Deterministic delivery of remote entanglement on a quantum network

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Large-scale quantum networks promise to enable secure communication, distributed quantum computing, enhanced sensing and fundamental tests of quantum mechanics through the distribution of entanglement across nodes1,7. Moving beyond current two-node networks8–13 requires the rate of entanglement generation between nodes to exceed the decoherence (loss) rate of the entanglement. If this criterion is met, intrinsically probabilistic entangling protocols can be used to provide deterministic remote entanglement at pre-specified times. Here we demonstrate this using diamond spin qubit nodes separated by two metres. We fully heralded single-photon entanglement protocol that achieves entangling rates of up to 39 hertz, three orders of magnitude higher than previously demonstrated two-photon protocols on this platform4. At the same time, we suppress the decoherence rate of remote-entangled states to five hertz through dynamical decoupling. By combining these results with efficient charge-state control and mitigation of spectral diffusion, we deterministically deliver a fresh remote state with an average entanglement fidelity of more than 0.5 at every clock cycle of about 100 milliseconds without any pre- or post-selection. These results demonstrate a key building block for extended quantum networks and open the door to entanglement distribution across multiple remote nodes.

The power of future quantum networks will derive from entanglement that is shared between nodes. Two critical parameters for the performance of such networks are the entanglement-generation rate $r_{\text{gen}}$ between nodes and the entangled-state decoherence rate $r_{\text{dec}}$. Their ratio $\eta_{\text{link}} = r_{\text{gen}}/r_{\text{dec}}$, which we term the quantum link efficiency14, quantifies how effectively entangled states can be preserved over the timescales necessary to generate them. Alternatively, the link efficiency determines the average number of entangled states that can be created within one entangled-state lifetime. A link efficiency of unity therefore represents a critical threshold above which entanglement can be generated faster than it is lost. Exceeding this threshold is central to allowing multiple entangled links to be created and maintained simultaneously, as is required for the distribution of many-body quantum states across a network2,15.

Consider an elementary entanglement-delivery protocol that delivers states at pre-determined times. This can be achieved by making multiple attempts to generate entanglement and then protecting successfully generated entangled states from decoherence until the required delivery time (Fig. 1a, steps (1)–(3)). If we try to generate entanglement for a period $t_{\text{gen}}$, then the cumulative probability of success will be $p_{\text{suc}} = 1 - e^{-r_{\text{gen}}t_{\text{gen}}}$. For a given $p_{\text{suc}}$, the average fidelity $F_{\text{suc}}$ with respect to a maximally entangled state of the successfully generated states is solely determined by the quantum link efficiency $\eta_{\text{link}}$ (Methods). We plot $F_{\text{suc}}$ versus $p_{\text{suc}}$ for several values of $\eta_{\text{link}}$ in Fig. 1b.

This protocol allows entangled states to be delivered at specified times, but with a finite probability of success. By delivering an unentangled state (state fidelity $F_{\text{unent}} \leq 1/2$) in cycles in which all entanglement-generation attempts failed, the protocol can be cast into a fully deterministic black box (Fig. 1a, step (4)). The states output from such a black box will have a fidelity of

$$F_{\text{det}} = p_{\text{suc}} F_{\text{suc}} + (1 - p_{\text{suc}}) F_{\text{unent}}$$

(1)

The maximum achievable fidelity $F_{\text{det}}^{\text{max}}$ of this deterministic state-delivery protocol, found by optimizing $p_{\text{suc}}$, is also determined only by the quantum link efficiency $\eta_{\text{link}}$. For $F_{\text{unent}} = 1/4$ (a fully mixed state), we find (Fig. 1c)

$$F_{\text{det}}^{\text{max}} = \frac{1}{4} \left[ 1 + 3(\eta_{\text{link}})^{1/2} \right]$$

(2)

For $\eta_{\text{link}}$ greater than about 0.83, there exists a combination of $p_{\text{suc}}$ and $F_{\text{suc}}$ high enough to compensate for cycles in which entanglement is not heralded, enabling the deterministic delivery of states that are entangled on average ($F_{\text{det}}^{\text{max}} \geq 1/2$). Deterministic entanglement delivery is therefore a critical benchmark of the performance of a network, certifying that its quantum link efficiency is of order unity or higher. Furthermore, the ability to specify in advance the time at which entangled states are delivered may assist in designing multi-step quantum-information tasks such as entanglement routing16,17.

However, so far, quantum link efficiencies of order unity or greater have remained out of reach for solid-state quantum networks. Quantum dots have been used to demonstrate kilohertz entanglement rates9,14, provides a substantial advantage in typical remote-entanglement settings. Recent experiments have highlighted the potential of single-photon protocols by generating local entanglement23,24, and remote entanglement in post-selection18,19. By realizing an alternative entanglement protocol for NV centres—point defects in diamond with a long-lived electron spin and bright optical transitions—have been used to demonstrate entanglement rates $r_{\text{gen}}$ of tens of megahertz10,14 and, in separate experiments, decoherence rates $r_{\text{dec}}$ of the order of one hertz20, which together would give link efficiencies $\eta_{\text{link}}$ of roughly 10$^{-2}$. Here we achieve quantum link efficiencies $\eta_{\text{link}}$ well in excess of unity by realizing an alternative entanglement protocol for NV centres in which we directly use the state heralded by the detection of a single photon (Fig. 2)21,22. The rate for such a single-photon protocol scales linearly with losses, which, in comparison with previously used two-photon-mediated protocols10, provides a substantial advantage in typical remote-entanglement settings. Recent experiments have highlighted the potential of single-photon protocols by generating local entanglement23,24, and remote entanglement in post-selection18,19. By realizing a single-photon protocol in a fully heralded fashion and protecting entanglement through dynamical decoupling, we achieve the deterministic delivery of remote-entangled states on an approximately 10-Hz clock.

Our experiment uses NV centres that reside in independently operable cryostat set-ups separated by 2 m (further experimental details are given in Methods). We use qubits formed by two of the ground-state spin sublevels of the NV centre (|$|$) $\equiv |m_s = 0\rangle$ and (|$|$) $\equiv |m_s = -1\rangle$, where $m_s$ is the projection of the spin along its quantization axis).
Fig. 1 | Deterministic remote-entanglement delivery. a, Deterministic entanglement delivery guarantees the output of states with an average entanglement fidelity of more than 0.5 at pre-specified times. In our protocol, underlying this deterministic delivery is a probabilistic but heralded entanglement process. Repeated entangling attempts (dashed helical links) are made (1) and then, upon heralded success (2), the entangled state (solid helical link) is protected from decoherence (represented by the lock) until the specified delivery time (3). If no attempt at entanglement generation succeeds within one cycle, an unentangled state must be delivered (4). b, For the underlying entanglement-generation and state-preservation protocol (steps (1)–(3) in a), the effectiveness of the trade-off between the average fidelity of the entangled state that is delivered and the success probability is determined by the quantum link efficiency $\eta_{\text{link}}$. The dashed line represents the classical threshold of $P = 0.5$, above which a state is entangled. c, Maximum fidelity of deterministically delivered states as a function of $\eta_{\text{link}}$. A critical threshold of $\eta_{\text{link}} \approx 0.83$ (vertical green line) must be surpassed to deliver an entangled state at every cycle on average.

