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Hyperentanglement-empowered intelligent quantum optics

Harshna VSL. Gounder^{1,2} and Alexander S. Solntsev^{1*}

Abstract: Hyperentanglement, a sophisticated form of quantum entanglement generated across multiple degrees of freedom (DOFs) such as polarisation, spatial modes, orbital angular momentum (OAM), spin angular momentum, time-bin and frequency, has the potential to significantly advance quantum technologies. This review explores the recent advances in hyperentanglement research in the last few years, focusing on its applications in quantum communication, sensing and computing. We focus on key aspects such as hyperentanglement generation and manipulation, while discussing the challenges and opportunities for scaling these technologies towards practical quantum devices. A major challenge is accurately manipulating the properties of optical nanodevices to allow for optimal hyperentanglement generation and we discuss the use of machine learning to enhance this process as an emerging approach. Furthermore, we examine the impact of using advanced nanotechnology for hyperentanglement generation to transform fields like medicine, defence technology and different physics applications.

Keywords: hyperentanglement; quantum sensing; quantum communication; quantum computing; high-dimensional entanglement; photonics; machine learning; metasurface optics; waveguide optics; nonlinear optics; deep learning

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1 Introduction

Hyperentanglement could transform quantum photonics, with applications in quantum information¹, quantum sensing², and quantum communication³. Unlike traditional entanglement, which typically involves generation in a single DOF⁴, hyperentangled states offer a richer resource with enhanced capabilities across various domains.

In quantum communication, hyperentanglement enables high-dimensional quantum key distribution (QKD) protocols^{5–7}. By encoding information across multiple DOFs, these protocols increase the dimensionality of the information space⁸, leading to higher key rates and enhanced security against eavesdropping attacks compared to conventional QKD schemes. Furthermore, hyperentanglement facilitates efficient superdense teleportation^{9,10}, enabling the simultaneous transfer of multiple qubits, thereby increasing the efficiency and capacity of quantum communication networks. In quantum sensing, hyperentanglement enhances the precision and sensitivity of quantum sensors¹¹.

Hyperentangled states can further improve the performance of quantum sensors, such as magnetometers¹² and gravimeters¹³, enabling more accurate measurements of physical quantities¹⁴.

Moreover, hyperentanglement enables multi-parameter sensing^{15,16}, allowing for simultaneous measurement of multiple physical parameters, providing a more comprehensive understanding of the environment. In quantum computing, hyperentanglement could play a role in enabling universal quantum computation and enhancing quantum parallelism^{17–19}. It can be used to implement universal quantum gates²⁰, forming the foundation for powerful quantum algorithms that can solve complex problems beyond the reach of classical computers. Furthermore, hyperentanglement can be leveraged to develop quantum error correction codes²¹, which are essential for mitigating errors and ensuring the reliability of quantum computation.

Beyond these core areas, hyperentanglement has the potential to impact other fields. In biology, it can be applied to enable advanced imaging techniques and facilitate the

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development of highly sensitive biosensors^{22–24}. In astrophysics, it could enhance imaging of distant objects such as exoplanets^{25,26}. And there is promise for applications in space communications^{27,28}, high-energy physics^{29,30} and defence^{31,32}.

Metasurfaces are structured surfaces that allow manipulation of several DOFs of light simultaneously³³, and therefore these systems are naturally applicable for hyperentanglement generation. The use of machine learning for designing metasurfaces and nanodevices³⁴ for the purpose of generating hyperentanglement is a new and promising area of research. While several studies have explored using machine learning for metasurfaces in quantum photonics to create single DOF entanglement or to control multiple DOFs separately^{35,36}, an emerging approach is to use machine learning for the design of hyperentanglement sources with the aim to enable advanced protocols and reduce decoherence³⁷. Recent research has shown that machine learning can enhance the design of both metamaterials^{38,39} and metasurfaces^{40,41}. By using machine learning for metasurface design, we may be able to overcome the challenge of design complexity⁴², leading to more accurate and efficient generation of hyperentanglement.

This review focuses on recent advances in hyperentanglement generation, manipulation and applications. We discuss the challenges and opportunities associated with harnessing the power of hyperentanglement for major applications including quantum communication, quantum sensing and quantum computing and explore how machine learning could offer the potential to overcome some of these challenges, as well as how using techniques for metamaterial design could show advances with applications across quantum technology.

2 Hyperentanglement generation

The underlying principle enabling the simultaneous generation of entanglement across multiple DOFs, lies in the simultaneous phase-matching conditions governed by the conservation laws inherent to the nonlinear process⁴³. For example, in spontaneous parametric down-conversion (SPDC), momentum conservation Eq. (1) represents the spatial and polarisation entanglement, while energy conservation dictates the frequency-time entanglement Eq. (2)¹. Hyperentanglement is generated when the pump field and the nonlinear medium are engineered such that the two-photon state is non-separable in more than one of these conserved quantities. A key challenge is maintaining indistinguishability across these multiple bases⁴⁴. This is crucial for high-fidelity interference and requires precise spatiotemporal and spectral overlap of the photon paths^{28,45}, typically achieved using carefully balanced interferometers⁴⁶ or, in the case of advanced integrated photonics⁴⁷, through inherent mode confinement that naturally enforces overlap across all DOFs. Hence, optimising experimental design is required

for successfully generating hyperentanglement, which is currently a challenge due to complicated multiple parameter tuning.

To explain the benefits of this complex state, it is important to distinguish between entanglement-empowered and hyperentanglement-empowered technologies. Entanglement-empowered technologies, typically based on a single DOF qubit (e.g. polarisation only), serve as the foundational resource for applications like standard QKD²⁸, metrology⁴⁸ or basic quantum computing gates²⁰. In contrast, hyperentanglement-empowered technologies offer two primary relative advantages including increased channel capacity and enhanced robustness/efficiency⁴⁹. Furthermore, the redundancy of having entanglement across several independent bases can be used for entanglement purification⁵⁰ and quantum error correction⁵¹, which significantly enhances quantum protocols over noisy channels.

2.1 Nonlinear optics generation methods

Photon entanglement in nonlinear optics is typically generated through SPDC^{52,53} or spontaneous four-wave mixing (SFWM)⁵⁴, where a single or pair of pump photons spontaneously decays into a pair of entangled photons as shown in Fig. 1. Another common method is optical parametric oscillator (OPO)⁴⁹ and these three methods are used for second order $\chi^{(2)}$ and third-order $\chi^{(3)}$ nonlinearities using devices with nonlinear crystals, waveguides and microresonators^{54,55}. Hyperentanglement generation of a quantum system could be achieved in various ways, for example using different spatial modes⁵⁶, time-frequency hyperentanglement in biphoton frequency combs⁵⁵ or two-level neutral atoms⁵⁷. To compare these three methods their processes and key advantages will be discussed.

SPDC is a very common method for hyperentanglement generation and typically uses nonlinear crystals such as beta-barium borate (BBO)⁵² or waveguides such as periodically poled lithium niobate (PPLN)⁵⁸. The setup needs to be engineered to combine the intrinsic energy-time conservation or frequency-bin entanglement with added DOFs. For example, entanglement in polarisation is enhanced using interferometers such as Sagnac⁴⁶ or dual-crystal setups and for OAM entanglement is introduced using spatial light modulators¹⁵. Although, this high level of external engineering contributes to the bulkiness and alignment sensitivity of the setup⁵⁹ whilst an advantage of using SPDC though is that it is highly versatile for discrete-variable photon pairs¹⁷.

The generation of hyperentanglement using SPDC is shown by Deng et al. who provide the type-I and type-II conditions for SPDC generation¹. This method allows for combining multiple DOFs and is a $\chi^{(2)}$ process where one pump photon decays into a signal and idler photon. The maximum probability of entanglement generation occurs when the conservation properties are satisfied where $\vec{k}$ represents the wave vector and ω is the wave frequency

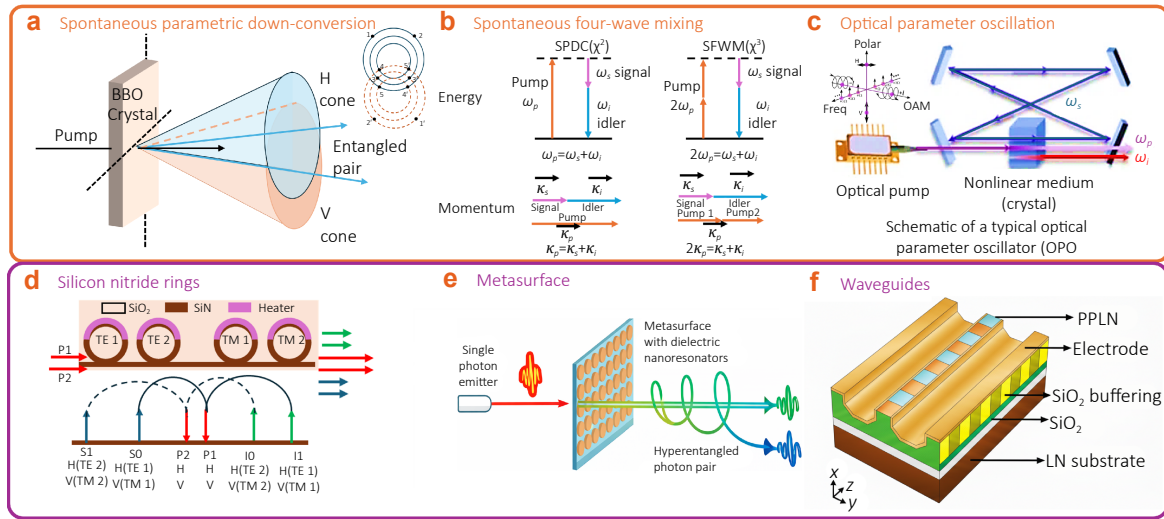


Fig. 1 | Comparison of different hyperentanglement generation methods and quantum nanodevices using advanced materials. Different hyperentanglement generation methods. (a) Diagram of non-collinear type-II SPDC process with two emission cones and two intersection directions giving different polarisations (centre), showing example of energy-momentum-polarisation hyperentanglement generation with two cones of light for type-II phase matching (top right); (b) Energy and momentum conservation diagrams of SPDC and SFWM processes. In SPDC one pump photon leads to the generation of two correlated photons (signal and idler), while in SFWM, two pump photons lead to the generation of two correlated photons; (c) Schematic and cavity modes of a typical OPO. The cavity modes are discrete, and the minimum mode spacing is $2\pi/\tau$, where τ is the cavity delay. The top left is a diagram showing that photon pairs produced via the nonlinear optical process can have simultaneous entanglement in three DOFs - polarisation, spatial mode, and frequency. Quantum nanophotonics design examples. (d) Schematic of the system of four rings used to obtain polarisation and frequency entangled photon pairs (top). Relative positions of the pump resonances and signal and idler frequency-bins (bottom), (e) Diagram of metasurface that is subwavelength thickness used to manipulate the laser beam and generate a hyperentangled photon pair. (f) The structure of the PPLNOI ridge waveguide is shown in Fig. 1(e) and the schematic energy diagram for the cascaded SHG and SPDC processes are shown in their paper⁵⁸. Figures adapted with permission from (a) both top right and centre ref.¹, Elsevier; (b) slightly modified ref.⁵⁹, Springer Nature; (c) top left ref.⁴⁹, Optica; centre ref.⁶⁰, Nature; (d) ref.⁴⁷, American Physical Society, (f) ref.⁵⁸, American Physical Society.

