YSO, where spin coherence times approaching 18 hours have been demonstrated (Wang et al. 2025a), which is highly attractive for storing quantum information and realizing spin–photon or spin–spin entanglement. In parallel, research explores dipole–dipole interactions between individual nearby ions as a route toward multi-qubit quantum architectures (Kinos et al. 2021).

A key challenge for single rare-earth ions is their weak spontaneous emission arising from long excited-state lifetimes, typically in the millisecond range. To ensure strong light–matter interactions, either large ensembles or enhancement by optical microcavities are employed. By coupling ions to high-quality cavities, emission rates can be enhanced and photon collection can be improved, enabling efficient quantum interfaces. Efficient coupling of rare-earth ions to optical cavities has been experimentally demonstrated (e.g., single-ion coupling with Er^{3+} (Dibos et al. 2018; Ulanowski et al. 2022; Deshmukh et al. 2023), Purcell enhancement with Er^{3+} (Merkel et al. 2020)), although further improvements are anticipated to achieve cavity-integrated rare-earth quantum interfaces for scalable quantum technologies.

Ensemble-based systems are naturally suited for multiplexing, as collective excitations across large numbers of inhomogeneously distributed ions inherently enable spatial, temporal, and frequency multiplexing—significantly enhancing both the communication rate and scalability of quantum repeaters, while being easy to operate. In contrast, efficient multiplexing single-emitter systems typically requires a different approach, as each emitter has to be controlled individually. Spectral multiplexing of around 100 single emitters within a single cavity has already been demonstrated (Ulanowski et al. 2022). Single emitters provide much better prospects for quantum gate operations, as individual ions can be directly addressed and manipulated as qubits. While implementing parallel gate operations within an ensemble is extremely challenging due to the large dipole blockade radius, this same feature naturally allows for certain multi-ion gates directly.

The choice of rare-earth ion species involves trade-offs between different properties, including coherence, optical interaction strength, and wavelength. Non-Kramers ions (even number of electrons) such as Pr^{3+} and Eu^{3+} exhibit exceptional coherence times because of their reduced sensitivity to magnetic-field fluctuations, with reported spin coherence times of about one minute in Pr:YSO (Hain et al. 2025) and up to 18 hours in Eu:YSO. Kramers ions such as Yb^{3+} and Er^{3+} are more sensitive to magnetic noise, if Zeeman levels are used for qubit encoding—coherence times in the range of seconds have been demonstrated with hyperfine levels (Rančić et al. 2018) and further room for improvement is expected. For optical strength, Nd is leading in combination with a high branching ratio to the ground state, making it extra suitable for cavity enhancement. For wavelength, several are attractive for quantum networking, as Yb emits near 978 nm, Nd around 883 nm, and Er operates directly in the telecom C-band around 1536 nm, making different species naturally compatible with both free-space and fiber-based communication systems.

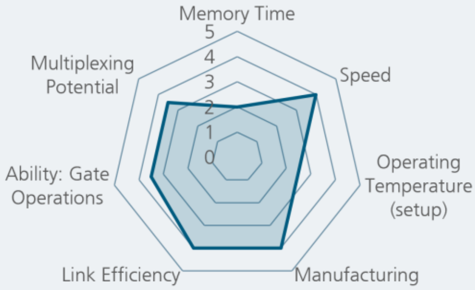
Recent research has explored hybrid multi-ion architectures that combine the advantages of different rare-earth species within the same host crystal. For example, a communication ion of Er^{3+} ions for telecom operation or Nd for rate, can interact with nearby Eu^{3+} ions that serve as long-lived qubits or quantum memories (Kimiaee Asadi et al. 2018). Coupling between the ions via electric dipole–dipole interactions enables entanglement transfer and quantum gate operations, offering a promising pathway toward scalable quantum-network and distributed quantum-computing platforms.