Fig. 2 | Benchmarking single-photon entanglement generation. a, Experimental protocol. (1) Before entanglement generation, an NV-centre state check verifies that the NV centre is in the correct charge state (the negatively charged state) and resonant with the excitation laser (discussed further in Methods); this state is denoted ‘ready’. This is repeated until the check passes. (2) Entanglement generation is attempted until success is heralded, in which case we continue to readout (step (3)). If 250 attempts have been made without success, we revert to step (1). (3) Upon heralded success, the spin states are read out in a chosen basis by using microwaves to rotate the state, followed by single-shot readout (light bulbs indicate the detection of the bright (1) or dark (0) spin state). b, The left panel shows the optical set-up used for entanglement generation, in which the optical excitation pulses for each node are derived at a beam splitter. The single photons emitted by the nodes as a result of these excitation pulses are interfered on another beam splitter, completing an effective interferometer between the nodes. The optical phase difference $\Delta \theta$ acquired in this interferometer must be known. At pre-determined intervals, light is injected into the interferometer, as shown in the right panel. This light is measured using the same detectors that herald entanglement, and the signal is fed back via a microcontroller to a piezo-electric fibre stretcher that is used to compensate for phase drifts. For the data reported here, we stabilize the phase difference every 180 ms. c, Measured $\langle XX \rangle$ and $\langle YY \rangle$ correlations (left) for $\psi_{\text{B}}$ (where 0/1 denotes the heralding detector) and $\alpha = 0.1$ as the readout basis is swept at node A (inset). The right panel shows the measured $\langle ZZ \rangle$ correlations. d, e, Fidelity of the heralded states with respect to a Bell state (d) and entanglement-generation success rate (e), for different values of $\alpha$. For c–e, solid lines (with shaded 1-s.d. statistical uncertainties) are the predictions of our model based solely on independently determined parameters (Methods). Error bars in c and d represent 1 s.d.
Decoupling duration (ms)

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Fig. 3 | Coherence protection of remote-entangled states. a, Dynamical decoupling protects the state of the NV-centre spins from quasi-static environmental noise. To protect a spin for a time $T$, $N = T/\Delta T$ inverting (π) microwave pulses are applied at 2ΔT intervals. For node A, $\Delta T = 40.320\,\mu s$; for node B, $\Delta T = 36.148\,\mu s$. b, Fidelity with respect to the initial state for dynamical decoupling of the state $|\uparrow\rangle + |\downarrow\rangle\rangle /\sqrt{2}$ at each of our nodes. Solid lines show exponential fits with coherence times of 290(20) ms and 680(70) ms for nodes A and B, respectively. c, Dynamical decoupling of entangled states created using the single-photon entanglement protocol for $\alpha = 0.12$ and $\alpha = 0.2$. Solid lines (with shaded 1 s.d. statistical uncertainties) show the predictions of our model (Methods) based on the data in b, from which the entangled-state coherence time is expected to be $\tau = 200(10)$ ms. Error bars in b and c represent 1 s.d.

Single-photon entanglement generation (Fig. 2a) proceeds by first initializing each node in $|\uparrow\rangle$ by optical pumping$^3$, followed by coherent rotation using a microwave pulse to create the state
\[
|\text{NV}\rangle = \sqrt{\alpha} |\uparrow\rangle + \sqrt{1-\alpha} |\downarrow\rangle
\]
where $\alpha$ is determined by the choice of microwave pulse. We then apply resonant laser light to excite selectively the 'bright' state $|\uparrow\rangle$ to an excited state, which rapidly decays radiatively back to the ground state by emitting a single photon. This entangles the spin state of the NV centre with the presence ($|\uparrow\rangle$) or absence ($|\downarrow\rangle$) of a photon in the emitted optical mode:
\[
|\text{NV, optical mode}\rangle = \sqrt{\alpha} |\uparrow\rangle |\downarrow\rangle + \sqrt{1-\alpha} |\downarrow\rangle |\downarrow\rangle
\]

Emitted photons are transmitted to a central station at which a beam splitter is used to remove their 'which path' information. Successful detection of a photon at this station indicates that at least one of the NV centres is in the bright state $|\uparrow\rangle$ and therefore heralds the creation of a spin–spin entangled state. However, given the detection of one photon, the conditional probability that the other NV centre is also in the bright state, but that the photon it emitted was lost, is $p = \alpha$ (in the limit $p_{\text{det}} \ll 1$, where $p_{\text{det}}$ is the photon detection efficiency). This degrades the heralded state from a maximally entangled Bell state $|\psi\rangle = (|\uparrow\rangle |\downarrow\rangle + |\downarrow\rangle |\uparrow\rangle) /\sqrt{2}$ to
\[
\rho_{\text{NV,NV}} = (1-\alpha) |\psi\rangle \langle \psi| + \alpha |\uparrow\rangle |\downarrow\rangle + |\downarrow\rangle |\uparrow\rangle
\]
The probability of successfully heralding entanglement is $2p_{\text{det}}\alpha$. The state fidelity $F = 1 - \alpha$ can therefore be traded off against the entanglement rate directly. The corresponding success probability of a two-photon protocol is $p_{\text{det}}^2 / 2$; for a given acceptable infidelity $\alpha$, single-photon protocols will therefore provide a rate increase of $4\alpha / p_{\text{det}}^2$. For example, for our system's $p_{\text{det}} \approx 4 \times 10^{-4}$, if a 10% infidelity is acceptable, then the rate can be increased by three orders of magnitude compared to two-photon protocols.