below¹.

$$\mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_i \quad (1)$$

$$\omega_p = \omega_s + \omega_i \quad (2)$$

For phase-matching, two primary types exist: type-I phase-matching, where the signal and idler share the same polarisation (both *o* or both *e*), while the pump has the orthogonal polarisation Eq. (3), and type-II phase-matching, where the signal and idler photons have orthogonal polarisations with one ordinary and one extraordinary such as in Eq. (4).

$$e_p \rightarrow o_s + o_i \quad (3)$$

$$e_p \rightarrow e_s + o_i \quad (4)$$

An example of hyperentanglement in the energy-momentum-polarisation state with type-II phase matching was pioneered by Kwiat et al.⁴³. In the configuration shown in top right of Fig. 1(a), conjugate points in the emission spectrum exhibit energy-time entanglement¹. Notably, photons emitted from specific regions within the emission cone display distinct entanglement properties. Importantly, in certain regions, photons are simultaneously entangled in polarisation (3 and 3'), momentum with definite polarisation (1-1'-2- 2'), energy-time, momentum and polarisation

simultaneously (4-4'-5-5'), vividly demonstrating the multi-dimensional nature of hyperentanglement across three DOFs⁴³. By carefully controlling experimental parameters, such as the wavelength of the pump laser⁶¹ and the crystal orientation¹⁵, researchers can generate a wide variety of hyperentangled states with diverse properties.

SFWM is a $\chi^{(3)}$ process where two pump photons are used to generate two new photons⁵⁹ as shown in Fig. 1(b) with phase-matching and energy-matching shown by Eqs. (5) and (6) respectively. This technique more commonly uses optical fibres or integrated microresonators such as silicon nitride (SiN) rings⁴⁷. It is used for generating hyperentanglement involving spectral properties such as integrated microresonators that generate photon pairs across discrete, correlated frequency channels (bins) and can be pumped with pulses for time-bin entanglement⁵⁴. It can also be combined with polarisation hyperentanglement through enhanced design⁶². An advantage of SFWM is that it is highly scalable due to on-chip integration and can be used for efficient dense frequency-bin encoding⁵⁹.

$$2\mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_i \quad (5)$$

$$2\omega_p = \omega_s + \omega_i \quad (6)$$

OPO uses the $\chi^{(2)}$ process of SPDC inside a resonant

optical cavity as shown in Fig. 1(c) which provides enhanced control and spectral purity⁶⁰. OPOs can be operated in the spontaneous regime, effectively acting as highly efficient cavity-enhanced SPDC sources⁶³. In this method a nonlinear crystal is placed inside a Fabry-Perot cavity or similar resonator⁴⁵. OPOs are used for generating continuous-variable entanglement which requires the amplitude and phase of light rather than single photons and can generate hyperentanglement in two DOFs such as polarisation and OAM⁴⁹. It can also generate narrow-band hyperentanglement by restricting the photon pair fields to cavity resonance modes for spectrally narrow pairs⁶⁰. Hence, an advantage is that OPOs have high efficiency and narrow spectral bandwidth. The papers discussed in this review have more focus on discrete-variable hyperentanglement, although some cases with continuous-variable hyperentanglement will also be discussed.

2.2 Miniaturisation for transition from bulk optics to nanodevices

There are several approaching methods for generating hyperentanglement from bulk devices to highly miniaturised and controlled quantum sources, such as integrated ring resonators⁴⁷ and metasurfaces^{33,41,64–66}. Metasurfaces as shown in Fig. 1(e), are an ultrathin, planar array of nanostructures (meta-atoms)⁴² made of a nonlinear material (e.g. lithium niobate)⁶³. The optical resonances (like bound states in the continuum (BIC)⁶³ or Mie resonances⁶⁵) in the meta-atoms enhance the vacuum field and boost the SPDC or SFWM rate significantly compared to an unpatterned thin film. Another high-performance integrated platform is nanophotonic waveguides^{58,67}. These are direct miniaturisations of SPDC, typically using thin-film PPLN, which confine the $\chi^{(2)}$ interaction to a sub-micrometre-sized waveguide, providing the highest on-chip brightness⁵⁸. Additionally, ring resonators use high-confinement materials like silicon or SiN micro-ring resonators⁴⁷.

Even though SPDC is effective, it still uses bulk crystals which have the potential to be miniaturised. Metasurfaces take this to the nanometre scale, operating as ultracompact, planar arrays that are typically subwavelength in thickness^{33,68}, and integrated ring resonators are at the micrometre scale⁶³. Integrated ring resonator and metasurface approaches can use either the $\chi^{(2)}$ or $\chi^{(3)}$ nonlinearity, often involving SFWM with cavity-enhanced (ring resonator) or resonance-enhanced (metasurface) processes. These rings make a resonant cavity that naturally satisfies the phase-matching condition by selecting only certain wavelengths (resonant modes)⁵⁸. The phase-matching conditions are also affected for each process - for SPDC it is required for precise control of angle or poling⁶⁵; for ring resonators phase matching is satisfied by resonant cavity modes⁶³; and for metasurfaces longitudinal phase matching is relaxed due to the subwavelength thickness⁶⁹.

Each method has advantages for hyperentanglement such as metasurfaces are the most compact and have direct control which enables Bell state generation and tuning of hyperentanglement via geometry⁶⁸, although nanophotonic waveguides offer the highest on-chip brightness and can facilitate direct, on-chip polarisation entanglement⁵⁸. The use of nanodevices has great potential for hyperentanglement generation with the use of machine learning to enhance its efficiency³⁴. Overall, each method is effective for different approaches, although moving to integrated miniaturised devices would provide great advances and using intelligent design could help make these technologies more scalable.

2.3 Quantum nanophotonics design examples

A few example methods are shown here to demonstrate the growing interest in developing nanodevices^{65,70} and using different materials³⁹ to enhance photonics methods for hyperentanglement generation. Vendromin et al. used four ring resonators for generating polarisation and frequency-bin hyperentangled photon pairs on photonic integrated circuits (PICs)⁴⁷. As shown in Fig. 1(d) they use SFWM where each ring is pumped with a continuous wave generating photon pairs with the same polarisation in two pairs of frequency-bins. The device consists of four SiN ring resonators, coupled to a SiN channel waveguide and encased in silicon dioxide (SiO₂) with two pump fields P1 and P2, centred on resonances at 1550 nm and 1549 nm respectively. Each pump field is equally split into both horizontal and vertical polarisation. The rings, with varying widths for transverse electric (TE) and transverse magnetic (TM) polarisation resonances, are designed to selectively couple with the respective polarised components of the P1 and P2 pump fields, and their radii are approximately 80 μm . In Fig. 1(d) (bottom) the relative positions of the pump resonances and signal and idler frequency-bins are shown. Their results show a common generation rate for each ring of around 2.9×10^4 Hz with a total generation rate for the output state from the four rings of 1.16×10^5 Hz and a purity above 99% of the generated state.

Ma et al. also showed recent research with successful results in using nonlinear symmetry breaking for generating tunable biphoton hyperentanglement using semiconductor metasurfaces⁷⁰. They used an indium gallium phosphide (InGaP) metasurface due to its large nonlinear coefficient, a wide band gap and transparency at red wavelengths with picosecond control to generate polarisation and spatial hyperentanglement. The use of a single-sided SiO₂ substrate introduces asymmetric conditions during photon generation, allowing the resulting hyperentangled photon pairs to have tunable asymmetric states. This capability provides a distinct advantage over conventional unstructured nonlinear crystals, which are typically restricted to producing fixed symmetric entanglement. Their results show an ultrahigh coincidence ratio of approximately 7×10^4 which outper-

forms existing semiconductor flat optics by two orders of magnitude using asymmetric nonlinear response with quantum metasurfaces which can be used for on-demand quantum states.

Huang et al. generated hyperentanglement in polarisation and time-energy DOFs using a cascaded second-harmonic generation (SHG) PPLN waveguide in a fibre Sagnac loop⁵⁸. They manipulated the polarisation state using a PPLN-on-insulator (PPLNOI) chip through the transverse electro-optic effect which has advantages of integration, low drive voltage and fast-speed response. The structure of the PPLNOI ridge waveguide is shown in Fig. 1(f) and the schematic energy diagram for the cascaded SHG and SPDC processes are shown in their paper⁵⁸. They achieved two-photon interference visibility higher than 99% for polarisation entanglement and 98.5% for time-energy entanglement.

The current techniques are showing recent advances as the next generation of quantum photonics using advanced nanodevices including metasurfaces, ring resonators and waveguides for hyperentanglement generation, which is a rapidly growing field with large potential. Although, the use of intelligent metasurface design for hyperentanglement should be considered for future work.

2.4 Intelligent quantum optical design

The requirement for sophisticated, automated solutions defines the concept of intelligent quantum optics. In this review, intelligent quantum optics refers to how machine learning techniques, such as deep learning and reinforcement learning, are used for two primary purposes: i) autonomous design and optimisation of hyperentangled quantum sources (addressing the nanodevice complexity) and ii) real-time adaptive control of multi-DOF quantum states and protocols (addressing the measurement and manipulation complexity).

Despite the advancements in miniaturisation, several limitations affect the scalability of current hyperentanglement technologies. A primary challenge in nanophotonic platforms is fabrication-induced noise³⁵; even sub-nanometre deviations in waveguide width or meta-atom geometry can severely degrade the performance of nanodevices. Furthermore, existing designs often suffer from low spectral overlap and modal dispersion, which limits the indistinguishability of photons when transmitted over long distances⁸. In bulk systems, the limitation is the alignment sensitivity of cascaded crystals and interferometers, which prevents the stable generation of more than three DOFs⁶⁸. Transitioning to intelligent frameworks is therefore necessary aiming to overcome inherent physical and structural constraints³⁴.

The practical future integration of machine learning with hyperentanglement occurs through two distinct pathways. The first option could be using inverse design with neural networks or genetic algorithms to map desired hyperentangled states back to specific nanodevice geometries^{36,41}.