Another direction in rare-earth qubits is the development of molecular spin qubits, where rare-earth molecular complexes act as coherent spin interfaces while offering the flexibility of molecular engineering. Recent studies on europium-based molecular complexes have demonstrated excellent optical coherence and long nuclear spin lifetimes, enabling optical spin initialization and direct optical access to nuclear spin states (Vasilenko et al. 2026). An important advantage of these systems is that the ligand-field environment can be chemically engineered to tune the linewidth and oscillator strength of optical transitions. In addition, isotopically enriched ^{151}Eu and ^{153}Eu complexes can be synthesized, providing control over hyperfine splitting energies and improved coherence properties. Another promising solid-state platform is erbium-doped silicon (Er:Si), which combines the favorable coherence properties and telecom-band optical transitions of erbium with the scalability of silicon-based fabrication. Recent experiments have demonstrated optical initialization and readout of individual erbium spins together with lifetime-limited photon coherence, underscoring its potential for scalable quantum repeater implementations (Gritsch et al. 2025; Früh et al. 2026; Sandholzer et al. 2026; Rinner et al. 2026).

Semiconductor quantum dots

PROs
- Single photon emission (quantum source)
- NIR–C band emission
- Integratability with semiconductor platforms / scalability
- High repetition rate

CONs
- Comparatively low coherence time (but: room for improvement)
- Spectral diffusion and instability (esp. C-Band QDs)
- Limited reproducibility (manufacturing; level of individual QD: introducing spectral inhomogeneity)



Distance (fiber length / spatial separation)	36 km entanglement photon-pair distribution with high fidelity with QFC	[1]
Fidelity	82% teleportation fidelity with dissimilar QDs in hybrid network 72% teleportation fidelity with frequency conversion to telecom > 68% raw overall fidelity for write-store-retrieve-read-out protocol	[2] [3] [4]
Op. Wavelengths	Typically 780–825 nm 280–1550 nm possible, but limited optical properties at telecom wavelengths	[5] [6]
Generation Rate	GHz range achievable for photon generation	[7]
Coherence Time	Typically 1–100 μs (can be extended (20 ms) with nuclear spin ensembles)	[8] [4]
Efficiency (retrieval or storage-and-retrieval)	N/A (but good efficiency is demonstrated as photon sources)	
Op. Temperature	~ 4 K typically	

[1] Strobel et al., Optica Quantum 2.4, 274-281 (2024); [2] Laneve et al., Nat Commun 16, 10028 (2025); [3] Strobel et al., Nat Commun 16, 10027 (2025); [4] Appel et al., Nat. Phys. 21, 368–373 (2025); [5] Endo. et al. (2026): 10.24406/publica-7704; [6] Arakawa and Holmes, Appl. Phys. Rev. 7, 021309 (2020); [7] Müller et al., Phys. Rev. Research 2, 043292 (2020); [8] Zajac et al. (2025): arXiv:2503.13775v2

Absorbing | **Emitting** | **Single-Entity** | Ensemble | **Cluster States**

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Semiconductor quantum dots (QD) are known for their attractive optical properties as deterministic entangled-photon sources (EPSs). Numerous studies have demonstrated QD-based EPS with high repetition rates, high fidelity, and emission at telecommunication wavelengths, although simultaneously achieving all these KPIs remains technically challenging (Endo et al. 2026). Given their favorable optical properties, quantum dots are considered promising candidates for hybrid quantum repeater architectures, where they can function as EPSs in combination with absorptive quantum memories. Recent experiments have achieved an entanglement fidelity above 90% for photon pairs generated by a QD-based EPS, after one photon was converted to the telecom band via QFC, transmitted over a 35.8 km field-installed fiber link, and subsequently converted back to 780 nm (Strobel et al. 2024), illustrating their potential for interfacing with quantum memories in fiber networks.

Exploring efficient light–matter interfaces between photons from QDs and absorptive quantum memories is a crucial step. Ongoing work includes, for example, coupling to atomic vapor (Maaß et al. 2025), rare-earth-ion-doped crystals (Tang et al. 2015) and Group-IV vacancy color centers in diamond (Strocka et al. 2025) (as a theory-based modeling proposal). As another important effort toward quantum network, two papers have recently also demonstrated quantum teleportation using quantum dots as on-demand quantum emitters, achieving teleportation fidelities of up to 82% (Laneve et al. 2025) and 72% with QFC to the telecom band (Strobel et al. 2025).

Beyond their application as EPSs, quantum dots have also been shown to generate multi-qubit photonic graph states, which are essential resources for all-photonic quantum repeaters. Significant progress has recently been made in this direction. For example, GHz-rate generation of strings of indistinguishable photons entangled in cluster states has been demonstrated with InGaAs self-assembled quantum dots, achieving an entanglement decay length of approximately ten photons and photon indistinguishability on the order of 80% (Cogan et al. 2023).