The primary challenge in implementing single-photon entanglement is that the resulting entangled state depends on the optical phase acquired by the laser pulses used to create spin–photon entanglement at each node, as well as on the phase acquired by the emitted single photons as they propagate (Fig. 2b). The experimental set-up therefore acts as an interferometer from the point at which the optical pulses are split to the point at which the emitted optical modes interfere. For a total optical phase difference of $\Delta \theta$, the entangled state created is
\[
|\psi_{\text{det}}(\Delta \theta)\rangle = |\uparrow\rangle |\downarrow\rangle \pm e^{i \Delta \theta} |\downarrow\rangle |\uparrow\rangle
\]
where $0/1$ (with corresponding $\pm$ phase factor) denotes the detector at the central station that detected the incident photon. This optical phase difference must be known to ensure that entangled states are available for further use.

We overcome this entangled-state phase sensitivity by interleaving periods of optical-phase stabilization with our entanglement generation. During phase stabilization we input bright laser light at the same frequency as the NV-centre excitation light and detect the light reflected from the diamond substrate using the same detectors that are used to herald entanglement. The measured optical phase, estimated from the detected counts, is used to adjust the phase back to our desired value using a piezoelectric fibre stretcher. We achieve an average steady-state phase stability of $14.3(3)^\circ$, limited by the mechanical oscillations of the optical elements in our experimental set-up (the error quoted here and elsewhere is one standard deviation; Methods, Extended Data Fig. 6).

To demonstrate the controlled generation of entangled states, we run the single-photon entangling protocol with a bright-state population of $\alpha = 0.1$. After entanglement is heralded, we apply basis rotations and single-shot state readout$^2$ at each node (A and B) to measure $\langle \sigma_A^{\alpha} \sigma_B^{\beta} \rangle$ correlations between the nodes, where hereafter the standard Pauli matrices are referred to in the shorthand $\sigma_X$, $\sigma_Y$, $\sigma_Z = X, Y, Z$. We observe strong correlations for $\langle XX \rangle$ and $\langle YY \rangle$ and, when sweeping the readout basis for node A, oscillations of these coherences, as expected from the desired entangled state (Fig. 2c, left). In combination with the measured $\langle ZZ \rangle$ correlations (Fig. 2c, right), this finding unambiguously demonstrates the establishment of entanglement between our nodes.

We explore the trade-off between the entangled-state fidelity and the entanglement rate by measuring $\langle XX \rangle$, $\langle YY \rangle$ and $\langle ZZ \rangle$ correlations for a range of different initial bright-state populations $\alpha$. Using these
correlations, we calculate the fidelity of the heralded state relative to the desired maximally entangled Bell state for each value of $\alpha$ (Fig. 2d), along with the measured success rate (Fig. 2e). As predicted, the fidelity increases with decreasing $\alpha$ as the weight of the unentangled state $\alpha |\uparrow\uparrow\rangle + (1-\alpha) |\downarrow\downarrow\rangle$ diminishes (equation 5). For small $\alpha$, the fidelity saturates because the dark-count rates of the detectors become comparable to the detection rate.

Choosing $\alpha$ to maximize fidelity, we find that our protocol allows us to generate entanglement with a fidelity of 0.81(2) at a rate of $\tau_{\text{ent}} = 6$ Hz (for $\alpha = 0.05$). Alternatively, by trading the entanglement fidelity for rate, we can generate entanglement at $\tau_{\text{ent}} = 39$ Hz with an associated fidelity of 0.60(2) ($\alpha = 0.3$). This represents an increase in the entangling rate of two orders of magnitude compared to previous NV-centre experiments and of three orders of magnitude compared to two-photon protocols under the same conditions. Compared to the maximum theoretical fidelity for $\alpha = 0.05$ of 0.95, the states we generate have a 3% reduction in fidelity due to residual photon distinguishability, 4% from double excitation, 3% from detector dark counts and 2% from optical-phase uncertainty (Methods).

To reach a sufficient link efficiency $\eta_{\text{link}}$ to enable deterministic entanglement delivery, the single-photon protocol must be combined with robust protection of the remote-entangled states that are generated. To achieve this, we carefully shielded our NV centres from external noise sources, including residual laser light and microwave amplifier noise, leaving as the dominant noise the slowly fluctuating magnetic field induced by the surrounding nuclear spin bath.

We mitigate this quasi-static noise by implementing dynamical decoupling with ‘XY8’ pulse sequences (Fig. 3a, Methods, Extended Data Fig. 9). The fixed delay between microwave pulses in these sequences is optimized for each node (Methods). Varying the number of decoupling pulses allows us to protect the spins for different durations. This dynamical decoupling extends the coherence time of node A and node B from about 5 $\mu$s to 290(20) ms and 680(70) ms, respectively (Fig. 3b). The difference in coherence times for the two nodes is attributed to differing nuclear-spin environments and microwave-pulse fidelities.

To investigate the preservation of remote-entangled states, we incorporate dynamical decoupling for varying durations after successful single-photon entanglement generation (Fig. 3c). We find...
an entangled-state coherence time of 200(10) ms (decoherence rate $r_{\text{dec}} = 5.0(3)$ Hz). The observed entangled-state fidelities closely match the predictions of our model, which is based solely on independently determined parameters (Methods, Extended Data Table 1). In particular, the decoherence of the remote-entangled state is fully explained by the combination of the individual decoherence rates of the individual nodes.

The combination of dynamical decoupling and the single-photon entanglement protocol achieves a quantum link efficiency of $\eta_{\text{link}} \approx 8$, well above the critical threshold of $\eta_{\text{link}} \approx 0.83$ and comparable to the published1 state-of-the-art in ion traps, $\eta_{\text{link}} \approx 5$.

These innovations enable the design of a deterministic entanglement-delivery protocol that guarantees the delivery of entangled states at specified intervals, without any post-selection of results or pre-selection based on the nodes being in the appropriate conditions (Fig. 4a). Phase stabilization occurs at the start of each cycle, after which there is a pre-set period before an entangled state must be delivered. This window must therefore include all NV-centre state checks (necessary to mitigate spectral diffusion via feedback control and to verify the charge- and resonance conditions9), entanglement-generation attempts and dynamical decoupling necessary to deliver an entangled state. Fast conditional logic is used to adapt the experimental sequence dynamically on the basis of the detection of a heralding signal10,28,29. Further details on the experimental implementation are given in Methods and Extended Data Fig. 1.

We run our deterministic entanglement-delivery protocol at two values of $\alpha$ (0.2 and 0.12) and for delivery rates of $7–12$ Hz. We divide the experiment into runs of 1,500 cycles (that is, 1,500 deterministic-state deliveries), for a total dataset of 42,000 cycles.