Instead of manual trial-and-error, the machine learning model explores a non-intuitive parameter space to find the exact meta-atom dimensions that satisfy multiple conservation laws simultaneously. The second option could be adaptive control, deep reinforcement learning (DRL) models^{48,71–73}. These models receive real-time feedback from single-photon detectors and dynamically adjust external parameters such as the temperature of a PPLN waveguide or the phase shift in an interferometer to maintain high state fidelity. This closed-loop integration allows the system to learn how to remove environmental decoherence and fabrication errors without requiring a complete physical model of the noise.

This review explores the recent advances in hyperentanglement research, focusing on its generation, manipulation, and applications in quantum communication, sensing, and computing. We show some examples of using different generation methods and discuss the major shift from bulk crystals to integrated platforms like waveguides and metasurfaces. We examine the intelligent challenge inherent in these advanced systems: the complexity of designing nanoscale devices to satisfy multi-DOF phase matching conditions and the difficulty of controlling these states in noisy environments and for long-distance communication. This review has a key section to analysing how the practical integration of machine learning, provides a powerful solution to these challenges, enabling enhanced fidelity, robustness, and scalability. This enables the impact of hyperentanglement-empowered intelligent systems on several important applications.

3 Hyperentanglement applications

In this section, we review approaches and applications of hyperentanglement generation across quantum communication, sensing and computing, with several optimisation techniques to increase entanglement fidelity and reduce noise. Some examples of different combinations of DOFs using hyperentanglement include polarisation (horizontal or vertical) and its spatial mode (which path it takes)²⁰, polarisation and energy-time⁴⁸, polarisation and OAM⁷⁴, polarisation and frequency⁷⁵, high-dimensional time-bin¹⁹ and spin angular momentum (SAM) and OAM³ encoding.

3.1 Quantum key distribution

A prominent application of hyperentanglement is quantum communication to enable secure long-distance information transfer. Nemirovsky-Levy et al. leverage hyperentanglement using SAM and OAM and a multiplexing/demultiplexing protocol to propose a quantum repeater for secure, high-rate quantum communication³. The protocol first multiplexes the SAM and OAM from input photons P1 and P2 onto a single carrier photon C using Bell basis measurements as shown in Fig. 2(a). After transmission, a demultiplexing

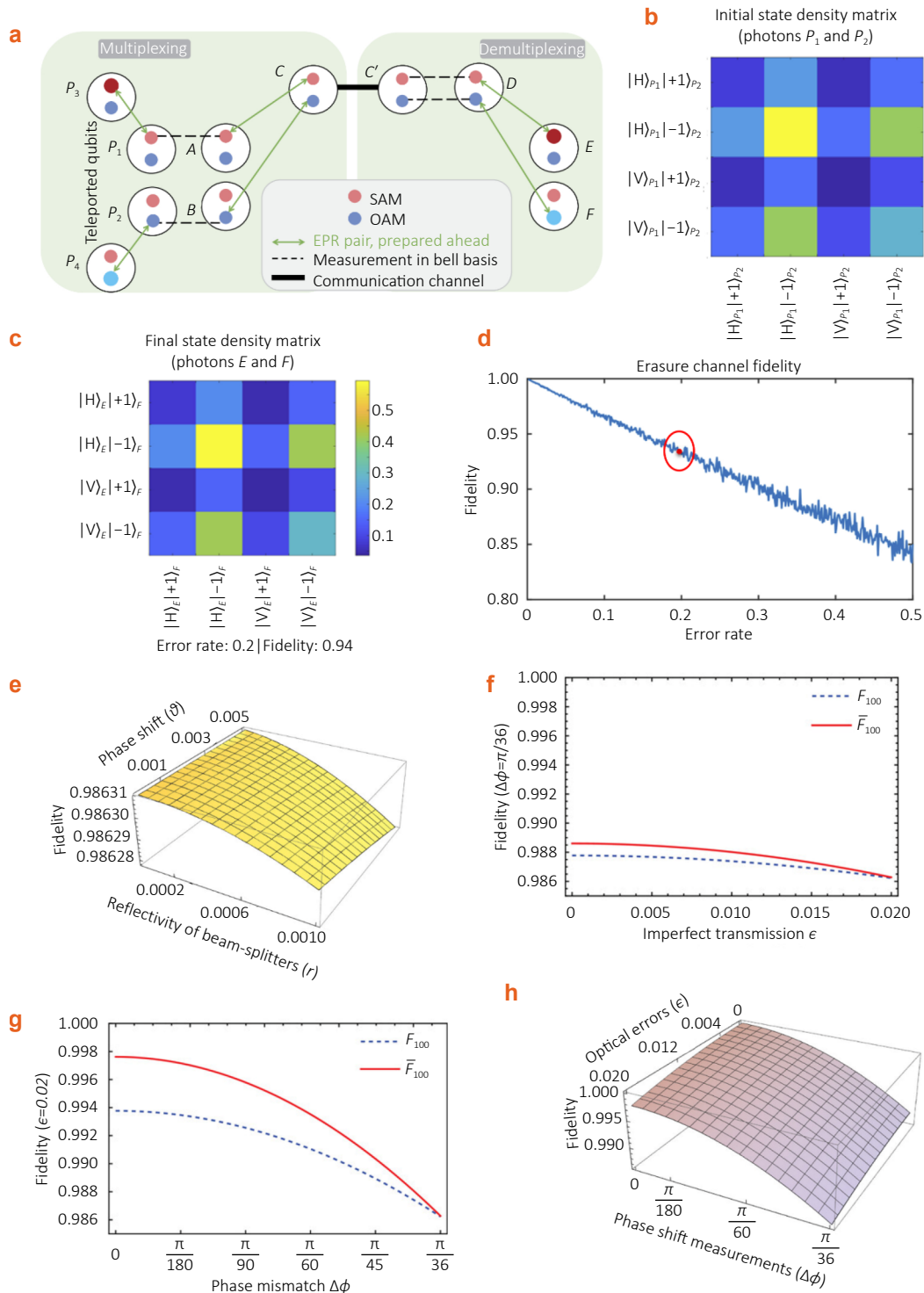


Fig. 2 | Quantum key distribution. Demonstration of hyperentanglement with SAM and OAM DOFs using multiplexing technique with the results (a–d) showing (a) structural design of demultiplexing technique with P_n for photon number of $n = 1, \dots, 4$ and states A–F with C' being the demultiplexed state, (b) density matrices of hyperentangled photon pairs for initial state before multiplexing, (c) final state after demultiplexing and (d) fidelity consistent with plotted against error (0.2 error rate indicated by the red circle) where each point is the average fidelity of 70 randomised states. High-dimensional quantum gates (e–h) showing the average fidelity F of the CSWAP gate $U^{2^{n-2}}_{\text{CSWAP}}$ with (e) $r \in [0, 1 \times 10^{-3}]$ and $\theta \in [0, 5 \times 10^{-3}]$ under realistic conditions $\Delta\phi = \pi/36$ and $\epsilon = 0.02$, (f) for the input state $|100\rangle$ as a function of the imperfect transmission ϵ with $\Delta\phi = \pi/36$, (g) for the input state $|100\rangle$ as a function of the phase mismatch $\Delta\phi$ with $\epsilon = 0.02$ and (h) $\epsilon \in [0, 0.02]$ and $\Delta\phi \in [0, \pi/36]$ under realistic conditions $r = 1 \times 10^{-3}$ and $\theta = 5 \times 10^{-3}$ rad. Figures reproduced with permission from: (a–d) ref. 3, Optica; (e–h) ref. 20, Wiley.

stage separates the DOFs onto two new hyperentangled output photons E and F . This entire process effectively generates two entangled qubit pairs by sending only one photon, thereby increasing the information capacity for protocols like QKD. The density matrices illustrate the transfer success where Fig. 2(b) shows the initial state with photons $P1$ and $P2$, and Fig. 2(c) shows the final state with photons E and F for a photon loss error rate of 0.2. Both matrices show the highest probability in the same hyperentangled state, which is horizontal polarisation and OAM of -1 , confirming the hyperentangled state is reliably preserved. Furthermore, the channel fidelity graph shown in Fig. 2(d) confirms the high reliability of the protocol, showing a strong fidelity (approaching one) which increases as the error rate decreases.

Gao et al. used high-dimensional quantum gates which they state has remarkable advantages over their 2D counterparts for information processing tasks²⁰. They use hybrid encoding for the control qubits and target qudits encoded in polarisation and spatial DOFs respectively, with the circuit constructed using only $2 + 3d$ linear optics where they achieved results for $d \geq 2$. Their results give high average fidelity of 0.994 for the CSWAP (controlled-SWAP) gate $U^{2 \otimes 2 \otimes 2}_{\text{CSWAP}}$ for different realistic conditions. They show maps of the gate's performance as a function of key experimental control parameters, emphasising the importance of precise calibration and stability for achieving high-fidelity quantum computation. In Fig. 2(e) the fidelity of the CSWAP gate is shown as a function of the reflectivity of beam-splitters (r) protocol and phase shift (θ), Fig. 2(f) imperfect transmission due to optical errors (ϵ), Fig. 2(g) phase mismatch due to errors in phase shift measurements ($\Delta\phi$) and Fig. 2(h) $\Delta\phi$ with ϵ . The results show that phase mismatch has a bigger effect on high-dimensional entanglement than imperfect transmission, although using both together in Fig. 2(h) gives more accurate results and Fig. 2(e) shows a similar rate using both reflectivity of beam-splitters and phase shift together for higher fidelity.

In QKD, issues can occur because of decoherence of entanglement due to noise in quantum channels and interactions with the environment which lead to reduced efficiency^{3,76}. Entanglement distillation is a widely used technique to overcome these issues and the research work by Xu et al. adopted hyperentanglement based entanglement distillation⁷⁵. Their protocol is shown in Fig. 3(a) where they used frequency encoded qubits which avoid the bit-flip errors when the channel is linear. They use two entangled subspaces encoded in polarisation (control qubit) and frequency (target qubit) DOFs of a single photon pair. The distillation of the polarisation entanglement depends on postselection based on the measurement results of the frequency DOF. Their process involves five steps starting off similarly to the paper by Graham et al.¹⁰ where Alice and Bob obtain their entangled photons from a primary source in the hyperentangled state given by Eq. (7). The final step

includes Alice and Bob's postselection based on the frequency qubit after performing the CNOT (controlled-NOT) operation. After the CNOT operation, it becomes a new mixed state and the frequency state will be flipped ($|\psi^\pm\rangle \rightarrow |\varnothing^\pm\rangle$) when paired with the $|\psi^\pm\rangle_{ab}$ states in polarisation Bell state. When the photon pairs are in the frequency Bell state $|\psi^\pm\rangle_{ab}$ they will be discarded in postselection and if they are in the $|\varnothing^\pm\rangle_{ab}$ frequency state they will be kept.

$$|\varnothing\rangle = |\psi^+\rangle_{ab} \otimes |\psi^+\rangle_{ab} \quad (7)$$

Using this frequency state achieved a 50% improvement in distillation rate for the initially mixed state and significantly improved the fidelity of the polarisation state before distillation.