On the other hand, the application of quantum dots as quantum memories is currently limited by their relatively short coherence times, typically in the range of 1–100 μs, which are shorter than those of several alternative material platforms (Zajac et al. 2025). Some studies suggest that the memory with millisecond-scale coherence times could be achievable by leveraging nuclear spins (Chekhovich et al. 2015; Dyte et al. 2025). Recently, Appel et al. demonstrated a nuclear spin ensemble surrounding GaAs QDs as functional quantum register and implemented a full write-store-retrieval-read-out protocol with >68% raw overall fidelity and a storage time of 130 μs. The study suggested that the coherence time could be extended to 20 ms or beyond with dynamical decoupling techniques (Appel et al. 2025).

While significant progress has been made in research on QD technologies, there are differing views on their industrial potential. On the one hand, commercially available QD quantum emitters (single photon sources) already exist, indicating their relative technological maturity, though they remain expensive (Endo et al. 2026). The integrability of QDs with semiconductor platforms is attractive for industrial adoption. On the other hand, achieving reproducibility at the individual QD level is challenging—unlike atomic systems—resulting in spectral inhomogeneity. Most QD systems require operation in a cryostat at 4 K, which could also be a disadvantage for industrialization.

4.2 Moving Forward

The further development of quantum repeaters requires dedicated and targeted research for overcoming the technological gap toward commercialization. In this section, we discuss the most relevant challenges for the future development of quantum repeaters in terms of criticality (how important is it to address this challenge?) and difficulty (how difficult is overcoming this challenge?), as well as potential strategies for addressing these challenges. The challenges and potential solutions presented are derived from expert interviews and workshop assessments, thus reflecting the experts' expectations and visions of repeater technologies, grounded in their own knowledge and experience. An overview of the results is provided in Table 1.

Quantum repeaters are an early-stage deep technology with research and development mostly located at universities and research institutions, which limits the speed of progress on the long remaining path from research toward commercialization. Experimental setups are often built by graduate students over **long research time scales**, which could be significantly sped up by collaborations with actors outside of academia, such as startups, which are more focused on developing toward commercial products. In the same way, aligning academic research with the needs of industry actors and startups is valuable for speeding up commercialization. This includes the challenge of achieving **robust long-time operation** of the anticipated repeater nodes and integration with existing **telecom infrastructure**. The latter requires an operation at or conversion to **telecom wavelengths**, which is provided by many hardware platforms directly, while others need to be paired with frequency conversion (Huang and Kumar 1992; Bock et al. 2018) or bichromatic photon pair sources (Lago-Rivera et al. 2021; Zhu et al. 2026). **Standards** are required along the whole system architecture to facilitate development, integration, and competition for the best technological solutions.

Table 1: Challenges for future development of Quantum Repeaters

Challenges	Potential Strategies (if applicable)	Criticality	Difficulty
Research time scales and development focus	➢ Collaboration between academia and non-academia	**High**	**Medium**
Achieving high overall efficiency and coherence time (simultaneously)	➢ Targeted R&D ➢ Improve fiber coupling ➢ Cryotemperatures ➢ Improve Cavities	**High**	**Medium** **(Low: cAE)**
Robustness / long-time operation	➢ academia → commercialization, physics → engineering	**High**	**Medium** **(Low: AE, QD)**
Scaling of systems (control of individual qubits)	Platform specific approaches ➢ e.g., sA: Tweezer platforms combined with cavity systems ➢ e.g., cAE: Mode multiplexing, multiple ensembles, waveguides	**High**	**Medium** **(Low: AE, RE)**
Quality / reproducibility of material & components	➢ Material science and enabling technologies	**High**	**Low** **(High: RE, CC)**
Lack of standards (wavelengths, bandwidth, components, ...)	➢ (International) standardization processes	**High**	**Low**
Telecom wavelengths / wavelength interfaces	➢ Choice of platform ➢ Frequency conversion ➢ Bichromatic photon pair source	**High**	**Low**
Nanofabrication and Resonators	➢ Improve cavities ➢ Engineering efforts ➢ Heterointegration	**Medium–High** **(High: sA/I)**	**High** **(Medium: RE)** **(Low: QD, AE)**
Integration with existing telecom infrastructure (incl. software)	➢ Design of interfaces ➢ Engineering, standardization, cross-cutting competencies	**Medium–High**	**Medium**
Increase entanglement generation / distribution rates	➢ Optimize functionality with fixed set of parameters (theory) ➢ Hybrid systems ➢ Multiplexing	**Medium–High**	**Medium** (network complexity)
Miniaturization and integration (system engineering)	➢ Integrated optics ➢ Engineering efforts ➢ Heterointegration	**Medium**	**Medium** **(Low: QD)**
Component cost (Laser, cryostats, magnets)	➢ Scaling / Learning curve	**Low–Medium** **(High: cAE)** **(Low: wAE)**	**Medium** **(High: RE)**
Cryogenic Architectures (→ miniaturization / integration)	➢ Improve cryo-technologies (compactness) ➢ Integration with other systems requiring cryo-temperatures ➢ Semiconductor detectors	**Low**	**Medium** **(Low: sA/I)**