We first confirm that heralded entanglement occurs with the expected probabilities (Fig. 4b) by determining the fraction of cycles in which entanglement is heralded, in which no entangling attempts succeed and in which entanglement attempts do not occur at all because the NV-centre state check never succeeds. To establish reliable and useful quantum networks, it is important that entangled states can be delivered with high confidence over long periods. The nodes must therefore not be offline, for example, owing to uncompensated drifts in the resonant frequencies of the optical transitions. We therefore do not stop the experiment from running once it starts and include any such offline cycles in our datasets. Their negligible contribution (0.8% of cycles) confirms the robustness of our experimental platform and the effectiveness of our NV-centre frequency and charge-state control (discussed further in Methods).

For each value of $\alpha$ and for each pre-set delivery interval, we determine the average fidelity of the deterministically delivered states by measuring their $\langle XX \rangle$, $\langle YY \rangle$ and $\langle ZZ \rangle$ correlations (Fig. 4c). We find that for $\alpha = 0.2$ and a rate of 9.5 Hz, we are able to create states with a fidelity of $0.56(1)$, demonstrating successful deterministic-entanglement delivery.

Our model (solid lines in Fig. 4c) captures the trends of the deterministic entanglement-delivery data effectively. However, the observed state fidelities are slightly lower than the predicted ones, hinting at sources of decoherence that are not included in our model (Methods, Extended Data Fig. 4). Identifying these potential sources will be the subject of future work.

During cycles in which entanglement is not successfully heralded, the spin states are nonetheless delivered and read out. In these cases, we deliver the state that the NV centres are left in after a failed entanglement attempt, which has a low fidelity with respect to the desired Bell state (for example, $F_{\text{unent}} = 0.04$ for $\alpha = 0.2$). Although this stringent test highlights the robust nature of our protocol, we could instead deliver a mixed state ($F_{\text{unent}} = 1/4$) or a classically correlated state ($F_{\text{unent}} = 1/2$) when a successful event is not heralded. The resulting fidelities for our experimental data if classically correlated states were delivered are also plotted in Fig. 4b (grey circles). In this case, we would be able to deliver entangled states deterministically with fidelities of $0.62(1)$ at a rate of 9.9 Hz.

The deterministic entanglement delivery between remote NV centres demonstrated here is enabled by a quantum link efficiency exceeding unity. Straightforward modifications to our experiment are expected to increase the quantum link efficiency further. Refinements to the classical experimental control will allow us to reduce the duration of the entanglement attempt from 5.5 $\mu$s to less than 2 $\mu$s, which would more than double the entangling rate. Furthermore, the entangled-state coherence time could be improved substantially by exploiting long-lived nuclear-spin quantum memories10,30,31. We anticipate that this will allow for link efficiencies in excess of 100 in the near future. Further improvements to the photon detection efficiency (including enhancement of the zero-phonon line emission)32,33 would lead to an additional increase of at least an order of magnitude.

In combination with recent progress on robust storage of quantum states during remote entangling operations16,34, the techniques reported here reveal a direct path to the creation of many-body quantum states distributed over multiple quantum network nodes. Moreover, given the demonstrated potential for phase stabilization in optical fibre over distances of tens of kilometres34, our results open up the prospect of entanglement-based quantum networks at metropolitan scales.

### Online content

Any Methods, including any statements of data availability and Nature Research reporting summaries, along with any additional references and Source Data files, are available in the online version of the paper at https://doi.org/10.1038/s41586-018-0200-5.

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**Additional information**

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**METHODS**

Deterministically delivered entangled-state fidelity as a function of quantum link efficiency. We assume an entanglement-generation rate \( r_{\text{ent}} \) and an entangled-state decoherence rate \( \tau_{\text{dec}} \). If the rate at which entanglement attempts occur is much faster than \( \tau_{\text{ent}} \) (that is, there is a low probability of success), then we can approximate entanglement generation as a continuous process. In this case, the probability density for successfully generating entanglement at a time \( t \) after beginning our attempts is \( p_{\text{succ}}(t) = r_{\text{ent}} e^{-r_{\text{ent}}t} \). The corresponding cumulative probability of success is

\[
F(t) = \int_0^t p_{\text{success}}(t) \, dt = 1 - e^{-r_{\text{ent}}t}.
\]

If we deliver our entangled state at time \( t_{\text{del}} = \beta t_{\text{dec}} \) (where \( \beta \) parameterizes the time in the decocherence rate), then the average fidelity of the delivered state (given a success occurred) is

\[
F_{\text{det}} = \int_0^{t_{\text{del}}} F(t) \, dt = 1 - e^{-r_{\text{ent}}t_{\text{del}}}.
\]

Once we succeed at creating entanglement, the state will decohere until the time at which we deliver it. For single-qubit depolarizing noise at each site, the fidelity of the resulting state after storage for a time \( t \) is

\[
F(t) = \frac{1}{4} + \frac{3}{4} e^{-t/\tau_{\text{dec}}}.
\]

As discussed in the main text, we can choose to draw a black box around this process, delivering an unentangled state (state fidelity \( F_{\text{unent}} \leq 1/2 \)) for cycles in which no attempt at entanglement-generation succeeds so that a state is always delivered. This means that the states output from this black box will have a fidelity with respect to a Bell state \( F_{\text{det}} \), given by equation (1), where \( F_{\text{det}} \) is as in the above equation. The maximum achievable fidelity when outputting a fully mixed state (\( F_{\text{unent}} = 1/4 \)) upon failure \( F_{\text{det}} \) (equation (2)) is found by optimizing \( F_{\text{det}} \) for a given quantum link efficiency \( \eta_{\text{link}} \).

The full state of a quantum system can only be experimentally determined using an ensemble of identical states. This means that, in the absence of information about which deterministic entanglement-delivery cycles have a heralded success, the only accurate description of the output of such a black-box system is that a statistical mixture is deterministically output at each cycle.

**Experiment design.** We use chemical-vapour-deposition homoepitaxially grown diamonds of type Ia with a natural abundance of carbon isotopes. Both diamonds were cut along the (111) crystal axis and were grown by Element Six. They are situated in custom-built confocal microscope set-ups within closed-cycle cryostats (4 K, Montana Instruments) separated by 2 m. We use fast microwave switches to control all other experimental hardware and also communicate with each other to synchronize the experiment.

**Herald photon-detection window.** We use a combination of polarization and temporal filtering to separate the excitation pulse from photons emitted by the NV centre. This necessitates a compromise between collecting as much of the emission light as possible, while ensuring that contamination from the pulse is minimized. In our experiment, we choose a temporal filter window (Extended Data Fig. 3) so that the pulse (assumed to have a Gaussian profile) is suppressed to the level of the detector dark counts by the beginning of the window. The end of the window about 30 ns after the pulse is chosen so that, for all of the datasets collected, the rate of detected NV-centre photons is greater than ten times the dark-count rate at all points within the window. We use a complex programmable logic device to apply this temporal filtering during our experiment and herald the successful generation of an entangled state in real time.