Huang et al. successfully demonstrated a three-user quantum network by leveraging hyperentanglement in polarisation and time-energy DOFs, which were multiplexed into three single-mode fibres⁷⁴. Using three interferometric quantum gates, they were able to transfer entanglement from time-energy to OAM DOFs across the fully connected network. As shown in Fig. 3(b), the results showed two-photon interference fringes measured using the idler photons in two non-orthogonal phase bases (at 0 and $3\pi/2$ with varying phases). The high average visibility of $96.6\% \pm 0.4\%$ achieved across the three entangled links strongly verifies the presence and quality of the time-energy entanglement. The density matrix reconstructed for the final OAM entangled states as shown in Fig. 3(c) also gave a high fidelity of $96.6\% \pm 0.6\%$ relative to the ideal Bell state across all channel pairs. The high real probability amplitudes on the diagonal of this matrix confirm the successful generation of the desired OAM entangled states, and the presence of imaginary amplitudes indicates the expected coherence, collectively validating the construction of a high-quality, three-user quantum network.

Sohr et al. successfully used hyperentanglement in polarisation and energy-time DOFs to implement quantum privacy amplification (QPA), significantly increasing the secure key rate in QKD⁷⁷. As shown in Fig. 3 of their paper (top row) maps the secure key rate against the quantum bit error rate (qber) for each DOF, showing that the area for secure operation is substantially larger with QPA than without it. The QPA scheme drastically expands the QKD system's tolerance for noise. While the initial secure qber threshold (black lines) was around 11% in the polarisation DOF, the QPA technique enables secure key generation (positive gain) even when the qber reaches up to 40% in either DOF. The larger heatmap shows that the positive QPA gain begins at low noise levels - down to 9.1% qber in the polarisation DOF and 7.2% qber in the energy-time DOF individually. With QPA a maximum gain of 0.105 is achieved highlighting that QPA can generate a secure key in channels too noisy for the original protocol (region I) and greatly improve the key rate in moderate noisy regions (II, III, and IV). This demonstrates that QPA with

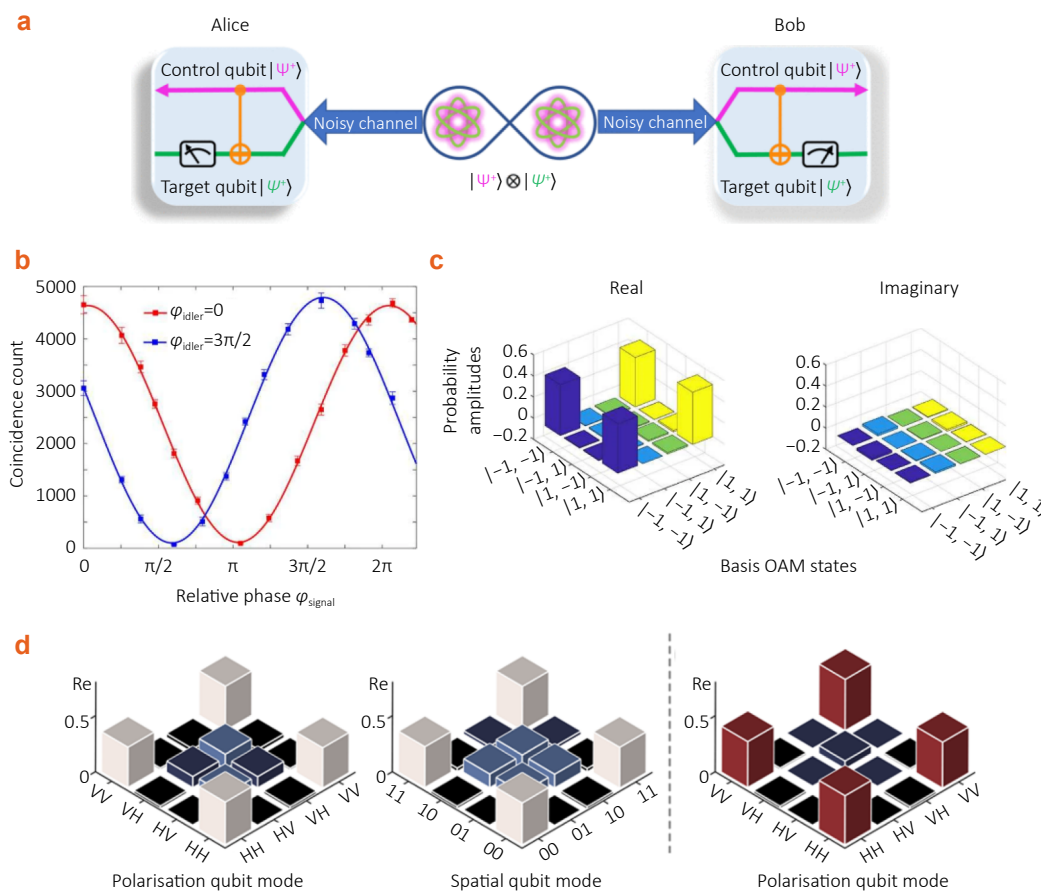


Fig. 3 | Examples for quantum information processing. (a) Entanglement distillation. Conceptual illustration of entanglement distillation protocol using polarisation-frequency hyperentanglement. (b) Multiuser quantum network. Experimental results for time-energy and OAM entanglement. Two-photon interference fringes for time-energy entanglement for different phase values of the idler photons in red and blue. Each data point is the average coincidence count per second of hyperentangled photon detections and (c) The real and imaginary parts of the reconstructed density matrix for the basis OAM entangled states (the qubit basis states entangled in spin-up (-1) or spin-down (+1) OAM states) plotted against probability amplitudes are shown. (d) Chip-to-chip teleportation networks. Quantum state tomography results before and after purification. Density matrices of the polarisation qubit and spatial-mode qubit before purification with a 20% bit-flip error rate (left). Density matrices of the polarisation qubit after purification under a 20% bit-flip error rate (right). Figures reproduced with permission from (a) ref.⁷⁵, Institute of Electrical and Electronics Engineers; (b) and (c) ref.⁷⁴, Springer Nature; (d) ref.⁶², Ding and Rottwitt.

hyperentanglement is a powerful tool for generating secure keys in high-noise environments.

Xie et al. introduced a protocol for generating parallel quantum entanglement among multiple pairs of quantum memories (QMs) housed in spatially separated nodes¹⁹. These QMs function as stationary qubits for creating nonlocal entanglement. Each QM pair is generated via distribution of optical entanglement, as detailed in Fig. 2 of their paper. The process involves coupling the QMs to optical cavities that deterministically interact with single photons, utilising a series of components: a Pockel cell *PC* to flip polarisation, optical switches *OS*₁ and *OS*₂ to direct and merge time-bin (an optical switch that directs photons in the time-bin states $|0\rangle$ and $|1\rangle$) and spatial modes, and various polarisation components (including the polarisation beam splitters *PBS* and *PBS*⁺). The core entanglement distribution step relies on the photon state exchange (PSE) circuit shown

at the bottom of the figure. The key result is the protocol's robustness over distance. For hyperentanglement involving three QMs, the protocol can tolerate a significantly lower overall efficiency threshold, demonstrating its ability to establish entanglement even with high channel loss. Specifically, it maintains secure operation with the threshold efficiency of optical switches of 0.739 for 25 km and 0.557 for 50 km. This tolerance for low efficiency is crucial for scaling quantum networks, and their efficiencies for two or three QMs in the same node surpass those of previous schemes.

3.2 Chip-to-chip teleportation networks for quantum teleportation

For enhanced network scalability, leveraging high-dimensional quantum states could allow for enhanced quantum teleportation rates and using on-chip devices could further

improve this^{59,61,62,78}. Quantum teleportation of path-encoded qutrits has been shown by Luo et al. using a hybrid polarisation-path approach for Bell-state measurements using free-space setups⁷⁹. The paper by Yu et al. demonstrated that chip-to-chip hyperentanglement distribution improved using entanglement purification based on integrated silicon chips⁶². Their results are shown in Fig. 3(d) where a 20% bit-flip error rate is applied for the polarisation-spatial hyperentangled state. The fidelity of the polarisation qubit (far left) is 0.737 ± 0.003 for the Bell-state $|\Phi^+\rangle = 1/\sqrt{2}(|HH\rangle + |VV\rangle)$ and the fidelity of the spatial qubit (middle left) is 0.738 ± 0.003 for the $|\phi^+\rangle = 1/\sqrt{2}(|00\rangle + |11\rangle)$ Bell-state. These results were reasonable but further improved using entanglement purification with results for the polarisation qubit (right) showing an increase in fidelity to 0.848 ± 0.005 which is an 11% increase and also shows an improved Bell-state density matrix with more defined states.

Similar results are shown in the paper by Zhang et al. where they performed high-dimensional subspace teleportation with a quantum on-chip autoencoder and achieved fidelity rates above 0.894 and they also showed similar results with qutrit autoencoders⁸⁰. Their work lays the groundwork for machine learning techniques in quantum systems to enhance noise robustness and increase coherence using subspace encodings. Thomas et al. showed similar work by performing distribution of four-dimensional path-encoded entangled quantum states between photonic chips using a multimode phase stabilisation algorithm⁴⁴. They performed complete quantum state tomography across two chips with the minimum number of local projective measurements to achieve high fidelity of the distributed entangled state of 0.86 compared to 0.81 without phase stabilisation. All of these results show that using on-chip devices for high-dimensional entanglement can increase the distribution rate of quantum information where information is encoded in more than two modes per photon and improves error correction more than from using traditional binary qubits⁴⁴.

3.3 Quantum secure direct communication

Quantum secure direct communication (QSDC) is a method which can directly transmit secret messages through a quantum channel without the need for a pre-shared cryptographic key⁸¹. Hyperentanglement can enhance QSDC by utilising quantum states entangled in multiple DOFs and increases the communication capacity with a higher overall success probability. By allowing more DOFs to be used for secure communication, hyperentanglement creates multiple parallel secure channels within the same quantum state which can make QSDC faster, more effective and secure. Furthermore, concepts like hyper-encoding, where information is independently encoded across multiple DOFs (e.g.,

polarisation and spatial mode)^{1,82}, can also be applied to enhance the security and capacity of other quantum communication protocols, such as device-independent quantum secure direct communication (DI-QSDC). DI-QSDC^{82,83} enhances the security of traditional QSDC⁸¹ by ensuring that communication relies solely on the observation of Bell inequality violations, independent of the specific internal workings or characteristics of the devices used by the communicating parties. This eliminates the need to trust the devices themselves, making the communication more robust and secure against potential attacks that could exploit device vulnerabilities.