Source: Expert Workshop / Fraunhofer ISI

The performance of quantum memories has to improve to offer simultaneously high overall **efficiency** and long **coherence times**. Similarly, the **rates** of entanglement generation and distribution, especially over distance, have to be further improved. Both can be addressed by targeted research and development toward improving fiber coupling, cavity performance, or by developing hybrid systems (combination of hardware platforms). Multiplexing is another key solution to achieve a competitive data rate. Theoretical research could be targeted toward optimizing performance at a given set of parameters. Operation at colder temperatures can improve performance. However, this requires **cryogenic architecture**, which increases system complexity and cost. As trapped single atoms and ions can be cooled via laser cooling, they do not require cryogenic setups (only good vacuum conditions). Other hardware platforms benefit from the fast development of cryogenic systems in recent years, offering compact systems capable of cryogenic (helium) reliquefication.

Nevertheless, **miniaturization and integration** of the subsystems of a quantum repeater remain challenging and call for engineering efforts and integrated optics. **Low-cost components**, such as lasers, magnets, and cryostats, are crucial for opening a path toward broad future commercialization, though their criticality differs among platforms. A continuously increasing demand is expected to have a positive effect on component prices by enabling scaling effects and learning curves.

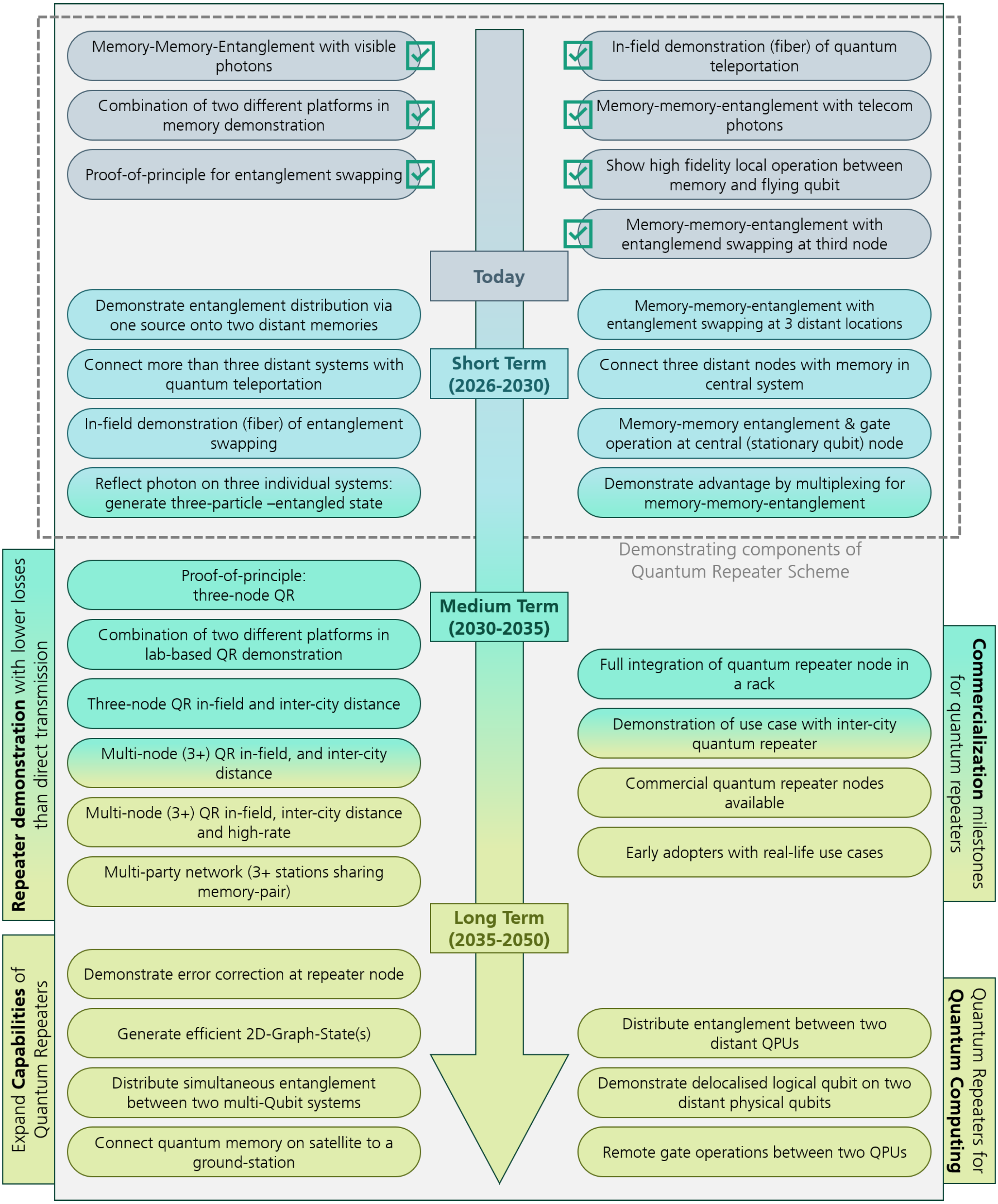
Efficient and high-quality **nanofabrication** of crucial components, such as resonators, has to be further developed to enable compact and high-performing subsystems. For many platforms (e.g., sA/sI), it is crucial to integrate cavities of highest quality. Heterointegration, the combination of different quantum systems within an integrated component, is considered a promising approach (Kim et al. 2020). The **quality and reproducibility** of relevant materials and components are essential for facilitating future research and development on quantum repeaters.

Beyond the challenges introduced here, many platform-specific challenges have to be addressed, such as the scaling of the systems in terms of **multi-qubit control.** This highlights the importance of platform-specific strategies for the future development of quantum repeaters. Finally, the **resources (time, funding)** poured into pushing the technological maturity of quantum repeaters will be crucial for the speed at which the challenges introduced in this section can be addressed.