**Theoretical model of deterministic entanglement delivery.** We develop a detailed model to determine the expected performance of the deterministic entanglement-delivery experiment, based on the independently measured parameters given in Extended Data Table 1.

Once the set-ups are determined to be ready, the core entanglement sequence begins with single-photon entanglement generation. This proceeds by first initializing each node in \( V \), followed by a coherent rotation using a microwave pulse to create the state given in equation (3). Resonant excitation of the NV-centre nodes excites only the bright \( |\downarrow\rangle \) level to an excited state, which rapidly decays radiatively back to the ground state by emitting a single photon. This entangles the state of the NV centre with the presence \(|\uparrow\rangle\rangle\) or absence \(|\downarrow\rangle\rangle\) of a photon in the emitted optical mode (equation (4)). These photons emitted by each NV centre are transmitted to a central station at which a beam splitter is used to remove their ‘which path’ information. Successful detection of a photon at this station indicates that at least one of the NV centres is in the bright \( |\uparrow\rangle \) state and thus heralds the creation of a spin–spin entangled state. This entangled state, expressed as \(|\pi_{\text{node} A}, \pi_{\text{node} B}\rangle \), is (in un-normalized form)

\[
\rho = |\psi^+\rangle \langle\psi^+| + p_{\text{det}}|\uparrow\rangle \langle\uparrow| + p_{\text{det}}|\downarrow\rangle \langle\downarrow|
\]

where

\[
|\psi^+\rangle = \begin{pmatrix} 0 & 0 & \sqrt{p_{\text{det}}} & 0 \\ 0 & 1 & -\sqrt{p_{\text{det}}} & 0 \\ -\sqrt{p_{\text{det}}} & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}
\]

This state is parameterized by

\[
\begin{align*}
p_{\text{det}} &= \frac{1}{2}(1 - p_{\text{det}}) \left( |\pi_{\text{det}}^A\rangle \langle\pi_{\text{det}}^A| + p_{\text{det}} |\pi_{\text{det}}^B\rangle \langle\pi_{\text{det}}^B| \right) \\
&\quad + 2(1 - p_{\text{det}}) p_{\text{det}} |\pi_{\text{det}}^A\rangle \langle\pi_{\text{det}}^B| \\
p_{\text{det}} &= \frac{1}{2}(1 - p_{\text{det}}) \left( |\pi_{\text{det}}^A\rangle \langle\pi_{\text{det}}^B| + p_{\text{det}} |\pi_{\text{det}}^B\rangle \langle\pi_{\text{det}}^A| \right) \\
&\quad + (1 - p_{\text{det}}) p_{\text{det}} |\pi_{\text{det}}^A\rangle \langle\pi_{\text{det}}^B|
\end{align*}
\]

where \( V \) is the visibility of two-photon interference, \( p_{\text{det}} \) is the dark-count probability per detector (given by the product of the dark-count rate \( \nu_{\text{dark}} \) and the 25-ns length of the detection window), and \( p_{\text{det}}^A \) and \( p_{\text{det}}^B \) are the probabilities of detecting a photon emitted by node A and node B, respectively. In the limit \( p_{\text{det}} \ll 1 \), for balanced detection probabilities \( p_{\text{det}} = p_{\text{det}}^A = p_{\text{det}}^B \) and assuming no other imperfections, \( p_{\text{det}} \) tends to equation (5).

The corresponding probability of successfully heralding entanglement is

\[
P_{\text{herald}} = (1 - p_{\text{det}}) \left[ (1 - p_{\text{det}}) \left( 2 - 3p_{\text{det}}^A + 2p_{\text{det}}^B \right) \right] + p_{\text{det}}^A + p_{\text{det}}^B + p_{\text{det}}^A p_{\text{det}}^B \\
\]

The modelled success rate (plotted in Fig. 2e) is calculated by dividing \( p_{\text{herald}} \) by the entangling-attenuation duration (5.5 ns).

We model double excitation (discussed further below) by applying a Pauli Z transformation to each of the NV-centre states with probability \( p_{\text{Z}} \). Phase instability is modelled similarly, by applying a Pauli Z transformation to one of the states with probability \( p_{\text{Z}}/2 \).

\[
\begin{pmatrix}
\frac{1}{2} & \frac{1}{2} & 0 & 0 \\
\frac{1}{2} & \frac{1}{2} & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}
\]

where \( t_p \) denotes the time since phase stabilization.
Finally, we model the effect of dynamical decoupling by assuming that it acts as a depolarizing channel for each qubit. We therefore apply single-qubit depolarizing errors with a probability determined by the measured dynamical-decoupling coherence times. For decoupling for a total time of $t_d$, the total probability of a depolarizing error (that is, the application of a Pauli $X$, $Y$, or $Z$ transformation with an equal probability) is $3(1-e^{-t_d/\tau})/4$.

This model, based only on independently determined parameters (Extended Data Table 1), captures the trends of our deterministic entanglement generation data effectively (Fig. 4). However, we find that its predictions are slightly offset from the experimental measurements, suggesting that it does not include a small source of indifiability that is present in the experimental data. One potential origin of this discrepancy could be the increased number of attempts (up to two orders of magnitude) at generating entanglement after NV-centre state verification made here as compared to previous experiments. Any additional sources of indifiability that may occur over this period (for example, owing to the passive charge-state stabilization process, discussed further below) are not included in the model. A detailed study of these potential imperfections is outside the scope of this work. Nonetheless, as an estimate of the order of this effect, we find that a small systematic correction of $3\%$ to the heralded entangled-state fidelity is sufficient to effectively match our model to the data (Extended Data Fig. 4).

Passive charge-state stabilization of individual NV centres. The negatively charged NV centre (NV$^-$) can be ionized under optical illumination via a two-photon absorption process. Owing to the different level structure of the neutral charge state NV$^0$, the NV centre will remain dark if such an ionization event occurs during one of our entangling attempts. Ionization therefore hampers the performance of our deterministic entangling protocol by diminishing the success rate and delivery of a separable state upon success. Previous experiments with NV centres that worked in the regime of probabilistically generated yet heralded remote entanglement overcame NV-centre ionization by frequent charge-state verification between protocols and by actively converting the NV centre back to NV$^-$ via interleaved resonant excitation of the optical transitions of NV$^0$.