Zeng et al. significantly increased the secret message capacity of DI-QSDC by employing a polarisation-spatial-mode hyper-encoding technique, as shown in Fig. 4(a)⁸². The advantage of this DI-QSDC protocol is its resistance to device-based attacks, which is achieved by verifying security through the violation of Bell's inequality. To maximise data rate, the message sender (Alice) prepares hyperentangled photon pairs and encodes messages independently in both polarisation and spatial-mode DOFs. In the spatial DOF, Alice uses a beam displacer (BD) to perform a Pauli-X operation and combines it with a phase operation δ_z to achieve the Pauli-Y operator. For the polarisation DOF, the Pauli-X and Pauli-Z operations are executed using a combination of half-wave plates (HWP) and quarter-wave plates (QWP). By applying four specific unitary operations to the hyper-encoded states, a single hyperentangled pair can encode four classical values of information (00, 01, 10, 11) at once. To protect against interception, Alice applies a random permutation to the photon sequence (S) before sending it to Bob. The protocol demonstrated a maximal secure communication distance of approximately 2.511 km with high fidelity values of above 0.925 as the threshold for correct secure messages being transmitted, successfully eliminating message leakage in both DOFs. This establishes an effective and highly secure method for high-capacity quantum communication. Although, with increasing transmission distance the fidelity increases but information capacity decreases. They tested four fidelity conditions with $F = 1, 0.99, 0.98$ and 0.97 with transmission distance of 2.511 km, 2.196 km, 1.975 km and 1.6050 km and even though secret message capacity is decreasing, there is still reasonably higher secret message capacity when using the hyper-encoding DI-QSDC technique as shown in Fig. 4(b).

The paper by Xiao et al. uses an alternative approach for QSDC using single-photon measurements (SPMs) on hyperentangled states⁸¹. Their method uses polarisation and spatial mode DOFs to encode information in parallel. This hyperentanglement technique significantly boosts the protocol's efficiency, allowing for the transmission of two bits of information per photon pair, effectively doubling the message capacity compared to traditional QSDC protocols. The principle of the SPM in the receiver's (Bob's) location, which uses the spatial-mode and polarisation DOFs, is

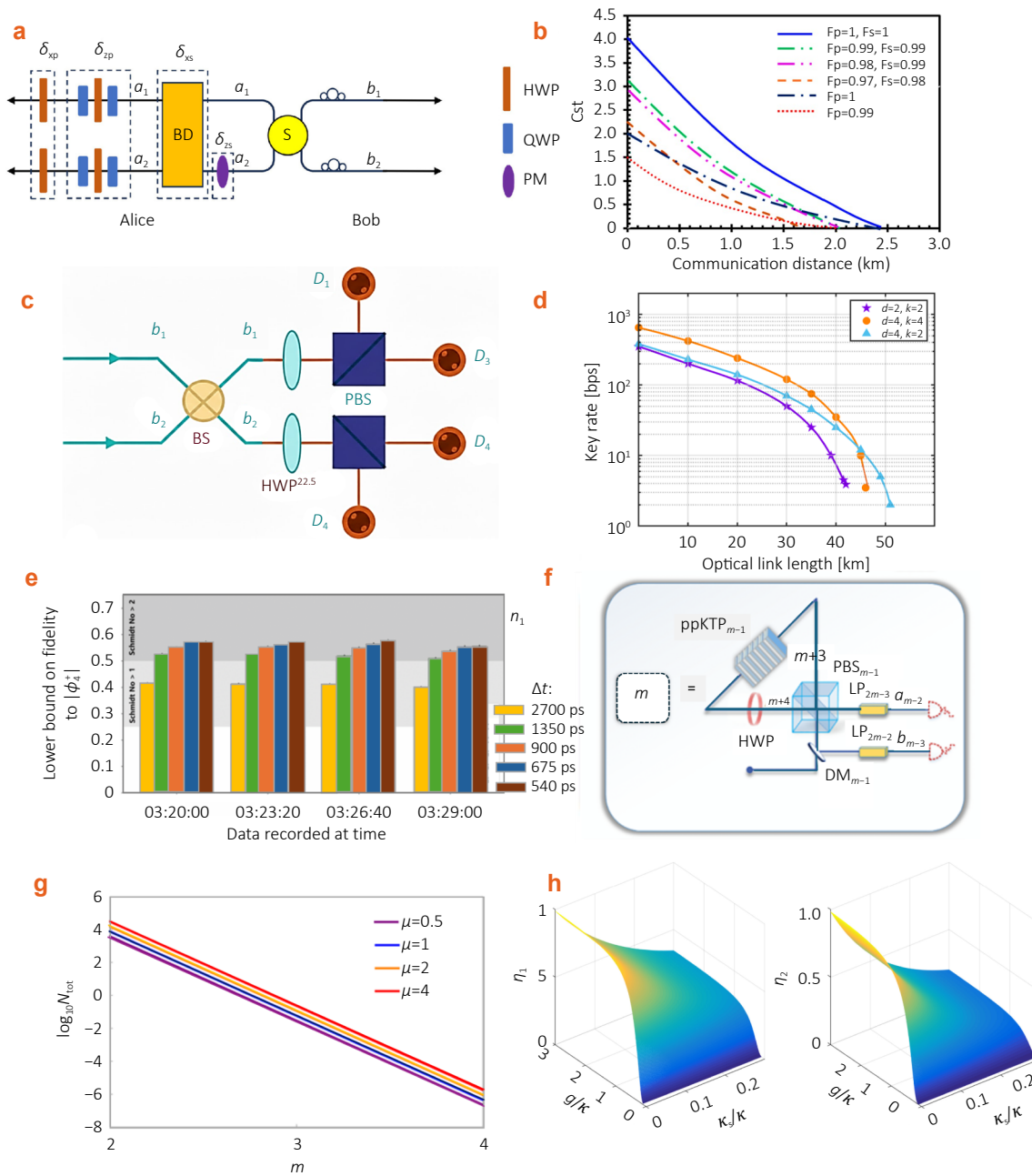


Fig. 4 | Quantum secure direct communication. (a) The schematic diagram of hyperentanglement in polarisation-spatial-mode hyper-encoding in this high-capacity DI-QSDC protocol. (b) The total secret message capacity C_{st} of the high-capacity DI-QSDC protocol altered with the communication distance d and fidelity F_p and F_s for polarisation (p) and spatial (s) modes. (c) The principle of the SPM in Bob's location using the spatial-mode and polarisation DOFs, respectively. They are using single-photon measurement. Long-distance quantum communication. (d) Results of QKD using hyperentanglement in polarisation and time-bin DOFs showing secure key rates to achieve high-dimensional coding up to 50 km distribution in a noisy fibre channel and six 10 Gbps classical communication channels over different fibre lengths. (e) High-dimensional time-bin setups QKD experiment, high-dimensional protocols were used to show an improved noise resistance over a 10.2 km free-space channel. The first transmission of genuine high-dimensional entanglement in a single DOF over a long-range free-space channel. Multi-photon hyperentanglement. (f) Generation of m -photon hyperentanglement in polarisation-time-bin DOFs with cascaded SPDC approach. (g) The function relationship between the number of generated hyperentangled photon pairs (N_{tot}) with different values of m (number of photons in the entangled state) plotted for differing values of μ (mean photon number of the source). (h) Generation of hyperentangled states where η_1 is the efficiency of generating the hyperentangled two-photon Bell-state and η_2 is the efficiency of generating the hyper-entangled four-photon Cluster state which are the functions of coupling strength g/k and side leakage rate κ_s/k . Distributed under Creative Commons license CC BY 4.0 (a) and (b) ref.⁸², ScienceDirect Fundamental Research; figure adapted with permission from (c) ref.⁸¹, Quantum Image Processing; (d) ref.⁸⁵, Optica; figure reproduced with permission from (e) ref.⁸⁷, Physical Review A; (f) and (g) ref.⁸⁸, Physical Review Applied, (h) ref.¹⁸, Optics & Laser Technology.

shown in Fig. 4(c). They pass the photon in b_1 and b_2 modes through the 50:50 beam-splitter (BS) and uses the HWP at 22.5° from horizontal. The BS and HWP are used to perform the Hadamard operations in the spatial and polarisation DOFs respectively. The PBS can transmit the photon in $|H\rangle$ and reflect the photon in $|V\rangle$. The single-photon detector is given by D_i where $i = 1, 2, 3, 4$. They found that when they have a high fidelity of 0.996 the maximal channel loss is also low at 1.1 dB. Without considering decoherence, the secret message capacity is 1.32×10^{-5} hyperentangled pair generation with channel loss of 6 dB per short-pulse timeframe. In this case it is shown that the secret message capacity is also proportional to the fidelity in both DOFs, but with increasing fidelity there is also more channel loss. This should be considered for improvement in future research. However, it is still shown that SPM simplifies the measurement process and increases the success probability of the protocol to enhance the performance and practicality of quantum communication protocols.

3.4 Long-distance quantum communication

Conventional entanglement can achieve long-distance quantum communication, although there can be issues with decoherence⁸⁷ and noise⁵. Hyperentanglement allows for more secure long-distance information sharing capacity particularly over noisy fibre channels⁸⁴ or interrupted systems such as radar systems⁸⁸ such as for defence technology. A notable example is the work of Zhong et al. who achieved long-distance hyperentanglement distribution over 50 km of noisy fibre channel, setting a new benchmark for high-dimensional entanglement-based QKD⁸⁴. As shown in Fig. 4(d), they used different subspace sizes between $k = 2$ and $k = 4$ and a $d \times d$ entangled state. Their results showed the highest optical link length above 50 km at $d = 4$ and $k = 2$ with the highest key rate at 1.36 ± 0.02 bps for 20 km channel distance and 1.35 ± 0.02 bps for 50 km. It was also shown that the intensity of noise increases linearly with channel length. However, they concluded that with a close distance and high information capacity of $k = 4$ achieves a higher key rate with high noise tolerance and this smaller subspace increases the communication distance, so higher subspaces were not tested. This is also something that could be considered for future work. Using this high-dimensional entanglement protocol allowed them to overcome having to go over stringent filtering and other difficult strategies to achieve good distance with successful results up to 50 km for this $k = 4$ configuration. They used an asymmetric Faraday-Michelson interferometer with a periodically poled potassium titanyl phosphate (PPKTP) to split each pulse emitted from the laser into two time-bins of 5 ns. This advancement highlights the potential of hyperentanglement to significantly enhance the security and reach of quantum communication networks.