4.3 Future Milestones

As established in the discussions above, the path toward a commercial quantum repeater is long. As technological developments usually emerge in a nonlinear way, characterized by disruptive leaps, periods of stagnation, and interdependencies with other (technological) developments, a reliable prediction of when the first commercial quantum repeaters will be available is not possible. Nevertheless, experts involved in the research on quantum repeaters can offer a valuable overview about the next likely steps toward this goal. The final part of the roadmap synthesizes the expert input into an iterative milestone plan of technology demonstrations for the next decades. Core is the ordered list of intermediate milestones toward capable quantum networks based on quantum repeaters (**Fehler! Verweisquelle konnte nicht gefunden werden.**). The timeline is based on an experts' assessments and is intentionally kept broad to reflect the large uncertainties in this regard. The intention of this section is to give an impression on how the future development could unfold. The discussion should not be taken either as a prediction of future development or as a recommendation for specific next steps. The milestones are kept platform-agnostic—each hardware platform anticipates individual development steps, which are omitted for the sake of simplicity.

Figure 13: **Roadmap for quantum repeater development**



Source: Expert workshop / Fraunhofer ISI

The first milestones given in Figure 13 (in grey box) have been already achieved by some of the technology platforms. The first step is to demonstrate **memory–memory entanglement with visible photons** and then move toward **telecom wavelengths** to achieve longer communication distances. While telecom wavelengths are essential for fiber-based applications, the demonstration of memory–memory entanglement with visible photons can be a valuable step for some platforms to demonstrate general capability or to focus on improving other parameters (e.g., rate). Experiments demonstrating long-distance memory–memory entanglement are summarized in Table 2 below. The table shows that many of the hardware platforms introduced in the previous section have already achieved the telecom milestone with quantum frequency conversion (QFC) techniques or SPDC as bichromatic photon pair source.