Such active stabilization protocols would require additional logical overhead in our scenario, where entanglement is generated deterministically. Instead, we passively stabilize the charge state during our entangling sequence by shining in an additional weak laser beam that is resonant with the optical transition of NV$^0$ (Extended Data Fig. 5). This provides negligible disturbance to the spin-initialization fidelity of NV$^-$ while bringing the NV centre back into NV$^-$ if it was converted to NV$^0$. We additionally identify that the optical reset beam (duration, $1.5\mu$s) is the main cause of ionization in our system and carefully balance the power of both beams so that the spin state is still well initialized and that ionization is a negligible process for our deterministic entangling protocol (up to 15,000 entangling attempts). Reducing the applied power further by eloping the spin-reset duration would decrease the entanglement rate and limit our quantum link efficiency. This highlights the basic limitations of our sequence to probe the ionization rate. We use simultaneous charge- and spin-reset beams followed by a single microwave π rotation that brings the NV centre into $|\downarrow\rangle$ and thus guarantees optical excitation during the next round. The NV centre is then read out after a final optical reinitialization into the bright state $|\uparrow\rangle$. By increasing the number of sequence repetitions, we observe a decay in the final readout fidelity that is associated with the ionization rate. By increasing the optical intensity of the charge-state reset beam, we obtain a negligible decay as a function of sequence repetitions, allowing us to overcome ionization in our deterministic entangling protocol. The illumination strength of the charge-reset beam is weak enough to avoid inducing noticeable spectral diffusion of the NV-centre emission; our measured entangled states are consistent with a high degree of indistinguishability for both NV-centre emission profiles (discussed further below).

Optical-phase stabilization. The single-photon entanglement experiment requires that the optical phase of an effective interferometer between the two nodes is known (Fig. 2). The optical-phase difference between the paths of this interferometer must be known to ensure that entangled states are available for further use. This is achieved by interleaving periods of optical-phase stabilization with our entanglement generation.

For phase stabilization we input bright laser light at the same frequency as, but orthogonally polarized to, the light used for excitation of the NV centres. The orthogonal polarization is chosen because we use a crossed polarizer to filter out the excitation light from the NV-centre emission. Using orthogonally polarized light for phase stabilization allows us to collect more light reflected from the diamond substrate. Before doing this, we verified that there is no measurable difference in the relative phase of the two polarizations within our interferometer.

Measurements of the phase drift (Extended Data Fig. 6a) show a slow drift on a second timescale, but also several strong resonances (Extended Data Fig. 6b). These resonances are thought to be from mechanical elements in the path of the beam, including the microscope-objective mount. As we were unable to completely suppress these resonances in the current set-ups, we need to measure the phase over a complete oscillation to estimate the mean phase reliably. The phase must therefore be measured for approximately 10 ms.

We calculate an estimate of the counts detected at the heralding single-photon detectors. This estimate is used to adjust the phase back to our desired value using a custom-built piezoelectric fibre stretcher and a proportional-integral-derivative routine within our ADwin microcontroller. We find that it takes two to three proportional-integral-derivative cycles to stabilize the phase optimally. We stabilize the phase for three cycles during the single-photon entanglement experiment and for two cycles during the deterministic entanglement experiment. This difference is because phase stabilization occurs during every cycle of the deterministic entanglement-delivery experiment (about 100 ms), whereas it occurs only every 180 ms during the single-photon entanglement experiment and so the phase drifts slightly less after one experimental cycle.

We achieve an average steady-state phase stability of $14.3(3)^\circ$, as measured by calibration routines spaced throughout the measurement of our dataset (Extended Data Fig. 6c, d). This stability is limited by the previously identified mechanical oscillations of the optical elements in our experimental set-up. The standard deviation of the phase averaged over a 10-ms period during active stabilization is $4.8(1)^\circ$.

Optical phase stabilization is also likely to be feasible for long-distance network links. Using long-wavelength off-resonant light for phase measurements would enable continuous stabilization during entanglement attempts with a negligible effect on the NV-centre state. An experimental study has shown that two network nodes separated by 36 km over a commercial fibre network would still allow for interference visibilities of $99\%$. For longer distances, it would also be possible to track the phase passively at the time of entanglement delivery and feed this information into a feedback loop in which the state is stored, requiring only a coherence time longer than the communication time.

Two-photon quantum interference. The quality of photon-mediated heralded entanglement between two emitters hinges on the indistinguishability of their emitted photons. We probe this indistinguishability by interfering emitted single photons on a beam splitter and measuring the number of events in which single-photon detectors connected to the output ports of the beam splitter both detect a photon. For completely indistinguishable single photons, Hong–Ou–Mandel interference ensures that both photons always exit from the same port of the beam splitter, so no coincident events should be detected.

Our two-photon quantum interference experiment proceeds by exciting each emitter with a series of well-separated optical excitation pulses (separated by 1 μs). We collect statistics on coincidence events in which one detector registers a photon after one excitation pulse and then the other registers a photon after a later excitation pulse. For an infinite pulse train, the number of coincidence events detected for each number of pulses between the detection events should be constant. However, for a finite pulse train, there are some pulses for a given pulse separation for which there is no partner excitation pulse and therefore no coincident events at that, in reality decaying number of coincidence events as a function of pulse difference (Extended Data Fig. 7a).

We use a linear fit to the coincidence events to infer the number of coincidences that would be detected from the same pulse (pulse difference of zero) if fully distinguishable single photons were input (Extended Data Fig. 7b). Because these are single photons, a counting argument shows that, for balanced emission probabilities from each emitter, the expected number of events is half of the value of the linear fit at zero pulse difference.

The ratio $r$ between the measured number of coincident events within the same pulse and the expected number of events for fully distinguishable photons is related to the single-photon wavefunction overlap $V = |\langle \psi^1 | \psi^2 \rangle|^2$ by $V = (1 - r)$ (again for balanced emission probabilities from each emitter). Incorporating the effect of the known imbalance in emission probabilities in our experiment, we find $V = 0.90(2)$.