Bulla et al. reported the first successful transmission of

genuine high-dimensional entanglement over a significant distance of a 10.2 km free-space channel⁸⁵. This work demonstrates the feasibility of utilising high-dimensional quantum states in challenging, real-world communication scenarios. Their experiment, which showed the dimensionality of the entanglement, focused on a high-dimensional time-bin setup for QKD. The results in Fig. 4(e) show that the fidelity is highest for short time-bins, peaking at a time difference $\Delta t = 540$ ps. The reason shorter time-bins improve performance is that they effectively filter out more accidental noise counts. The researchers also noted that the minimal time-bin size is physically constrained by the coherence time of the single-photon source (SPDC) and the electronic jitter of the detection equipment. All of these effects can decrease the precision of time-tagging. The noise affects the certified fidelity stronger for lower values of Δt and below 540 ps they found that the certified fidelity starts to rapidly decrease, so this should be considered for future experimental results. They used an 808.9 nm pump in a PPKTP crystal with a Mach-Zehnder-Interferometer (MZI) which generates hyperentangled photons that are separated and guided to Alice and Bob. By showing that the fidelity of the observed quantum state is high relative to a maximally entangled state in a four-dimensional Hilbert space, the study successfully proved the existence of genuine high-dimensional entanglement in a single DOF. This finding is crucial for advancing quantum communication beyond traditional two-level (qubit) systems.

3.5 Multi-photon hyperentanglement

Advances in leveraging hyperentanglement for enhanced security⁷ and communication capacity⁸² are further strengthened by recent progress in generating multi-photon hyperentangled states⁸⁶. Zhao et al. present protocols for directly generating a multi-photon hyperentangled state, overcoming the limitations of methods that rely on inefficient post-selection techniques⁸⁶. These protocols utilise a cascaded SPDC approach as shown in Fig. 4(f) to generate hyperentangled states encoded in polarisation-spatial modes and polarisation-time-bin DOFs with great performance. The paper aims to demonstrate a method for generating hyperentangled states with a desired number of photons (m) by adjusting the properties of the light source (specifically, the mean photon number (μ)). Their results are shown in Fig. 4(g) where they investigate how the number of generated hyperentangled photon pairs (N_{tot}) varies with different values of m and μ and showed increased performance where a greater μ of four generated the highest levels of hyperentanglement per second. Their results also show that if the repetition rate of the laser is 10^9 Hz and the PPKTP efficiency is 7.6×10^{-6} and m is three, then N_{tot} increases from 2.89×10^{-2} pairs per second when $\mu = 0.5$ to 2.31×10^{-1} pairs per second for $\mu = 4$. Due to the positive gain from multi-photon events, the number of generated hyperentangled

pairs increases with a higher mean photon number.

Dong et al. prepared a hyperentangled four-photon cluster state in the polarisation and spatial-mode DOFs¹⁸. The scheme employs the parity-check gate (PCG) and controlled-Z gate (CZG), with the assistance of the error-heralded (EH) block constructed by a quantum dot (QD) cavity coupled system and several linear optical elements. The PCG is exploited to generate a hyperentangled two-photon Bell-state from two single-photon states. The CZG is employed to prepare a hyperentangled four-photon Cluster state, utilising hyperentangled two-photon Bell-states as resources. Figure 4(h) shows the relationships between the efficiencies η_1 and η_2 for these states respectively with high efficiencies above 90%. As both plots show similar results, this suggests that the parameters (coupling strength and side leakage rate) affect the generation of both the two-photon Bell-state and the four-photon cluster state in a similar way showing the optimal conditions for generating hyperentangled states. The results show that when coupling strength is $g = 2\kappa$ and side leakage rate $\kappa_s = 0.02\kappa$ then the efficiencies are $\eta_1 = 90.07\%$ and $\eta_2 = 85.48\%$, however when increased to $g = 3\kappa$ and $\kappa_s = 0.01\kappa$, then $\eta_1 = 95.03\%$ and $\eta_2 = 92.63\%$ which are very high efficiencies. This shows that the two schemes increase in efficiency with increasing g/κ and decreasing κ_s/κ .

3.6 Quantum sensing, imaging and metrology

Hyperentanglement can increase quantum advantage in sensing¹¹ and metrology¹². Walborn et al. demonstrated this by using Heisenberg scaling in the precision of parameter estimation and using photon pairs entangled in polarisation and spatial DOFs to estimate a small tilt angle of a mirror¹¹. Their results in Fig. 5(a) show that polarisation entanglement, combined with initial spatial correlation, provides a significant enhancement in Fisher information $F^{(2)}(\theta)$, which achieves sub-shot-noise precision and reduces measurement uncertainty below the classical $\sqrt{N}$ limit. Shot noise is a measure of uncertainty that involves discrete events such as counting photons or electrons. Their results show that there is increased sensitivity with high spatial correlation of 0.84 ± 0.14 (blue line) which has a much larger enhancement in $F^{(2)}(\theta)$ as compared with low spatial correlation of 0.18 ± 0.10 (orange line). They have discussed that sub-shot noise precision has many applications including the alignment of mirrors in interferometers, enhancing the sensitivity of atomic-force microscopy⁸⁹ techniques for biological nanoimaging and detecting extremely weak gravitational waves in astroparticle physics⁹⁰. Using hyperentanglement overcomes classical limitations of measurement accuracy to allow for more sensitive and precise measurements.

Kaur et al. demonstrated an advanced method for quantum imaging using hyperentangled photon pairs with the

momentum and polarisation DOFs¹⁵. This technique is a form of quantum ghost imaging: one photon interacts with a transparent polarisation phase pattern, while its hyperentangled partner (which has never interacted with the pattern) is measured jointly in a specific polarisation basis and a quantum superposition basis of its position, which is equivalent to measuring its momentum. This approach is highly relevant for secure image transfer over long, free-space paths. Their results which are shown in Fig. 5(b) illustrate that using hyperentanglement significantly improves imaging quality compared to traditional methods. The subplot on the right, which is a single-photon image captured without hyperentanglement, appears very poor and noisy. In contrast, the left subplot generated using a hyperentangled pair where the first photon's polarisation state is vertically polarised - shows the best image clarity. Although the middle subplot, captured with a horizontally polarised state, but no image is formed with this combination. The overall comparison confirms that the successful first combination of hyperentanglement states is an effective method for enhancing quantum imaging clarity and resolution.

Hong et al. showed a method that can be applied to high-precision quantum metrology and entanglement-assisted absorption spectroscopy where they enhanced quantum state tomography with high-dimensional frequency entanglement¹⁶. They used the Hong-Ou-Mandel (HOM) experiment which performs Fourier transform between the entangled photons to overcome limitations of modal capacity of the detection geometry and can also be applied to wavelength-multiplexing quantum networks. Their results are shown in Fig. 5(c) where they plotted the determined dimensionality of the discrete frequency hyperentanglement using the plot of Shannon dimensionality D_{eff} as a function of the imbalance of the first HOM interferometer T . The plot shows that using HOM interference, the dimensions of the discrete frequency entanglement is increasing showing successful results for both theoretical (solid line) and experimental (stars) using high-dimensional entanglement.

Courme et al. state that high-dimensional spatial entanglement has been previously measured using electron multiplying charge coupled device (EMCCD) cameras, intensified scientific complementary metal-oxide semiconductor (i-sCMOS) cameras and single-photon avalanche diode (SPAD)-CMOS sensor cameras⁵⁶. However, all of these methods require post-processing of the recorded data which limits the efficient measurement of high-dimensional entanglement to certify if it is genuine entanglement⁵⁶. To overcome this, they use a single-photon sensitive time-stamping camera where spatially entangled photon pairs are generated via type-I SPDC process with high-dimensional entanglement of greater than fourteen spatial DOF dimensions. They show their method in Fig. 5(d) and results demonstrating clear images of the far-field and near-field are shown in their paper⁵⁶. Their results show the entanglement of forma-