Table 2: Selection of demonstrations of memory–memory entanglement

Platform	Achieved distance between nodes	Wavelength	Reference
NV centers	Spin qubit nodes separated by 2 m	Visible photons	(Humphreys et al. 2018)
$Nd^{3+}:YVO_4$ and SPDC	A fiber length of 10 m	NIR photons	(Liu et al. 2021)
single ions $^{40}Ca^+$	230 m / a fiber length of 520 m	NIR photons	(Krutyanskiy et al. 2023b)
$^{151}Eu^{3+}$:YSO and SPDC	14.5 km / a fiber length of 17.8 km	Telecom from SPDC	(Zhu et al. 2026)
single atoms ^{87}Rb	400 m / a fiber length of 33 km	Telecom with QFC	(van Leent et al. 2022)
Rb cold atomic ensembles	Two memories in a lab / a fiber length of 22 km (field-deployed) and 50 km (coiled fibers)	Telecom with QFC	(Yu et al. 2020)
Rb cold atomic ensembles	12.5 km in a metropolitan area	Telecom with QFC	(Liu et al. 2024)
NV centers	10 km / a fiber length of 25 km	Telecom with QFC	(Stolk et al. 2024)
SiV centers	6 m / a fiber length of 40 km (spools of low-loss fiber) and 35 km (loop deployed in urban environment)	Telecom with QFC	(Knaut et al. 2024)
single ions $^{40}Ca^+$	A fiber length of 10 km (spooled fiber)	Telecom with QFC	(Liu et al. 2026)

Source: as indicated; Fraunhofer ISI

Quantum teleportation with telecom-wavelength photons has also been demonstrated. Combining two remote GaAs quantum dots emitting in the NIR and QFC, a post-selected teleportation fidelity up to 72% was achieved (Strobel et al. 2025). Another valuable development step includes moving from lab environments to **"in-field" demonstrations**: The in-field demonstration of quantum teleportation has been achieved with quantum dots between two buildings in a university campus in Rome over a hybrid network combining fiber connections and a 270 m free-space optical link (Laneve et al. 2025), with a $^{40}Ca^+$ single-ion memory and SPDC pair-source over a 14.4 km urban dark-fiber link in Saarbrücken (Kucera et al. 2024) and with warm atomic ensembles over Deutsche Telekom's 30-km metropolitan fiber testbed (Borowska et al. 2026), for example.

Proof-of-principle for deterministic **entanglement swapping** has been demonstrated with trapped ions (Riebe et al. 2008). Building on this capability, Krutyanskiy et al. demonstrated a quantum repeater node that independently established entanglement across two 25 km-long optical fibers, and then extended it over both fibers via a deterministic Bell-state measurement (Krutyanskiy et al. 2023a). Recently, all-photonic entanglement swapping between two independent quantum-dot emitters, each generating polarization-entangled photon pairs, was reported. The study supports the potential of quantum dots as entangled-photon sources for repeater networks, where they could be interfaced with suitable quantum memories (Beccaceci et al. 2025).

Ronald Hanson's group has demonstrated a three-node lab-based quantum network based on NV centers with local entanglement swapping in a central node (between electronic spin and nuclear spin) (Pompili et al. 2021). Demonstrating memory–memory entanglement of two distant memories with entanglement swapping at three distinct and distant locations would be a next step of improving these capabilities in the upcoming years. The demonstration of entanglement swapping in-field, i.e., with at least one quantum system deployed outside the laboratory environment, would showcase the robustness of the scheme as a foundational step toward future real-world implementations.