Dephasing of entangled states due to double excitation. An optical Rabi pulse is used to excite the NV-centre nodes to a higher level via a spin-conserving transition. The NV centre subsequently decays back to its original level through spontaneous emission, thereby entangling the spin state of the NV centre and the emitted optical mode. For optical Rabi pulses of finite duration, there is a chance that the NV centre will spontaneously emit a photon during the optical pulse and be re-excited before the end of the pulse. The first emitted photon will be lost to the environment, because it is impossible to distinguish it from the excitation light. However, if the subsequent emitted photon is detected in this double-excitation process, this will falsely herald entanglement. We measured the width of our optical pulse (Extended Data Fig. 8) and used a quantum-jump-based simulation to calculate the corresponding double-excitation probability. Given that the NV centre emitted a photon within the detection window; the probability that double excitation occurred was on the order of hundreds in $1000s$. State storage via dynamical decoupling. The coherence time of NV centres is limited by interactions with other magnetic impurities. In our samples, the dominant source of magnetic field noise is the surrounding bath of slowly fluctuating $^{13}$C.
nuclear spins (natural abundance of 1.1%), which results in typical coherence times of 5 μs. We use dynamical-decoupling 'XY8' sequences of the form \((t-\pi_x-2t-\pi_y-2t-\pi_x-2t-\pi_y-2t-\pi_x-2t-\pi_y-2t-\pi_x-2t-\pi_y-2t)^N\) to elongate the coherence times of both NV centres (Fig. 3), with microwave inversion pulses \(\pi\), the waiting time \(t\) and the number of pulses \(N\). Each decoupling duration is obtained by arbitrary combinations of \(t\) and \(N\). We find the optimal combination for a targeted protection duration of about 100 ms by varying \(t\) for a fixed \(N = 1,024\). We choose \(N = 1,024\) because the infidelity introduced from inversion-pulse errors is moderate for both nodes.

Extended Data Fig. 9 shows the results of our decoupling-optimization procedure. We prepare the NV centre in a balanced superposition and choose waiting times that are integer multiples of the inverse \(^{13}\)C-nuclear-spin Larmor frequency \(\nu_L\) to avoid coupling with the nuclear-spin bath (node A, \(\nu_L = 443.342\) kHz; node B, \(\nu_L = 442.442\) kHz). Following previously reported techniques\(^{35}\), we further avoid coupling to other magnetic noise sources that result in loss of NV-centre coherence by picking five waiting times with a total variation of 16 ns for each multiple of the inverse Larmor frequency. The data (grey) are then sorted for the waiting time with the best state-preservation quality (blue) at each multiple, giving the minimal NV-centre coherence decay for this number of inversion pulses. We then pick the waiting time that guarantees a low number of inversion pulses while still providing high-quality state protection (red).

**Data availability.** The data sets generated and analysed during this study are available from the corresponding author on reasonable request.

35. Aslam, N., Waldherr, G., Neumann, P., Jelezko, F. & Wrachtrup, J. Photo-induced ionization dynamics of the nitrogen vacancy defect in diamond investigated by single-shot charge state detection. *New J. Phys.* **15**, 013064 (2013).
Extended Data Fig. 1 | Deterministic entanglement-delivery sequences.

Pulse sequences for each step of the deterministic entanglement delivery protocol are shown. These sequences are also used in the single-photon entanglement-generation experiment. (1) Optical phase stabilization. Bright light is input to measure and stabilize the interferometer (see Methods). The duration is different for the single-photon entanglement experiment. (2) NV-centre state check. By shining in two lasers that are together resonant with transitions from all of the ground states, the NV centre will fluoresce regardless of its ground-state occupation. By counting photons emitted by the NV centre we can verify that both NV centres are in the desired charge state NV\(^{-}\) and that they are on resonance with the applied lasers. The NV centre is deemed to be on resonance if the number of photons detected during the charge/resonance check surpasses a certain threshold. If no photons are detected, then the NV centre is assumed to be in the NV\(^{0}\) state and a resonant laser is applied to reset it to NV\(^{-}\). (3) Heralded single-photon entanglement generation. Entanglement generation proceeds by optically re-pumping the spins to \(\left| \uparrow \right\rangle \) (including passive charge-state stabilization; see Methods) before a microwave (MW) pulse is used to create the desired bright-state population \(\alpha\) at each node. A resonant excitation pulse then generates spin–photon entanglement. A subsequent microwave \(\pi\) pulse is used to ensure that the NV-centre state is refocused before the next stage should success be heralded. (4) Dynamical decoupling. Microwave pulses are used to implement dynamical decoupling (see Methods). (5) Single-shot readout. The NV-centre nodes can be read out in arbitrary bases in a single shot. If required, a microwave pulse is applied to rotate the qubit state before a resonant laser is applied. Fluorescence photons from the NV centre are detected if it is in the state \(\left| \uparrow \right\rangle\).
Extended Data Fig. 2 | Flowchart of the experimental sequences.

The decision trees of the ADwin microprocessors (Jaeger ADwin Pro II) that create the overarching measurement and control loops for network nodes A and B are shown. Both nodes use arbitrary-waveform generators (AWGs) for microwave and laser pulse sequencing (Tektronix AWG5014C). We additionally use a complex programmable logic device (CPLD) to herald the successful generation of an entangled state in real time (described further in Methods).

a, Decision tree when benchmarking the entangled state. b, Deterministic entanglement delivery. Here the ADwin microprocessors keep track of the time since the end of the phase stabilization ($t = 0$). 'CR check': as explained in Extended Data Fig. 1, the NV centre is deemed to be on resonance with the excitation lasers if the number of photons detected during the charge/resonance check surpasses a certain threshold ($n_{ph} > thr$); this is repeated until the threshold is passed. 'comm.' and 'comm. timeout': both ADwin microprocessors exchange classical communication, such as the success of the charge/resonance check, via a three-step-handshake; if one microprocessor waits longer than 1 ms for a response from its counterpart, then the communication times out and we return to the previous logical step (arrow). 'Count attempts': the number of entangling attempts $N$ are counted until $N = N_{max}$. 'Count dec. time': the time since phase stabilization is tracked; if the time is equal to the pre-specified state-generation time $t_{gen}$, then the AWG is triggered and the local readout sequences are executed. 'Wait for basis rot.': ADwin microprocessors wait for a trigger input from the AWG ('AWG done'), which indicates that the last microwave rotation before optical readout has been completed. 'Trigger AWGs': the microprocessor of node A triggers the AWGs of both nodes to initiate the microwave and entangling sequences; we use a single microprocessor as the trigger source to avoid timing jitter between both generated sequences. 'SSRO': optical single-shot readout. 'Suc.: Trig. from CPLD' and 'Fail: Trigger from AWG': during entanglement generation, the CPLD communicates successful detection of a photon to the nodes; during the single-photon entanglement-benchmarking experiment, the AWG at each node flags failure of the round after 250 entangling attempts. 'Do stabilize?': The microprocessors communicate that phase stabilization will be the next step in the experimental sequence; the microprocessor at node A then proceeds with the phase stabilization while that at node B waits until the phase stabilization has finished. The deterministic entangling sequence is run a total of 1,500 times (500 times per readout basis) before a new round is called in, which starts again with the verification of resonant conditions for both NV centres.
Extended Data Fig. 3 | Temporal filtering of photons. Histograms are shown of the times at which photons are detected at each single-photon detector (blue) during a deterministic entanglement-delivery experiment with bright-state population $\alpha = 0.12$. The orange histograms show the photons that were detected within the temporal filter window and so were counted as valid entanglement events. The green line shows a Gaussian fit to the pulse with a full-width at half-maximum of 2.26 ns as measured in Extended Data Fig. 8. This is used to estimate the contribution of residual pulse photons within the filter window.
Extended Data Fig. 4 | Comparison of experimental model and data. Including a 3% source of infidelity in our model (which otherwise consists only of independently determined parameters) is sufficient to account for the offset observed between our model and our experimental data. a, The modified model, plotted with experimental data reproduced from Fig. 4. Dashed lines show the model given in the main text (without the infidelity parameter). b, This infidelity also applies to the model shown in Fig. 3, because an equally large number of entanglement repetitions was used in generating the data. Error bars for data and shaded model uncertainties are 1 s.d.
Extended Data Fig. 5 | Verifying passive charge-state stabilization into NV\(^-\).  