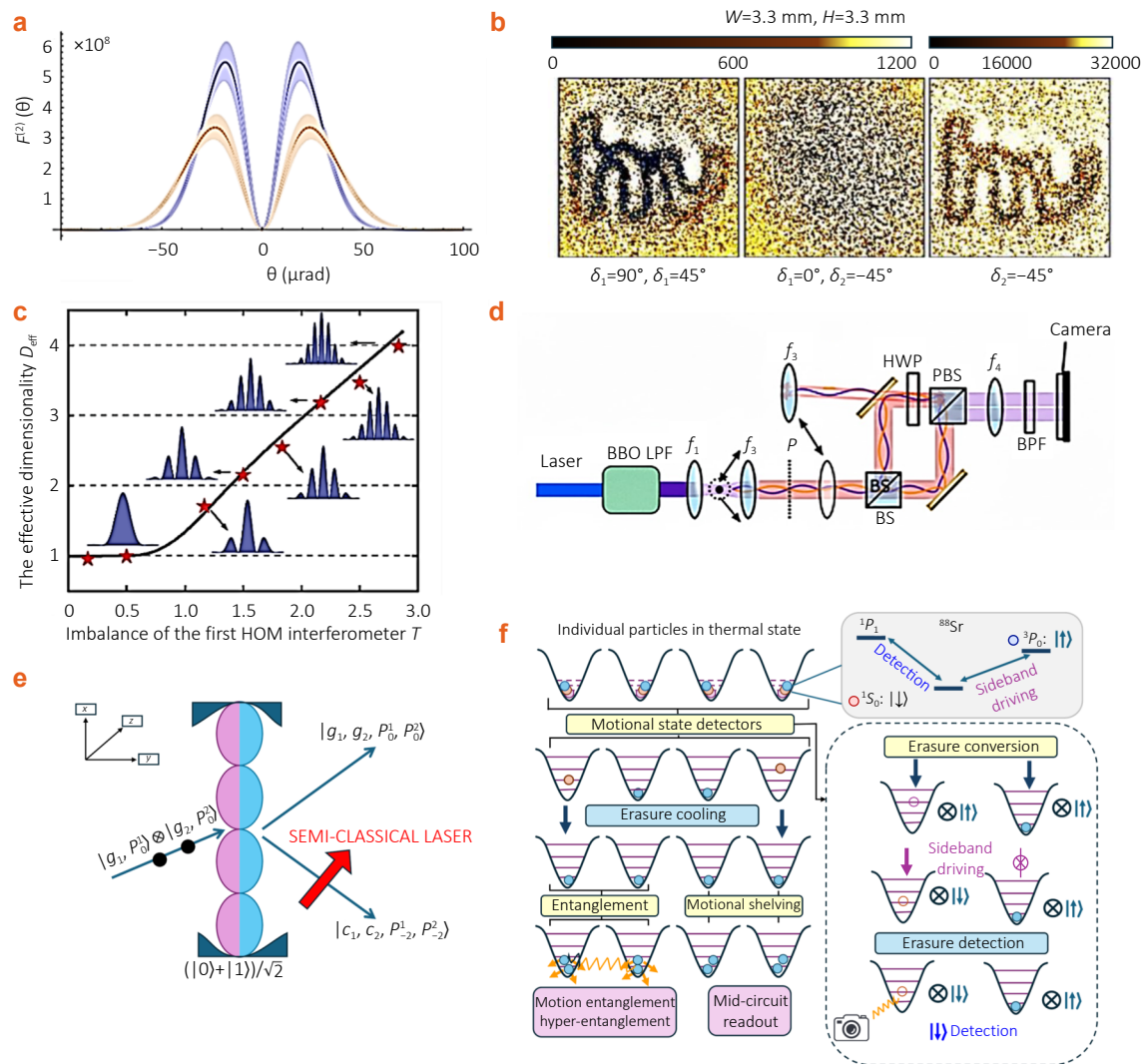


Fig. 5 | (a) Quantum sensing and imaging. Sub-shot-noise precision. Fisher information $F^{(2)}(\theta)$ as a function of θ for the input state for different values of initial spatial correlation due to primarily the polarisation entanglement with enhanced sub-shot-noise precision for differing levels of spatial correlation (blue and orange), (b) Different quality images using hyperentanglement of polarisation states with vertical polarisation (left), horizontal polarisation (middle) and without hyperentanglement (right). (c) Quantum state tomography. The effective dimensionality D_{eff} as a function of the imbalance of the first HOM interferometer T , which determines the dimensionality of the generated discrete frequency entanglement with solid line for theoretical prediction, the insets are for incident high-dimensional discrete frequency entanglement and stars for experimental results. (d) Single-photon sensitive-time-stamping camera. Experimental setup for single-photon sensitive-time-stamping camera where spatially entangled photon pairs are generated via type-I SPDC process with greater than 14 spatial DOF dimensions for far-field and near-field imaging. (e) Other applications. The schematic of the hyperentangled Bell state generation using off-resonant Bragg diffraction of two atoms initially in states $|g_1, p_0^1\rangle$ and $|g_2, p_0^2\rangle$ injected sequentially in a cavity which is in superposition state $(|0\rangle + |1\rangle)/\sqrt{2}$, (f) Scheme for erasure cooling, coherent manipulation and hyperentanglement of motional and electronic states. Figures reproduced with permission from (a) ref.¹¹, Physical Review A; distributed under Creative Commons license CC BY 4.0; (b) ref.¹⁵, Scientific Reports and (c) ref.¹⁶, Advanced Quantum Technologies; figure adapted from (d) ref.⁵⁶ Optics Letters; figure reproduced with permission from (e) ref.⁵⁷, IET Quantum Communication, (f) ref.⁵¹, Science.

tion to be greater than 2.8 along both transverse spatial axes with a dimension higher than fourteen. The paper by Jiang et al. also used single-photon detectors for heralded hyperentanglement concentration protocols (hyper-ECPs) to concentrate an unknown partially less polarisation-spatial hyperentangled Bell state with time-delay in these DOFs with results much higher than previous linear optical hyper-ECPs⁹¹.

3.7 Other applications

This section will discuss some other applications where hyperentanglement can be useful. Hasan et al. used hyperentangled swapping between separate pairs of neutral atoms through atomic Bragg diffraction which improves resistance to decoherence⁵⁷. Their methods are shown in Fig. 5(e) where they use Atomic Bragg diffraction which is a

Raman scattering phenomenon for the momentum exchange between a quantised cavity field and an atom. The atom's momentum is composed of transverse and longitudinal components and is altered in discrete multiples of the field's k -vector. This process governed by momentum and energy conservation results in distinct deflected and undeflected momentum states represented by specific solutions derived from the conservation relations. This interaction demonstrated through a two-level atom interacting with a cavity in a superposition state is described by a Hamiltonian that incorporates the atom's kinetic energy, detuning and atom-field coupling. This process is utilised to generate hyperentangled Bell states by sequentially injecting two atoms into the cavity, allowing for simultaneous entanglement of internal atomic states and external momentum states. They achieved the best results with a ^4He atom with fast interaction time of $13\ \mu\text{s}$ and finesse of the cavities of 7.85×10^6 showing high generation rate for hyperentanglement. Shaw et al. used motional DOFs in optical tweezers as quantum information carriers⁵¹. Optical tweezers and lattices also have medical applications in single-molecule biophysics for detecting protein aggregation to detect Alzheimer's disease^{92,93} and trapping of ultracold atoms^{94,95} and molecules⁹⁶. Their method is shown in Fig. 5(f) for manipulating and entangling the motional states of atoms held in optical tweezers. First, they employ a cooling mechanism based on motional state error-correction to initialise the atoms in their motional ground state, creating a low-entropy starting point. Subsequently, the coherent superposition of motional states is utilised for the mid-circuit readout of an optical qubit. This control then facilitates the generation of motion and electronic state hyperentanglement, which involves the simultaneous entanglement of the atom's spin and motional DOFs. Their protocol utilises specific pseudo-spin levels and a detection transition, where motional excitation errors are converted into erasure errors. This conversion is achieved by selectively transferring motion-excited atoms to the electronic ground state (1S_0), while atoms in the motional ground state are shelved in the 3P_0 state. Finally, atoms in the 1S_0 (red) state are selectively detected, without disturbing those in the 3P_0 (blue) state. Their results show high transduction fidelity up to 0.993.

3.8 Machine learning for quantum optical systems

This section shows the transition toward intelligent quantum optics by exploring how machine learning techniques such as deep learning^{36,40,98,99} and reinforcement learning^{72,48,73} frameworks address the core physical complexities of modern quantum systems. We categorise these advancements into three major areas: i) autonomous design and optimisation of sources (e.g. nanoscale geometries), ii) real-time adaptive control and manipulation of states (e.g. maintaining multi-DOF fidelity), iii) precise measurement

using enhanced data processing and estimation (e.g. maximising key rates). We examine how these functions are applied across various protocols for the areas discussed previously.

3.8.1 Autonomous source design and optimisation

3.8.1.1 Quantum nanodevices and materials science

Ijaz et al. says that traditional methods for metasurface design requires many trial-and-error computations, although machine learning can make design much faster and more efficient while using less computation resources⁴². They use decision tree (DT) and random forest (RF) regressors for metasurface design as shown in Fig. 6(f) (bottom left and right images) and trained the model for electromagnetic spectrum, shapes, materials, thickness and geometries of meta-atoms during forward and inverse training as shown in Fig. 6(f) (bottom left and right images). They performed forward training using meta-atoms images resized using principal component analysis (PCA) with ten components and the geometrical parameters to predict EM response data over 300–1200 nm. Inverse prediction of meta-atom parameters by applying DT and RF models (using PCA with 24 components) is performed. The results show a mean square error (MSE) rate of 8.61×10^{-10} and 1.56×10^{-2} for forward and 4.42×10^{-2} and 1.35×10^{-1} for inverse model for DT and RF respectively showing low error rates compared to other models in the upper right of Fig. 6(f). This histogram also shows high coefficient of determination (R^2) indicating high dependency of the output variable on the inputs which shows good predication capability for these two models. The materials they have tested for metasurface design are shown in the top left of Fig. 6(f) and the meta-atom designs they have tested are shown in the centre of Fig. 6(f).

Peng et al. uses transfer learning to improve the efficiency of training deep learning models based on residual neural networks (ResNets) for electromagnetic metamaterials³⁹. They use a quasi-analytical discrete dipole approximation (DDA) method to simulate electrically large metasurface arrays. Their approach uses transfer learning to significantly reduce the time for predicting metasurface design and effectively manage data processing in deep learning. Their results achieved test mean absolute relative error of 3% with a pre-trained neural network reducing data by a factor of 1000. Similar approaches using machine learning show potential to further enhance these metasurface methods and design.

3.8.2 Real-time state control and error correction

3.8.2.1 Quantum key distribution

Even though hyperentanglement has been shown as promising in diverse range of areas, there are still potential improvements. For QKD, Nemirovsky-Levy et al. say that the channel is fundamentally limited when dealing with linear elements and using hyperentanglement allows for