To combine the advantages of different technology platforms, such as long memory time with good matter-optical interfaces, **hybrid systems or heterointegration** is likely to play an increasing role in future developments. In the past, combining different platforms for memories and photon sources has been explored. For instance, storing the photons from quantum dots has been investigated, for example, by using atomic ensembles (Maaß et al. 2025), RE-doped crystals (Tang et al. 2015) and Group-IV vacancy color centers in diamond (Strocka et al. 2025) (as a theory-based modeling proposal). Some of the above-mentioned memory–memory entanglement experiments utilized hybrid systems consisting of RE-doped crystals as memories and SPDC as photon sources (Liu et al. 2021; Zhu et al. 2026). Connecting two different memory systems has also been demonstrated: the transfer of quantum state between cold atomic ensembles of ^{87}Rb and Pr^{3+}:YSO was achieved by means of a single photon at telecom wavelength using cascaded QFC (Maring et al. 2017). Recently, a hybrid architecture was presented that remotely connects processing nodes based on cavity-coupled trapped ions, with two repeater chains as the backbone using RE as quantum memories and SPDC as photon sources (Cussenot et al. 2025).

Finally, **high-fidelity local operation between memory and flying qubits** was also mentioned as a milestone achieved as of today. A two-qubit quantum gate between photons and atoms was demonstrated with a single trapped ^{87}Rb atom (Reiserer et al. 2014).

In general, the entanglement between a memory and a photon has been observed in many platforms, such as a trapped single ion (Blinov et al. 2004), atomic ensembles (Matsukevich et al. 2005), a trapped single atom (Volz et al. 2006), the electronic spin of a NV center (Togan et al. 2010), and a quantum dot spin (Gao et al. 2012).

With regard to the achieved fidelity of ion/atom–photon entanglement, >98% fidelity between a trapped $^{40}Ca^{+}$ ion and the polarization state of a telecom photon (Bock et al. 2018), a raw Bell-state fidelity of 93% with trapped Rb atom for atom–photon entanglement states (with inferred fidelity of 98% after correcting for atom readout errors) (Safari et al. 2026) have been reported. As for the two-qubit gate fidelity, >99.99% for trapped $^{40}Ca^{+}$ ions (Hughes et al. 2025); > 99.9% for electron–nuclear spin (with ^{14}N nuclear spin) gates (Bartling et al. 2025); 99.7(99.4)% for tweezer-trapped neutral ^{171}Yb atoms with (without) post selection (Muniz et al. 2025) were reported.

All previous memory–memory-entanglement demonstrations are based on emitting a flying qubit from a memory or with a source adjacent to one memory. **Entanglement distribution from one source onto two distant memories** should be technologically possible already and will likely be demonstrated soon. Connecting three nodes with a **memory in the central system** would be the complementary setup to be demonstrated in the upcoming years. Similarly, a connection of three systems via **quantum teleportation** is a valuable milestone, which should be achievable in the short term.

With the components and individual aspects of quantum repeaters demonstrated for various platforms, the path should be paved to enable **repeater demonstrations with lower losses than direct end-to-end transmission**. In the medium term, the proof-of-principle of a quantum repeater with the relevant functionalities is expected—it is not unlikely that this will be achieved by a hybrid setup combining the profiles of different hardware platforms. This will be the basis for in-field demonstrations over relevant distances (e.g., inter-city distance): first three-node demonstrations can be extended by multi-node (3+) networks, which are expected to be improved year after year with respect to the KPIs achieved (e.g., rate of entanglement distribution). Demonstrating the successful entanglement distribution to multiple (3+) stations, each sharing a memory-pair with each of the other stations, could be considered as a prototype quantum information network and is only expected in the long term.

These demonstrations should further enable substantial **commercialization** efforts, which are already underway and expected to continue in parallel. The first in-field demonstrations will be closely connected to the full integration of quantum repeater nodes into racks. The first inter-city use cases will be demonstrated still in research projects, however, likely kicking off the market for commercial quantum repeater nodes for real-life use cases, such as long-distance secure communication or distributed quantum computing. In addition, quantum repeater technology could create further opportunities for adoption by enabling entanglement-assisted communication over longer distances. Advances in quantum repeater technology could also support entanglement-assisted classical communication over extended distances, marking an important step toward more advanced quantum-enhanced network applications.

These milestones will be followed by **further improvement** of quantum repeater technologies. The 2^{nd} and 3^{rd} quantum repeater generations are expected to become more relevant in the long term, including the demonstration of error correction and repeater nodes and the efficient generation of 2D-graph states (see Figure 7). In the same way, scaling the complexity and the distance will become relevant, highlighted by one milestone for distributing simultaneous entanglement between two multi-qubit systems and another for connecting a quantum memory on a satellite to a ground station.