**a.** Elementary sequence to probe the NV-centre ionization rate. 

**b.** Applying our sequence many times results in decay of the NV-centre readout fidelity due to ionization (error bars represent 1 s.d.; lines show fitted exponential decays as guides to the eye). By exploring the ionization rate for different charge-reset powers, we find an optimal regime in which the spin initialization of NV\(^-\) is not affected by the additional blue-detuned beam and ionization is effectively mitigated over thousands of trials.
Extended Data Fig. 6 | Optical-phase stabilization. Single-photon entanglement requires that the optical phase of an effective interferometer between the two nodes is known. a, A typical trace of the interferometer optical phase as it is tracked passively for 2 s. b, Power spectrum of the optical-phase signal, showing peaks thought to be due to mechanical resonances of components in the set-up. c, Active phase stabilization is used to correct for phase drifts. Here the phase is stabilized and then the interferometer is allowed to passively drift for 2 s. The standard deviation of the phase as a function of time is plotted for a dataset of 100 of these measurements. The orange line shows a linear fit, used to estimate the rate of phase drift \( \nu_{\text{int}} \approx 20° \text{ s}^{-1} \). d, Here the phase is repeatedly actively stabilized every 180 ms. Entanglement generation occurs during the periods in between stabilization. The interferometer phase is measured directly after each successful heralded entanglement event. e, Histogram of the measured post-entanglement optical phases (blue). A Gaussian fit with a standard deviation fixed to the average measured standard deviation for all entanglement data taken, \( \sigma_{\text{int}} = 14.3(3)° \), is also plotted (orange).
Extended Data Fig. 7 | Two-photon quantum interference. a, Histogram for coincident events measured by two single-photon detectors in a two-photon quantum interference experiment, measured by cross-referencing photon detection events from a pulse train of 10 optical π pulses that excite both emitters. Hong–Ou–Mandel interference of simultaneously coinciding photons ideally results in vanishing coincidence events within a single excitation round. The time difference between individual excitation rounds is 1 μs. Histograms of coincidence counts are shown with a bin-size of 5 ns. b, Total number of coincidences as a function of the number of pulses separating the two detection events. We extrapolate the measured coincidences to infer the expected coincidences for distinguishable photons at zero pulse difference by fitting a linear regression (orange). Using this to normalize the 22 observed coincidences for zero pulse difference allows us to estimate the two-photon quantum interference visibility $V = 0.90(2)$. Error bars are 1 s.d.
Extended Data Fig. 8 | Width of the optical π pulse. We find a full-width at half-maximum of 2.26 ns. This measurement is necessary to compute the dual-excitation probability (Extended Data Table 1), given a radiative lifetime of 12 ns. Error bars are 1 s.d.
Extended Data Fig. 9 | Determining the optimal inter-pulse delay for state storage and 1,024 inversion pulses. We initialize a superposition state on the NV-centre electron spin, preserve it via dynamical decoupling and finally perform optical readout after another $\pi/2$ pulse. We probe the coherence of the NV centre by varying the inter-pulse delay $t$ in steps of the Larmor period $1/\nu_L \approx 2.25 \mu$s and shifting the delay in steps of 4 ns for a total of five data points per Larmor period (grey). For each multiple of the Larmor period we pick the best (the most preserving) inter-pulse delay (blue). We determine the optimal delay $t$ by selecting an inter-pulse delay that provides sufficient state preservation (about 100 ms) for a moderate number of pulses (red data point and inset text). Left, node A; right, node B. Error bars are 1 s.d.
Extended Data Table 1 | Independently measured experimental parameters for the performance of the nodes used in our experiment

| Parameter | Node A | Node B | Description |
|-----------|--------|--------|-------------|
| $T_2$ (ms) | 290(20) | 680(70) | Dephasing time of the electron spin state. |
| $T_1$ (s) | > 1 | > 1 | Relaxation time of electron spin eigenstates. |
| $p_{\text{det}} (10^{-4})$ | 2.8(1) | 4.2(1) | Probability to detect a ZPL photon after a single excitation. |
| $p_{\text{ionize}}$ | $\leq 10^{-6}$ | $\leq 10^{-6}$ | Probability of passive charge-state control failure per entangling attempt (detailed in methods). |
| $t$ (µs) | 40.320 | 36.148 | Optimized inter-pulse delay for state storage. |
| $F_0$ | 0.959(3) | 0.950(3) | Fidelity of the electron read-out for $|\uparrow\rangle$. |
| $F_{\pm 1}$ | 0.995(1) | 0.996(1) | Fidelity of the electron read-out for $|\downarrow\rangle$. |
| $V$ | 0.90(2) | 0.04 | Visibility of the two-photon quantum interference (detailed in methods). |
| $p_{2\text{ph}}$ | 0.04 | | Estimated probability of double excitation during the optical $\pi$-pulse (detailed in methods). |
| $\nu_{\text{dark}}$ (Hz) | 20 | | Dark count rate per detection channel. |
| $\sigma_{\text{Int}}$ | 14.3(1)$^\circ$ | | Initial uncertainty of the interferometric drift (detailed in methods). |
| $\nu_{\text{Int}}$ (/s) | $\sim 20^\circ$ | | Estimated drift rate of the free running interferometer (detailed in methods). |