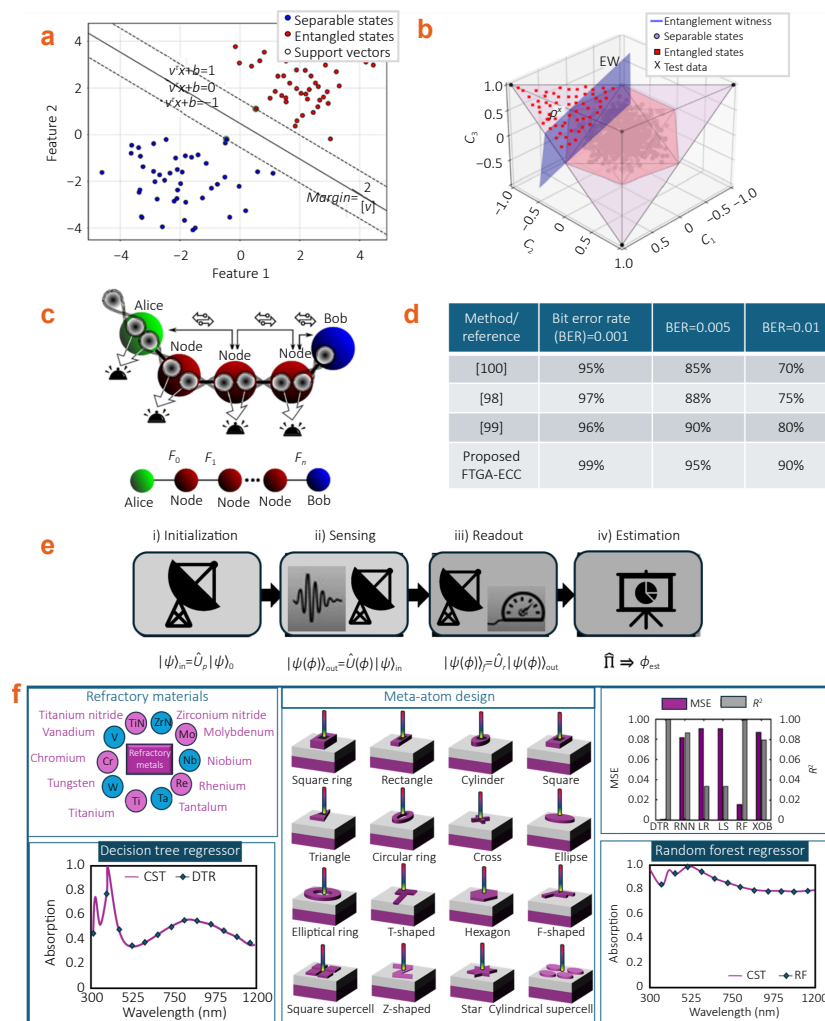


Fig. 6 | Machine learning for intelligent quantum optical systems. (a) Quantum Key Distribution. Support vector machines plot of a two-dimensional dataset with two classes separated by a hyperplane. Blue circles represent separable states and red circles are entangled states. The decision boundary $v^T x + b = 0$ (solid line) and margins $v^T x + b = \pm 1$ (dashed lines) with margin width $2/\|v\|$. Support vectors are circled in green and (b) Robust chance-constrained SVM classifier applied to two-qubit Werner density matrices to distinguish the entangled states from the separable states. The axes c_1 , c_2 , and c_3 are features selected from the density matrix. The light purple triangle region contains separable states (shown as purple dots) and entangled states (red squares). A dark blue plane labelled EW shows the entanglement witness which is the decision boundary learned by the robust SVM classifier. The black cross marked ρ^x is a test quantum state, whose position relative to the separating plane indicates its classification. (c) Quantum Secure Direct Communication. Schemes represent entanglement swapping from the initial to the final point in the quantum communications network where Bell-states are also measured. The top shows each node having a pair of particles belonging to two different entanglement states symbolised by the two black balls inside the nodes, black line between nodes is a quantum channel, green node is the initial point "Alice", red nodes are the intermediate nodes used for entanglement swapping and blue node represents the final point "Bob". The bottom shows the path between the initial and final points where $F_0, \dots, F_n$ are singlet fractions shared by two neighbouring nodes. (d) Long-distance quantum communication. Comparison of error correction performance using FTGA-ECC model in error-prone channel dataset with different machine learning models obtained from different papers. (e) Quantum sensing using advanced imaging and metrology. Flow chart showing the steps for a typical quantum metrology process including i) initialisation: a desired input probe state $|\psi\rangle_{in}$ is prepared, ii) sensing: the probe undergoes a dynamical evolution $|\psi(\phi)\rangle_{out} = \hat{U}(\phi)|\psi\rangle_{in}$ dependent on the unknown parameter ϕ to be measured, iii) readout: an operation is applied onto the output state $|\psi(\phi)\rangle_f = \hat{U}_r|\psi(\phi)\rangle_{out}$ and certain observable $\hat{I}$ is performed for measurement and iv) estimation: the unknown parameter ϕ is estimated from the measured data. (f) Quantum nanodevices using advanced materials science. Diagram showing the meta-atom structures (centre) and materials (top left) in MIM (Metal-Insulator-Metal) configuration with subwavelength designs for refractory materials-based solar absorber. Several machine learning regression models have been used (top right) for forward prediction of absorption including Decision Tree Regressor, K-Nearest Neighbour Regressor, Linear Regressor, LASSO Regressor, XGBoost Regressor and Random Forest Regressor. The bar graph shows the performance of each model with MSE and R^2 coefficients where the graphs (bottom left and right) show very high correlation between broadband spectrum predicted (with DTR and RF) and input data (conventional simulation tool (CST)) with low error rate. Figures reproduced with permission from (a) and (b) ref.⁹⁷, Mahdian; distributed under Creative Commons license CC BY 4.0 (c) ref.¹⁰⁰, Quantum Information Processing; (d) ref.¹⁰¹, IEEE Access; figures adapted with permission from (e) ref.¹², Advanced Quantum Technologies; (f) ref.⁴², Materials Today Communications.

more dimensions of qubit information sharing³. This is an efficient method although they also say they have issues with optimising detector allocation due to resource limitations. Machine learning can be used for example to predict which detector the photon can be allocated to allow for a potential solution to detector resource limitation.

Mahdian et al. show an example where they use machine learning to enhance entanglement detection for a support vector machine (SVM)⁹⁷ model as shown in Fig. 6(a). They classify entanglement detection across a hyperplane on features extracted from Pauli measurements where entangled states are shown by the red dots. The different method they used for QKD was a robust optimal entanglement witness (ROEW) optimiser as shown in Fig. 6(b) for entanglement separation that remains effective under unknown measurement noise⁹⁷. The graph shows a robust chance-constrained SVM classifier applied to two-qubit Werner density matrices for distinguishing entangled (red squares) from separable quantum states (purple dots) with both shown in the purple triangle region. They found that ROEW significantly improved entanglement detection even with minimal measurements and when it previously exceeded 10% error rates.

3.8.2.2 Quantum secure direct communication for long-distance channels

For QSDC across long-distance channels machine learning could also be applied to solve many challenges such as the performance of high-dimensional systems may deteriorate with increasing distance due to various disturbances in the channel such as noise, losses, chromatic dispersion or polarisation mode dispersion⁸⁴. Roik et al. used machine learning for finding routes in teleportation-based quantum networks using a proximal policy optimisation (PPO) algorithm¹⁰⁰. They use reinforcement learning to establish the connection between Alice and Bob and use repeated entanglement swapping of several intermediate nodes as shown in Fig. 6(c). This method efficiently searches for the best entanglement-preserving route possible between two given nodes using an evolving quantum network with the PPO algorithm. The results of finding routes in teleportation-based quantum networks when compared with Monte Carlo was able to keep the network functional for 93.4% of the time using PPO algorithm compared to 33.1% using Monte Carlo search even in damaged networks.

Anand et al. say that fault tolerance and resource efficiency in communication channels are a big limitation for practical implementations and more advanced optimisation techniques using machine learning are required¹⁰¹. They use a quantum-inspired genetic algorithm (QIGA) using simulated annealing initialisation for enhanced optimisation, combined with fault-tolerant genetic algorithm incorporating error-correcting codes (FTGA-ECC) for reliable data transmission in the error-prone channel and their results are shown in Fig. 6(d). They compared the error correction

capabilities of a few algorithms including methods using quantum-dot cellular automata (QCA)-based communication systems including quantum Fourier optics¹⁰², quantum multiple-access channel¹⁰³ and a review with machine learning methods on improving quantum communication channels¹⁰⁴ and found that the FTGA-ECC algorithm outperformed these previous methods correcting higher bit error rates (BER) of 0.01 with 90% error correction for FTGA-ECC compared with 75%, 80% and 70% for the other three methods respectively. The error correction rates for FTGA-ECC for lower rates was 99% for 0.001 BER and 95% for 0.005 BER which is a significant resilience to errors in quantum communication channels using machine learning methods.

3.8.3 Precise measurement enhancement

3.8.3.1 Quantum sensing using advanced imaging and metrology

Huang et al. says that practical constraints are there for four fundamental steps in quantum metrology including initialisation, sensing, readout and estimation as shown in Fig. 6(e) above¹². They state that coherence time has an impact on the performance of quantum sensors. The two main challenges that machine learning can help overcome in quantum metrology are 1) how can quantum entanglement be efficiently employed to enhance measurement precision and 2) how can efficient quantum parameter estimation be achieved. They have explained that deep reinforcement learning (DRL) models can help with these steps by allowing for a) entanglement generation and detection by using optimal control strategies for improved performance of quantum sensors and metrological devices^{48,71,105}, b) adaptive measurement strategies that dynamically adjust the measurement settings based on the outcomes of previous measurements for enhanced estimation of quantum states or parameters^{72,73,106}, c) quantum error correction that efficiently overcomes the effects of noise and decoherence in quantum systems for enhanced reliability and stability of quantum measurements¹⁰⁷ and d) system identification and calibration of quantum systems by learning optimal probing strategies and parameter estimation techniques which can improve the accuracy of quantum measurements¹⁰⁸. They state that using stochastic gradient descent for example for quantum metrology applications with a machine optimised control sequence can obtain fidelity over 0.99 and saves up to 80% time for state generation¹⁰⁹. DRL is used for quantum sensing because unlike architectures used for static pattern recognition such as feature extraction models like convolutional neural networks (CNNs) or sequence processors like transformers, DRL excels at adaptive, sequential decision-making and optimising quantum metrology with limited resources¹². This capability allows DRL to learn an optimal control policy - such as the best sequence of measurements or control pulses - by maximising a final

reward (measurement precision), making it uniquely applicable for real-time optimisation challenges in complex, dynamic quantum systems.

3.8.3.2 Additional applications

Machine learning for metamaterials in various devices has also revolutionised many applications in optics, healthcare, acoustics and power systems according to the paper by Tezsezen et al. saying that advances in superior metamaterials are required for targeted control of electromagnetic, mechanical or thermal properties of matter¹⁰. They provided an example from Singh et al. using feedforward deep neural network (DNN) and CNN architecture predicted the repetition period, height and size of scatters of optical dielectric metamaterials which had improved design time and predicted the diffraction profile with correlation coefficient of 0.996 and average MSE of 0.023¹¹¹. Other papers also give examples where the trade-off between power and efficiency must be precisely managed^{94,95} and could benefit from machine learning for optimisation.

Future research should investigate using machine learning to design intelligent quantum optical systems for hyperentanglement generation. Our future work will have a focus on this topic using a comprehensive machine learning analysis of metasurface features for enhanced hyperentanglement generation. Several papers have begun using physics informed machine learning^{34,112} for nanodevice optimisation and this should be considered for future research in this emerging field.

4 Conclusions and outlook

These advances collectively demonstrate the transformative potential of hyperentanglement in enhancing quantum communication, enabling more secure, efficient and high-capacity communication networks. It shows the recent advances in using hyperentanglement for a wide range of applications in quantum communication including QKD^{5,77}, quantum secure direct communication^{81,82} and teleportation^{9,10}. Furthermore, hyperentanglement is being explored for applications including quantum sensing, metrology, information processing, and many others. There is research in using quantum technologies for a potential wider scope of future impact for hyperentanglement generation including quantum correlation enhanced remote sensing¹¹³, quantum biological imaging¹¹³, free-space quantum satellite imaging¹⁵, quantum holography¹¹⁴, hyper-polarisation for quantum sensing for particle physics¹¹⁵, high energy physics²⁹ for dark matter detection using sub-shot noise sensing¹¹⁶, quantum-enhanced interferometry¹¹⁷, quantum biology for ionising radiation²², secure and enhanced quantum communication for defence applications^{31,32}, quantum healthcare¹¹⁸, quantum algorithms^{118,119} and also the use of machine learning for quantum devices and metrology^{12,38}.

As seen in the reviewed papers, hyperentanglement has

already shown several high-level advances, although there is still capability to use machine learning^{38,40,42} to help overcome some of the limitations of hyperentanglement generation. Future work should focus on machine learning based approaches for error reduction⁹⁷ and nanostructure and metasurface design³³. Phase control of multi-DOF interferometers using reinforcement learning⁴⁸ presents a compelling approach to maintain visibility under drift, with expected deliverables including reported stability bandwidth¹²⁰ and residual phase error. The outcomes would include controlling the system performance and its ability to mitigate environmental noise⁷⁷. Finally, developing learned tomography techniques¹⁶ that can significantly reduce the number of measurement settings required for hyperentangled states, with key metrics of compression ratio¹²¹ and fidelity could be explored. These tasks will be crucial in advancing hyperentanglement to a practical tool for quantum communication, sensing, and computing.

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Author contributions

Both authors contributed to the conception of the study, literature review, analysis, drafting, and revision of the manuscript.

Competing interests

The authors declare no competing financial interests.



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