As **connecting quantum computers over distance** is one of the main drivers of quantum repeater development, milestones toward this mission have been included in the proposed roadmap. In a first step, the entanglement distribution between two quantum processing units (QPUs) is anticipated, followed by a demonstration of delocalized logical qubits on at least two distant physical qubits and the realization of remote gate operations between two QPUs. With these capabilities the path toward a potentially powerful quantum internet would be paved. Nevertheless, these developments are mostly expected to take place in the long term and call for coordinated research and development efforts across multiple approaches toward realizing quantum repeaters.

Finally, many milestones are not included in this discussion. Each approach anticipates **platform-specific demonstrations** in the upcoming years, with examples being the read-in/read-out of nuclear spins in quantum dots or entanglement of remote erbium dopants in silicon nanophotonic resonators in rare-earth-ion-doped crystals. Similarly, the continuous improvement of KPIs (see section 3.4) for each of the presented milestones will be highly relevant for future developments of quantum repeaters. For example, achieving a competitive entanglement generation rate will require further development using parallel channels and multiplexing. However, the indication of concrete values is not possible in a meaningful way at this stage.

5 Conclusion

Developing quantum repeaters for entanglement distribution remains one of the central technological challenges on the path toward a large-scale quantum internet. Until quantum repeaters are available, quantum key distribution implementations largely rely on direct optical links or trusted-node architectures.

Current global efforts in this field underscore that quantum repeaters are a major worldwide research focus with rapid progress (Schmaltz et al. 2026). Nevertheless, the pathway from today's laboratory prototypes to commercially relevant quantum repeater systems will be long and characterized by many intermediate milestones. It is to be expected that several generations of demonstrators will be deployed before any repeater-based architecture can consistently outperform direct entanglement distribution over fiber or free-space links. If society is to eventually exploit the full potential of distributing and storing entanglement over continental or even global distances, **sustained long-term funding and patient private investment will be indispensable**.

Across all platforms, **numerous key performance indicators (KPIs) still require substantial improvement**. These include memory coherence time, fidelity of stored and transmitted quantum states, entanglement generation and swapping rates, interface efficiencies between matter and photonic qubits, as well as scalability and robustness of the underlying hardware. Addressing these aspects demands continued and focused research and development efforts.

At the same time, the field is highly dynamic and has seen substantial progress in recent years. Several promising approaches are emerging, including atomic ensembles, trapped atoms and ions, rare-earth-ion-doped crystals, color centers, and quantum dots. However, comparing these approaches in a meaningful way is a challenge in itself. KPIs are often not consistently defined, or they depend strongly on the specific experimental setup and protocol. This study aims to contribute to a clearer understanding of the trade-offs between different platforms and architectures, but further work is required, including **standardized KPI definitions and harmonized measurement procedures**.

Currently, all major approaches under investigation have their justification and relevance. The choice of platforms that will be implemented in future repeater demonstrations is far from decided, and it is plausible that hybrid systems will ultimately play a central role. Given their diverse strengths and weaknesses, it may become apparent that different platforms will occupy different niches in future quantum information networks—for example as end-nodes versus backbone nodes, or for shorter- versus longer-distance links. This underlines **the importance of monitoring all platforms from a neutral, system-level perspective**.

Looking ahead, the field requires **a robust long-term vision and realistic roadmaps that are regularly revisited and updated**. The explorative roadmap proposed in this study necessarily carries large uncertainties and must be continuously aligned with technological advances and emerging prototypes. It complements existing overarching targets such as the EU's objective of realizing a quantum internet by around 2040, and analyses from initiatives such as the QR.N consortium in Germany (and the prior project QR.X) and the Quantum Internet Alliance (QIA) active across Europe.

Finally, to move from laboratory experiments to deployable infrastructure, it will be crucial to integrate industrial stakeholders, push demonstrations into real-world environments, create startups, and **align efforts across research, industry, and policy**. Funding schemes and regulatory frameworks should support **this coordination and efforts toward commercialization**, while still leaving room for a broad range of technological approaches, ensuring that the full design space for quantum repeaters and networks can be explored.

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